Wind-Effected Dynamic Quadrotor Route Planning with Metaheuristic Methods in Different Weather Conditions

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Wind-Effected Dynamic Quadrotor Route Planning with Metaheuristic Methods in Different Weather Conditions

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Abstract—**In cases where quadrotors, which are increasingly important rotary-wing Unmanned Aerial Vehicles (UAVs), are required to visit more than one location, route planning should be done to reduce the cost of flight and increase the efficiency. In this study, it is aimed to reduce the flight time and increase the efficiency of Quadrotor Route Planning (QRP) based on the changes in wind speed and wind angle. To achieve this, a dynamic QRP application which can generate routes which are suitable for changing environmental conditions by using instantaneous wind data and real location coordinates has been developed. In this application, Genetic Algorithm (GA), Tabu Search (TS) and Traveling Salesman Problem (TSP) with GA metaheuristic methods were used comparatively to optimize QRP according to flight time. Among these methods, the TSP with GA method is the metaheuristic method that gave the most optimal results. When the results are examined, it is seen that wind effect dynamic QRP that uses TSP with GA method provides up to 26% improvements in flight time compared to Standard QRP that uses TSP with GA method.**

Index Terms—**genetic algorithms, heuristic algorithms, routing, unmanned aerial vehicles, wind.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are the latest generation aircraft that are not intended for human transportation and can be used for military and civil applications. Unlike manned aircraft, UAVs do not require personnel on board and are supported by autonomous structures during majority of the flight [1]. UAVs can fly autonomously by remote control from a ground station or by using various sensors and controller cards [2-3], and autonomous UAVs act according to a preset route plan, or a route plan created by processing the data from the sensors via Artificial Intelligence (AI) methods.

There are many types of UAVs. Those with the features of small size, rotary wing and Vertical Take-Off and Landing (VTOL) are often referred to as Quadrotor and Quadcopter. Quadrotors, significance of which is increasing nowadays, are mini UAVs used in military and civilian areas due to their low cost and ease of use [4]. Quadrotors, which were initially used in agriculture, surveillance-exploration, and defense industry, are now preferred in various areas from cargo transportation to moving object tracking [5-6].

The advances in technology increase the need for systems that can perform their tasks economically and dynamically in a very short time [7]. In this context, one of the most important research areas on quadrotors is Quadrotor Route Planning (QRP). One of the problems that researchers work on the most in QRP is the Traveling Salesman Problem (TSP) which is the basis for other optimization methods. With TPS, it is aimed to return to the starting point by stopping at each city or target, to which the distances are known, once and to find the shortest or the least costly route simultaneously [8]. Although TSP is easy to define, the fact that the increase in the number of locations in the route causes an exponential rise in the number of tours makes it impossible to solve the problem at the desired time. Therefore, this case is among NP-hard (Nondeterministic Polynomial Time-Hard) problems [9]. It is shown that more successful results are observed in solving NP-hard problems when classical methods are used in combination with metaheuristic solution methods [10-12]. Therefore, in this study, the optimum solution for QRP is sought by resolution of Genetic Algorithm (GA), TSP with GA, and Tabu Search (TS).

GA is a search and optimization method that works according to the rule of the survival of the best [13]. It is preferred for problems where a solution cannot be found or where the solution space is too large [14].

In the first stage of GA, the parameters of the problem under examination are coded appropriately, and chromosomes are formed. Afterwards, an initial population consisting of these chromosomes is created [13]. While the initial population, which greatly affects the solution performance of GA, is usually randomly generated in classical GA, in TSP with GA it is generated using the nearest neighbor algorithm [12]. In TSP with GA, instead of binary coding, permutation coding, which is used in solving problems where ranking is important and repetition is undesirable, is preferred as a coding method [15].

TS, which is another metaheuristic method, is a local search algorithm that is frequently used to solve integrated optimization problems such as TSP. In order to avoid getting stuck at local optimum points during the search in TS, the information that is obtained during a previous search is used [16].

QRP can be characterized by three-dimensional space, wind effect (wind speed, wind angle), lack of fixed paths

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between locations, limited battery quantity, etc., and it differs from Vehicle Routing Problems (VRP) due to these features [17-18]. QRP can be defined as obtaining an optimum route plan from a specific location that will allow visiting different locations (city, target, etc.) with most efficiency (energy, time, distance, etc.). Frequent changes in the locations included in route planning, instant changes in the wind speed and wind angle, limited battery amount and flight time make it difficult to obtain the optimum QRP.

One of the most important problems encountered during Quadrotor flights is windy weather conditions [19-20]. Windy weather conditions make it difficult for quadrotors to fly stably [21], increase battery consumption [18], [21-22] and increase flight time [23].

When the studies conducted on QRP considering the effect of wind are examined; estimating wind speed and wind direction [24-26], compensation of orbital deviations caused by wind effect in quadrotor flight control [17], investigation of quadrotor maneuverability in the wind field [20], examination of battery performance and energy consumption in windy weather conditions [22], [27], and quadrotor modelling and control where the distorting effect of wind is taken into account [4], [19], [28] are the most studied areas. Moreover, Tseng et al. [29] conducted a study examining the modelling and charging optimization of quadrotor battery performance under different conditions. Thibbotuwawa et al. [30] conducted a series of tests on several samples by scheduling missions resistant to weather uncertainty to investigate how customer satisfaction is affected by various parameters such as wind speed, travel time and fleet size. However, in our literature review, no studies were found in which the optimum route plan is dynamically created with metaheuristic methods, taking into account the changes in wind speed and angle in QRP.

In windless environment, the quadrotor ground speed vector is equal to the quadrotor air speed vector. In windy environment, on the other hand, the quadrotor ground speed vector changes depending on the quadrotor air speed vector and the wind speed vector [31]. It is aimed to minimize the total flight distance in the creation of the Standard QRP (SQRP), which is created in a windy environment without considering the effect of wind. However, the Dynamic QRP (DQRP), which is created considering the wind effect, aims to minimize the total flight time.

Flight time in SQRP is calculated assuming that the wind effect is zero (0) for all weather conditions. Therefore, when flying along the route established according to SQRP in a windy environment, the actual flight time will differ from the calculated flight time. This means that the optimum route for the flight time cannot be obtained [32]. Moreover, battery consumption, which is directly related to wind effect and flight time, is one of the major problems encountered during flights with quadrotor [22]. In the route plan created according to the SQRP, a quadrotor flying in windy weather conditions can complete its flight in longer time than the calculated flight time, or a flight might have to be terminated due to unexpected battery depletion before the route plan is completed [31-33]. Terminating the flight before the route plan is completed adversely affects the flight efficiency and significantly increases the flight cost.

In order to create a DQRP, flight times between locations are updated depending on changes in weather conditions, and the DQRP is created using up-to-date flight times. When flying along the route plan which is created according to the DQRP, the actual flight time and the calculated flight time will be very similar to each other. As a result, problems in accurate timing caused by changes in weather conditions will be minimized. In addition to this, with the DQRP created taking the wind effect into consideration, safer and more stable flights will be conducted compared to the SQRP created without taking the wind effect into consideration. Thus, it is estimated that the overall operating cost of the system will decrease and the vehicle / load safety will increase even more.

In this study, it is aimed to dynamically create the optimum QRP that will enable visiting predetermined locations, by using different metaheuristic methods and taking into account the wind effect. For this purpose, Wind Effected DQRP (WEDQRP) application, which uses Visual Studio C # programming language, real location coordinates and real wind data, was developed. The WEDQRP application developed was coded in a way to create a separate QRP for GA, TSP with GA and TS metaheuristic solution methods. GMAP.Net map plugin was used to determine the locations for which a route plan would be created in WEDQRP application. The location coordinates determined over the WEDQRP application and the real location coordinates were matched with each other through the GMAP.Net map plugin. Wind speed and wind angle data which are used in WEDQRP application are recorded instantly from the website of the General Directorate of Meteorology (MGM) [34]. WEDQRP is dynamically generated using real-time wind recordings from MGM site.

II. Quadrotor Route Planning

ARP was first introduced in 1959 by Dantzig and Ramser. ARP is the determination of routes in which distance and time are minimized in routing vehicles moving from one or more warehouses under certain constraints to meet the needs of customers. The purpose of ARP is to ensure that the vehicles carrying out distribution or collection follow the lowest cost route provided that they stop at each of the stops in different locations [35]. In the QRP, unlike the classical ARP, there are factors such as the absence of fixed highways, the fact that the quadrotor is greatly affected by the weather conditions and the limited amount of batteries.

In cases where more than one location is desired to be stopped by in quadrotors, route planning should be made to increase efficiency and reduce costs. QRP is the planning of the route that allows to stop by the locations and to return to the starting location under energy, distance and time constraints. In QRP, it is aimed to minimize the distance travelled by the quadrotor, to minimize the task completion time or to minimize energy consumption [36].

In order to provide the QRP solution in line with certain constraints and purposes, certain information such as the number of locations, coordinate information of the locations, distance information between locations, travel time between locations and weather conditions are required.

There are many possibilities for QRP solution. Among these possibilities, it is necessary to find the least costly one. This activity is a difficult and time-consuming process.

There are two basic methods in the QRP solution. These are precise solution methods and heuristic solution methods. Optimal results are achieved with precise solution methods. However, as the number of locations increases, it takes quite a long time to solve the problem with precise methods. Therefore, instead of the best solution for solving problems with multiple locations, heuristic methods that enable us to find a solution close to the best solution in a shorter time are preferred [37].

The following constraints should be considered in QRP solution [38]:

- Quadrotor ends the flight at the starting location.
- Each location is visited only once.
- Quadrotor must complete a route.
- Quadrotor flight time must be determined.

The formulation of a classical QRP model can be given with a graph in the form of $G=(L,\ E)$.

$$\begin{aligned} &G=(L,E):\ \textit{One graph},\\ &L=\{l_0,\ l_1,\ l_2,\ldots,\ l_n\}:\ \textit{Node (location) set},\\ &E=\{l_k,\ l_l\}\ :\ l_k,\ l_l\in< L,k\neq 1:\ \textit{Edge (path) set}.\end{aligned} \tag{1}$$

In the set L, l_0 represents the starting point, and n represents the locations.

The QRP mathematical model is a generalized version of the TSP integer linear programming model [39].

The objective function is given in Equation 2.

Minimize:

$$z=\sum_{k=1}^{n}\sum_{l=1,k\neq l}^{n}x(k,l)\,d(k,l) \tag{2}$$

Limitations:

$$\sum_{k=1,k\neq l}^{n}x(k,l)=1\ \ l=1,2,\ldots,n \tag{3}$$

$$\sum_{l=1,k\neq l}^{\mathrm{n}}x(k,l)=1\ \mathrm{k}=1,2,\ldots,n \tag{4}$$

$$\sum_{k,l\in S,k\neq l}^{\mathrm{n}}x(k,l)\leq|S|-1,\forall S\in(1,2,\ldots,n),\ \ |S|\geq 2 \tag{5}$$

$$x(k,l)=\begin{cases}1, \textit{If going from point k to point l}\\ 0, \textit{If not going from point k to point l}\end{cases} \tag{6}$$

In equation (2), the objective function minimizes the total distance travelled. The objective function can also be used for total time and energy consumption. The n in the equations represents the number of locations. In Equation (2), *d* (*k, l*) shows the distance between *k* and *l* points and *x* (*k, l*) expresses whether we have gone from point k to point *l*. Equation (3) means that each point will be left only once, and equation (4) means that each point will be reached only once. Equation (5) is a sub-round elimination constraint to get rid of any sub-rounds that may occur in order to limit the appropriate solutions to one round and S is the subset of locations. In Equation (6), in cases where *x*(*k, l*) is 1, it indicates that k point is left and *l* point is reached and in cases where *x*(*k, l*) is 0, it indicates that *l* point is not reached [40].

A. Metaheuristic Methods in Quadrotor Route Planning

Optimum solutions are reached with precise methods. However, for large scale problems, solving the problem with precise methods takes a lot of time. Heuristic methods are used to solve complex problems that cannot be solved with precise methods. Heuristic methods aim to find an acceptable solution close to the optimum in a much shorter time. Heuristic methods are divided into two subclasses as classical heuristic methods and meta-heuristic methods [37]. Metaheuristic methods are algorithms designed to solve complex optimization problems and they are usually inspired by natural events. Metaheuristic methods, which are preferred for reasons such as being easy to understand and applicable, provide optimum-like solutions quickly [41]. GA, TSP with GA and TS metaheuristic methods will be examined in this study.

1) Quadrotor Route Planning with Genetic Algorithm

GA was first proposed by John Holland (1975) and is an intuitive search technique based on evolutionary mechanism [42]. GA is used for problems whose mathematical model cannot be formed or precise solution cannot be reached and solution space is very large.

GA, taking the process of living things in nature as an example, is a method built on the fact that good individuals survive, breed and create new generations, and bad ones are eliminated by natural selection. The genetic algorithm uses natural selection operators such as crossover and mutation, with an initial generation of solution sequences [13].

In the GA method, the possible solution set is called the population. Populations consist of structures defined as individuals or chromosomes whose building blocks are genes. First, a population with n chromosomes is created. Then, for each chromosome in the population, f (x) fitness function is calculated. With the fitness function, among a space where all solutions are located, good solutions are taken and unsuitable solutions with bad harmony values are eliminated. The following procedures are repeated until a new population is formed [43].

Selection: According to suitability level, two chromosomes are selected among the population to crossover. Here, the one with a high degree of suitability has a high chance of being selected.

Crossover: Selected parental chromosomes are crossed to form new individuals according to the crossover rate. If crossing is not applied, individuals would become complete replicas of their ancestors.

Mutation: Changes are made according to the specific mutation rate by manipulating the locations of some sequences on the chromosome.

After the selection, crossover and mutation steps, new individuals are added to the population or replaced with individuals with poor fitness value. When the stop criterion or iteration is met, the program is stopped and the solution with the best fitness value in the population is taken as the optimum result.

The basic process steps of GA are as follows:

Step 1: Create starting population.

Step 2: Calculate fitness values of individuals in the population.

Step 3: Select individuals in the population according to the individual selection method for crossing.

Step 4: Create new individuals by crossing selected individuals according to the crossing probability.

Step 5: Mutate new individuals according to mutation probability.

Step 6: Identify new individuals as existing members of the population.

Step 7: Go to Step 2 until the specified number of iterations is reached or the target value is reached.

GA eliminates inappropriate solutions thanks to the operators it uses. GA terminates the solution search when the specified fitness value is reached, when a more successful solution than the best solution obtained cannot be produced, or when the number of studies reaches to the number of iterations determined.

2) Quadrotor Route Planning with TSP with GA

TSP can be defined as the problem of an artificial traveling salesman constructing a closed tour of minimum length provided that each city is visited once when n cities (locations) are given [44]. TSP is a problem in the difficult-to-solve category and its solution takes time. As the problem size increases in TSP, the possible number of turns increases. Thus, it becomes impossible to find a possible solution. Therefore, heuristic algorithms are used to solve TSP in big problems [45]. In the study, the TSP was solved with a different approach from classical GA by using GA for the analysis of TSP.

TSP with GA differs from classical GA in initial population creation and coding. In the first stage of GA, an initial population from which new generations will be derived should be established. In classical GA, the initial population is usually randomly created. In the study, a certain number of solutions were obtained by using the nearest neighbor algorithm instead of randomly generating the entire initial population and these solutions were included in the initial population. In the nearest neighbor algorithm used, the nearest neighbor ratio can be changed.

The steps to be followed in the nearest neighbor algorithm are as follows [46]:

Step 1: Start in any city and accept it as the current city.

Step 2: Select the non-visited city closest to the current city and make it the current city.

Step 3: Repeat step 2 until all cities are visited and then return to the starting city.

In Step 1 in the study, instead of starting from any location, the home location we determined is accepted as the starting location.

The most used coding methods in classical GA are binary coding and permutation coding. While in binary coding, each chromosome is expressed as a sequence consisting of 0 and 1, in permutation coding, each chromosome shows a sequence of characters that make up it. Since TSP with GA is a sequencing problem, permutation coding is used as a coding method for coding chromosomes [47].

If we take an example with seven locations, the labels of the locations are "Home, 1, 2, 3, 4, 5, 6". The tour can be displayed as "Home → 1 → 6 → 2 → 3 → 4 → 5 → Home" or as (H-1-6-2-3-4-5-H).

3) Quadrotor Route Planning with Tabu Search

In TS, which was developed by Glover in 1989, the information previously obtained during the search is used to avoid getting stuck at local optimum points. In this structure, called short-term memory, the solutions that are just visited during the search are kept in a tabu list and these solutions are prevented from being reconsidered during the algorithm [48]. In TS, movement is provided during the search procedure, from a potential solution to the solutions among neighboring solutions, and with higher suitability until certain stopping criteria is met.

The basic process steps of TS are given below [49]:

Step 1: Get a starting solution (S). Assign values for parameters (stop criterion, tabu list length, etc.) to which values should be assigned initially.

Step 2: Generate neighboring solutions belonging to S with a determined neighborhood structure and select all $S^1 \in N(S)$ the best acceptable ($S_{\text{the best}}$) among these solutions that are not in the tabu list.

Step 3: Replace current solution (S) with $S_{\text{the best}}$ and renew the tabu list.

Step 4: Go to Step 2 until the stop criteria are met.

B. Wind Effected Dynamic Quadrotor Route Planning

Wind speed, air speed and ground speed vectors will be used to create DQRP. The wind speed vector is shown in equation 7.

$$\overrightarrow{V_w} = (V_w,\ A_w) \tag{7}$$

In $\overrightarrow{V_w}$ wind vector, V_w shows the wind speed. Wind speed is the distance the wind travels per unit time with respect to the ground. A_w represents the wind angle used to describe the air movement direction.

In the study conducted, instantaneous weather forecast data obtained from MGM website are used. In the weather forecast data available on the MGM website, the wind direction is expressed with angle values between 0°-360°. In the study, the MGM wind directions were taken as a reference and the wind angles blowing to the south, west, north, east directions respectively correspond to 0°, 90° 180° and 270°. The wind directions created with reference to MGM wind data are shown in Figure 1.

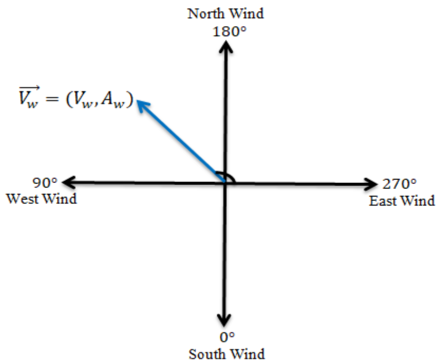

Figure 1. Wind Directions

$$\overrightarrow{V_a} = (V_a,\ A_a) \tag{8}$$

The air speed vector is the speed of the quadrotor through the air. V_a represents the airspeed and A_a indicates the airspeed direction angle. There are certain lower and upper limits of the air speed according to the quadrotor type and characteristics.

$$\overrightarrow{V_g} = (V_g,\ A_g) \tag{9}$$

The ground speed vector is the velocity of the projection of the quadrotor on the earth under the effect of the wind during flight. V_g represents the ground speed and A_g represents the route angle.

The relationship between air speed, ground speed and wind speed vectors are shown in Figure 2.

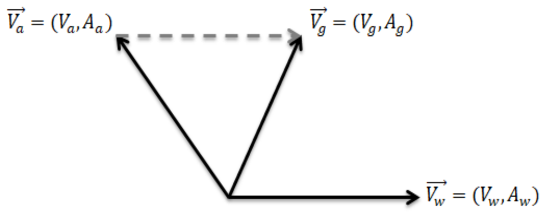

Figure 2. The relationship between air speed, ground speed and wind speed

Two basic methods (strategies) are proposed for the calculation of the velocity vector to be used in the WEDQRP application developed [23], [31], [50]. The demonstration of these methods on a 6- location route plan is shown in Figure 3. In the first method (Figure 3.a), the quadrotor travels at a constant ground speed of 30 km/h. In the second method (Figure 3b), the quadrotor travels at a constant air speed of 30 km/h.

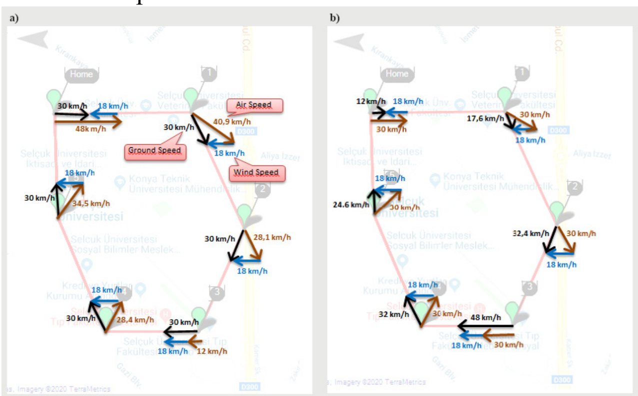

Figure 3. (a) constant ground speed and (b) constant airspeed methods for QDRP

When the ground speed $vg_{k,l}$ is accepted constant, the airspeed $va_{k,l}$ is calculated as in equation 10.

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

Here k and l represent the locations. The slope angle of the ground speed vector ($Vg_{k,l}$) is $ag_{k,l}$. The slope angle of the wind speed vector ($\vec{V_w}$) is $aa_{k,l}$. The wind speed and wind angle at the time of creation of the DQRP are taken from the MGM website and DQRP is created according to the wind data taken. It is assumed that wind data does not change during the flight after the DQRP is created.

When the airspeed $va_{k,l}$ is accepted constant, the ground speed $vg_{k,l}$ is calculated as in equation 11.

$$vg_{k,l} = \sqrt{\begin{aligned}&(va_{k,l} \times \cos aa_{k,l} + vw \times \cos aw)^2 + \\ &(va_{k,l} \times \sin aa_{k,l} + vw \times \sin qw)^2\end{aligned}} \tag{11}$$

$$aa_{k,l} = ag_{k,l} - \sin^{-1}\left(\frac{vw}{va_{k,l}} \sin\left(aw - ag_{k,l}\right)\right) \tag{12}$$

The slope angle of $\overrightarrow{Va_{k,l}}$ airspeed vector is $aa_{k,l}$.

When the ground speed is accepted constant, the flight time between locations will not change in windy and windless environments. In DQRP, it is aimed to determine the real flight times and to minimize the flight times. Therefore, in windy environment, the ground speed was calculated by using the constant air speed method in order to calculate the flight times depending on the wind [23], [51].

In QRP, the distance between locations was calculated with the haversin formula shown in equation 13.

$$\begin{aligned} &hav(Q) = \sin^2\left(\frac{Q}{2}\right) \\ &d = 2r \arcsin\left(\sqrt{hav(\varphi_2 - \varphi_1) + \cos(\varphi_1)\cos(\varphi_2)\, hav(\lambda_2 - \lambda_1)}\right) \\ &d = 2r \arcsin\left(\sqrt{\sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)\, \sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \end{aligned} \tag{13}$$

$$t_{k,l} = \frac{d_{k,l}}{vg_{k,l}} \tag{14}$$

In order to create DQRP with the WEDQRP application, firstly the locations are determined through the GMAP.net map plugin, and then metaheuristic method selection is made over the WEDQRP application, whose interface is shown in Figure 5. For each route plan in the population or solution set created according to the selected method, the ground speeds between locations in the route plan are calculated according to the formula in Equation 11, and distance data are calculated according to the formula in Equation 13. Flight times between locations are calculated according to the formula shown in Equation 14 using the ground speed and distance data between locations. Then the total flight time for that route plan is achieved by summing the calculated flight times between locations. These operations are carried out for all route plans created according to the metaheuristic method chosen by the user and the metaheuristic method parameters on the WEDQRP application. At the last stage, the route plan that gives the optimum result among the total flight times calculated for all route plans is determined. The determined optimum route plan is accepted as the DQRP of the chosen method.

Figure 4 shows the flight routes of SQRP created without taking wind effect into consideration and of DQRP created by taking wind effect into consideration for a flight with 7 locations using the TPS with GA method over the WEDQRP application.

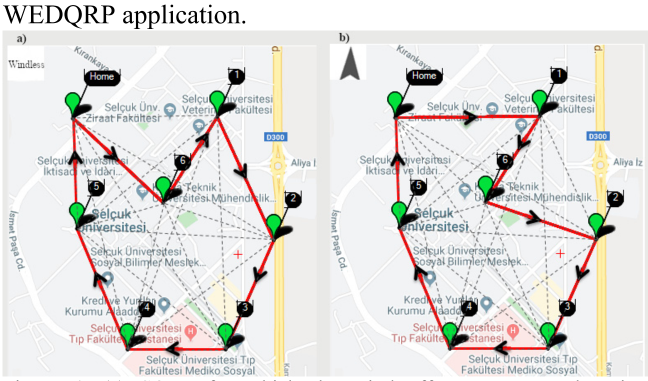

Figure 4. (a) SQRP for which the wind effect was not taken into consideration and (b) DQRP for which the wind effect was taken into consideration

In SQRP, the optimum flight route is found by minimizing the total flight distance. Since the wind effect is considered zero (none) for all weather conditions in the SQRP, the ground speed vector will be the same as the airspeed vector.

$$\vec{V_g} = \vec{V_a} \tag{15}$$

Due to the fact that the ground speed vector and the airspeed vector used in the creation of SQRP do not change in different weather conditions, a dynamic route planning cannot be formed. In order to create a dynamic route planning and thus obtain flight data closer to reality, the wind effect should be taken into account in QRP.

In order to create DQRP for the locations determined through the WEDQRP application, the flight times determined between locations are updated according to the changes in weather conditions and a DQRP is created using the updated flight times. In this way, with DQRP, an optimal QRP can be created in accordance with the current weather conditions.

III. EXPERIMENTAL STUDY

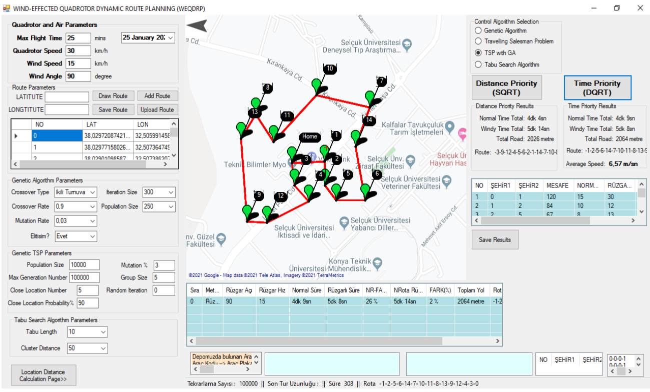

Figure 5. Developed WEDQRP interface

The wind data used in the developed WEDQRP application are received from the website of MGM before the quadrotor starts to fly, and DQRP is created according to this received wind data. After DQRP is created for each flight, the wind speed and wind angle will be considered constant during the flight of the quadrotor. QRP is also created by entering the maximum flight time on the application, taking the time limit into account. While creating DQRP with the WEDQRP application, the quadrotor starts the flight from a certain starting point and returns to the starting point (home) after visiting the locations it will go to. The most optimal and precise results among the metaheuristic methods tested on the developed WEDQRP application were obtained with the TSP with GA method. Therefore, the DQRPs shown in the figures were obtained by the TSP with GA method. In the results section, the results obtained from the metaheuristic methods used in WEDQRP application will be shared. The interface of the developed WEDQRP application is shown in Figure 5.

Since wind speed and wind angle are not taken into account in SQRP, only QRP can be performed in which the total flight distance is minimized. In Figure 6(a) below, the 15 locations determined for route planning are shown. In Figure 6(b), the SQRP representation created by minimizing the distance without taking the wind effect of these locations into account is presented.

In order to create SQRP for the locations determined in Figure 6 (a), the quadrotor speed was set as 30 km/h and the wind speed 0 km/h. The SQRP total flight distance created for the 15 locations determined was minimized and realized with the TSP with GA method as in Figure 6 (b). In the created SQRP, the quadrotor stops by the locations (Home-3-9-12-4-5-6-2-1-14-7-10-8-13-11-Home) respectively. The total flight distance for the created SQRP was calculated as 2026 m and the total flight time as 4 minutes and 4 seconds.

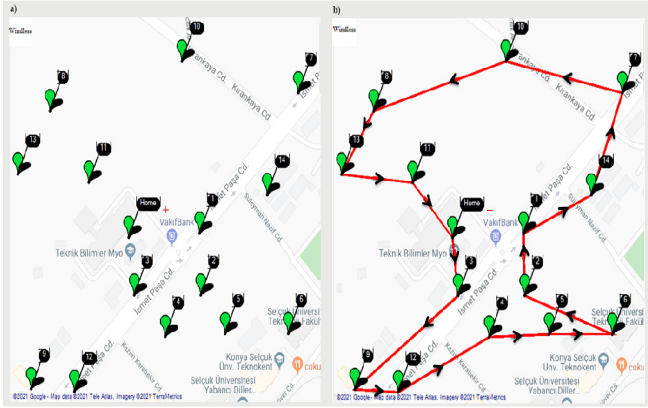

Figure 6. (a) Display of locations, (b) the SQRP created without taking wind effect into consideration

In the WEDQRP application developed, the ground speeds between locations change depending on the change in the quadrotor speed, wind speed and wind angle. The change in ground speeds between locations causes the formation of different DQRPs.

In order to create DQRP for 15 locations selected over the WEDQRP application, the quadrotor speed was determined as 30 km/h and the wind speed 18 km/h. The DQRPs created at different wind angles for 15 locations selected under the specified conditions are shown in Figure 7.

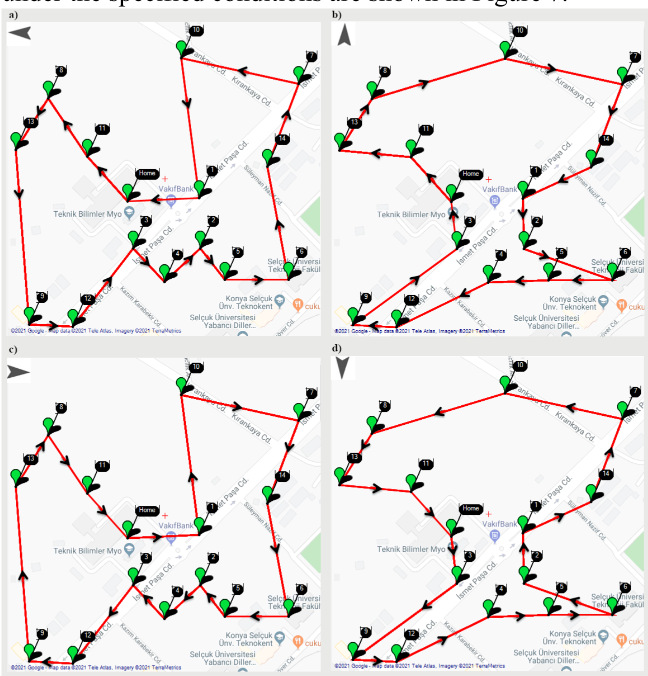

Figure 7. DQRP created at wind angles (a) 90°, (b) 180°, (c) 270°, (d) 360°

In all route plans shown in Figure 7, wind blows at a speed of 18 km/h. In determining the wind angles, angles belonging to 4 main directions (west, north, east, south) were chosen. The DQRPs created when the wind angle is 90°, 180°, 270° and 360° are shown in Figure 7, respectively. As the wind angle changes, the calculated ground speed between locations changes. In order to obtain the optimum route plan, different DQRPs are created depending on the change in ground speed. In the WEDQRP application developed, DQRP is created for all wind angle values between 0°- 360° degrees.

In order to create DQRP for 15 locations selected over the WEDQRP application, the quadrotor speed was set as 30 km/h and the wind angle was 90°. The DQRPs created at different wind speeds for 15 locations selected under the specified conditions are shown in Figure 8.

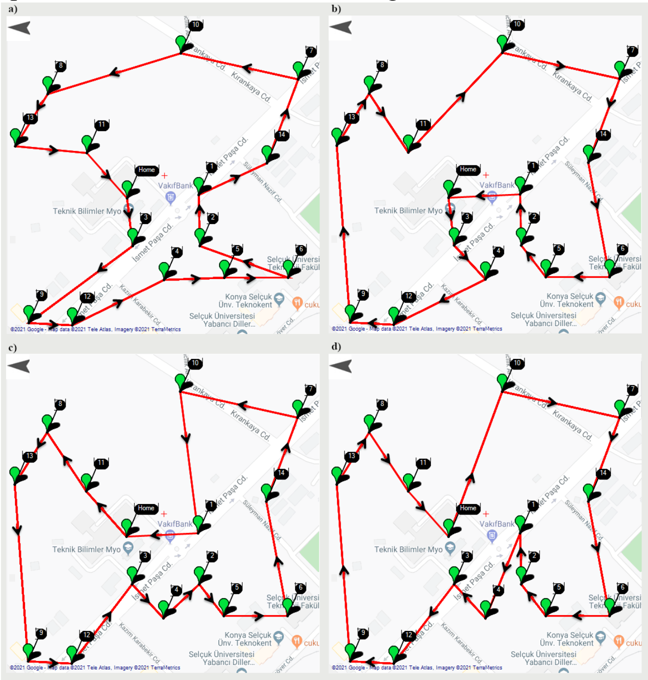

Figure 8. (a) DQRP occurring at 6 km/h, (b)12 km/h, (c)18 km/h and (d)24 km/h wind speeds

In all route plans shown in Figure 8, the wind angle is 90°. The DQRPs that occur when the wind speed is 6 km/h, 12 km/h, 18 km/h and 24 km/h are shown in Figure 8, respectively. Like the change in the wind angle, the change in wind speed also changes the calculated ground speeds between locations. Different DQRPs are created in order to obtain the optimum route plan depending on the change in the ground speed. DQRP is created for different wind speed values in the developed WEDQRP application

IV. Results

On the WEDQRP application, QRPs were created at different wind speed and wind angles with GA, TSP with GA and TS metaheuristic methods.

TABLE I. COMPARISON OF THE PERFORMANCES OF THE EXAMINED METHODS ON DIFFERENT LOCATIONS

The number of Location	Wind Speed [km/h]	Wind Angle [°]	GA	TS	TSP with GA
15 Location (Figure 6(a))	12	0 (360)	310 sec	315 sec	273 sec
		90	309 sec	309 sec	282 sec
		180	308 sec	307 sec	273 sec
		270	312 sec	312 sec	282 sec
	24	0 (360)	578 sec	602 sec	506 sec
		90	636 sec	663 sec	545 sec
		180	600 sec	620 sec	506 sec
		270	571 sec	586 sec	545 sec
33 Location	12	0 (360)	569 sec	586 sec	474 sec
		90	566 sec	592 sec	471 sec
		180	562 sec	574 sec	457 sec
		270	566 sec	576 sec	456 sec
	24	0 (360)	1124 sec	1154 sec	928 sec
		90	1125 sec	1170 sec	880 sec
		180	1114 sec	1158 sec	936 sec
		270	1129 sec	1169 sec	875 sec

The methods were run 25 times for each wind speed and wind angle value and the average values of the obtained flight times are given in Table 1. According to the results given in Table 1, the most optimal solution was obtained with the TSP with GA method. Graphical representation of the obtained results of the examined methods is given in Figure 9.

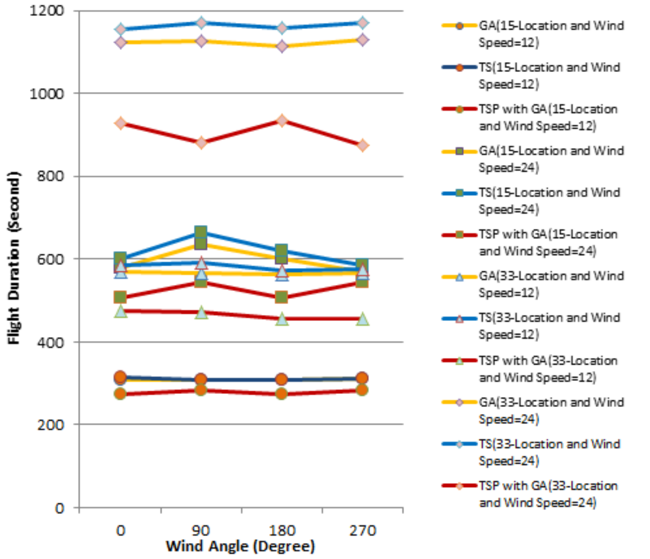

Figure 9. Comparison of the performances of the examined methods on different locations

The flight information of QRPs formed at different wind angles for 15-locations and 33-locations flights with the WEDQRP application is given in Table 2 (Quadrotor speed = 30 km/h, Wind speed = 18 km/h). SQRP does not change at different wind angles and wind speeds. Therefore, the route plan in the ROUTE column corresponding to the "Windless" value in the Wind Angle and Wind Speed columns in Table 2 and Table 3 is SQRP, the other route plans are DQRP.

In Table 2, to create 15-locations and 33-locations QRPs at different wind angles, the quadrotor speed was determined as 30 km/h and the wind speed as 18 km/h. In Table 2; The Number of Locations is the number of locations selected to create a route plan on WEDQRP, The Wind Angle is different wind angle values, SQRP created without considering ROUTE wind effect (windless) and DQRPs created by considering the wind effect, The Distance is the total flight distance calculated for the QRPs formed, SQRP Duration (Under the Effect of Wind) is How long the route plan created according to SQRP is flown under the effect of wind, DQRP Duration is How long the route plan created according to DQRP is flown under the effect of wind, and finally Performance is the comparison of the flight times obtained when flying under the effect of wind in the route plans created according to SQRP and DQRP by percentage.

The flight information of QRPs formed at different wind speeds for 15-locations and 33-locations flights with WEDQRP application is given in Table 3 (Quadrotor speed = 30 km/h, Wind angle = 90°).

In Table 3, to create 15-locations and 33-locations QRPs at different wind speeds, the quadrotor speed was determined as 30 km/h and the wind angle as 90°. The Wind Speed column in Table 3 contains data for different wind speeds.

TABLE II. THE FLIGHT INFORMATION OF QRPS FORMED AT DIFFERENT WIND ANGLES (QUADROTOR SPEED = 30 KM/H, WIND SPEED = 18 KM/H)

The number of Location	Wind Angle [°]	ROUTE	Distance [m]	SQRP Duration (Under the Effect of Wind)	DQRP Duration	Performance [%]
15 Location	Windless	H -3-9-12-4-5-6-2-1-14-7-10-8-13-11- H	2026	4 min 4 sec	-	-
	0 (360)	H-3-9-12-4-5-6-2-1-14-7-10-8-13-11-H	2024	5 min 30 sec	5 min 30 sec	0%
	45	H-1-10-7-14-6-5-2-4-3-12-9-13-8-11-H	2087	5 min 54 sec	5 min 54 sec	0%
	90	H-11-8-13-9-12-3-4-2-5-6-14-7-10-1-H	2087	6 min 0 sec	5 min 45 sec	4%
	135	H-11-13-8-10-7-14-1-2-6-5-4-12-9-3-H	2024	5 min 39 sec	5 min 36 sec	1%
	180	H-11-13-8-10-7-14-1-2-6-5-4-12-9-3-H	2024	5 min 31 sec	5 min 30 sec	0%
	225	H-11-13-8-10-7-14-1-6-5-2-4-12-9-3-H	2032	5 min 55 sec	5 min 54 sec	0%
	270	H-1-10-7-14-6-5-2-4-3-12-9-13-8-11-H	2087	6 min 1 sec	5 min 45 sec	5%
	315	H-3-9-12-4-5-6-2-1-14-7-10-8-13-11-H	2024	5 min 36 sec	5 min 36 sec	0%
33 Location	Windless	H -2-3-11-12-13-14-4-5-15-16-17-6-28-7-30-27-25-32-18-26-19-20-21-22-23-24-10-9-29-8-31-1-H	3524	7 min 5 sec	-	-
	0 (360)	H-2-10-9-22-23-24-11-12-3-4-13-14-15-5-16-17-6-28-7-30-27-25-32-18-26-19-20-21-29-8-31-1-H	8017	9 min 57 sec	9 min 58 sec	0%
	45	H-1-2-10-9-23-24-11-3-12-13-4-14-15-5-16-17-6-28-7-32-18-26-19-20-21-22-29-8-31-25-27-30-H	7929	9 min 56 sec	9 min 57 sec	0%
	90	H-30-7-32-26-18-28-6-17-16-15-5-14-4-13-12-11-24-23-22-21-20-19-25-27-31-8-29-9-10-3-2-1-H	7985	10 min 3 sec	9 min 16 sec	8%
	135	H-1-2-3-10-9-29-8-31-27-25-19-20-21-22-23-24-11-12-13-14-4-5-15-16-17-6-28-18-26-32-7-30-H	7936	10 min 10 sec	9 min 27 sec	8%
	180	H-2-3-11-12-13-4-14-15-5-16-17-6-28-7-30-27-25-32-18-26-19-20-31-8-29-21-22-23-24-10-9-1-H	8017	9 min 55 sec	9 min 50 sec	1%
	225	H-30-7-28-6-17-16-15-5-14-4-13-12-3-11-24-23-22-21-20-19-26-18-32-25-27-31-8-29-9-10-2-1-H	7929	9 min 53 sec	9 min 46 sec	1%
	270	H-30-7-32-26-18-28-6-17-16-15-5-14-4-13-12-11-24-23-22-21-20-19-25-27-31-8-29-9-10-3-2-1-H	7985	10 min 3 sec	9 min 15 sec	9%
	315	H-30-7-27-31-8-20-19-25-32-26-18-28-6-17-16-15-5-4-14-13-3-12-11-24-23-22-21-29-9-10-2-1-H	7936	10 min 8 sec	9 min 43 sec	4%

TABLE III. THE FLIGHT INFORMATION OF QRPS FORMED AT DIFFERENT WIND SPEEDS (QUADROTOR SPEED = 30 KM/H, WIND ANGLE = 90°)

The number of Location	Wind Angle [°]	ROUTE	Distance [m]	SQRP Duration (Under the Effect of Wind)	DQRP Duration	Performance [%]
15 Location	Windless	H -3-9-12-4-5-6-2-1-14-7-10-8-13-11- H	2026	4 min 4 sec	-	-
	0	H -3-9-12-4-5-6-2-1-14-7-10-8-13-11- H	2026	4 min 4 sec	4 min 4 sec	0%
	6	H-3-9-12-4-5-6-2-1-14-7-10-8-13-11-H	2024	4 min 12 sec	4 min 12 sec	0%
	9	H-11-13-8-10-7-14-1-6-5-2-4-12-9-3-H	2032	4 min 26 sec	4 min 24 sec	1%
	12	H -3-4-12-9-13-8-11-10-7-14-6-5-2-1-H	2064	4 min 44 sec	4 min 42 sec	1%
	15	H -1-2-5-6-14-7-10-11-8-13-9-12-4-3-H	2064	5 min 14 sec	5 min 8 sec	2%
	18	H -11-8-13-9-12-3-4-2-5-6-14-7-10-1-H	2087	6 min 0 sec	5 min 45 sec	4%
	21	H -11-8-13-9-12-3-4-2-5-6-14-7-10-1-H	2087	7 min 19 sec	6 min 47 sec	8%
	24	H -10-7-14-6-5-2-1-4-3-12-9-13-8-11-H	2141	10 min 24 sec	9 min 5 sec	14%
	26	H -11-8-13-9-12-3-4-1-2-5-6-14-7-10-H	2141	14 min 14 sec	11 min 47 sec	21%
	27	H -11-8-13-9-12-3-4-1-2-5-6-14-7-10-H	2141	18 min 50 sec	14 min 57 sec	26%
33 Location	Windless	H-2-3-11-12-13-14-4-5-15-16-17-6-28-7-30-27-25-32-18-26-19-20-21-22-23-24-10-9-29-8-31-1 H	3524	7 min 5 sec	-	-
	0	H -2-3-11-12-13-14-4-5-15-16-17-6-28-7-30-27-25-32-18-26-19-20-21-22-23-24-10-9-29-8-31-1 H	3524	7 min 5 sec	7 min 5 sec	0%
	6	H -1-31-8-29-9-10-24-23-22-21-20-19-25-27-30-7-32-26-18-28-6-17-16-15-5-14-4-13-12-11-3-2-H	3424	7 min 17 sec	7 min 2 sec	4%
	9	H -1-2-3-10-9-29-8-31-27-25-19-20-21-22-23-24-11-12-13-4-14-5-15-16-17-6-28-18-26-32-7-30-H	3341	7 min 45 sec	7 min 18 sec	6%
	12	H -30-6-7-32-26-18-28-17-16-5-15-14-4-13-12-11-24-23-22-21-20-19-25-27-31-8-29-9-10-3-2-1-H	3446	8 min 3 sec	7 min 51 sec	3%
	15	H -1-31-27-25-19-20-8-29-21-22-23-24-9-10-2-3-11-12-13-4-14-5-15-16-17-6-28-18-26-32-7-30-H	3480	8 min 58 sec	8 min 38 sec	4%
	18	H -30-7-32-26-18-28-6-17-16-15-5-14-4-13-12-11-24-23-22-21-20-19-25-27-31-8-29-9-10-3-2-1-H	3341	10 min 3 sec	9 min 16 sec	8%
	21	H-30-7-32-26-18-28-6-17-16-15-5-14-4-13-12-11-24-23-22-21-20-19-25-27-31-8-29-9-10-3-2-1-H	3341	12 min 7 sec	10 min 56 sec	11%
	24	H-30-7-32-26-18-28-6-17-16-15-5-14-4-13-12-3-11-10-9-24-23-22-21-20-29-8-31-19-25-27-1-2-H	3584	16 min 41 sec	14 min 40 sec	14%
	26	H-30-7-32-26-18-28-6-17-16-15-5-14-4-13-3-12-11-10-9-24-23-22-21-20-29-8-31-19-25-27-1-2-H	3610	22 min 30 sec	18 min 52 sec	19%
	27	H-1-2-31-27-25-19-8-29-20-21-22-23-24-9-10-11-3-12-13-4-14-5-15-16-17-6-28-18-26-32-7-30-H	3632	29 min 25 sec	24 min 11 sec	22%

V. CONCLUSION

When the data of the results obtained with the WEDQRP application were examined, the method that gave the most optimal result among the metaheuristic methods used was the TSP with GA metaheuristic method. The reason why the TSP with GA method yielded better results compared to other methods is the determination of the nearest neighbor algorithm in determining the initial population and the selection of the permutation coding method as the coding method. While the TSP with GA method gives similar results to other methods in low-location route plans, the difference increases substantially with the increase in the number of locations. As the number of locations increases, the probability of the routes that will occur increases as well. Since the population is formed according to the nearest neighbor method in the TSP with GA method, it is not affected by the increase in the number of locations as much as other methods.

When the DQRP results created on the WEDQRP application are examined, the changes in the wind angle while the wind speed is constant provides an advantage in the range of 0-9% compared to the flight time in the route plan created with SQRP. While the rate of change due to wind angle is lower at low wind speeds, it is higher in high wind speeds.

When the constant wind angle and variable wind speeds were examined in the created DQRPs, although the changes in wind speed up to 30% of the quadrotor speed caused changes in the flight route, there was no significant difference addition to the success between windless and windy routes. However, as the wind speed increases, the difference in flight times between the route plans created with DQRP and SQRP increases up to 26%. This reveals the success of the developed WEDQRP application.

Since the quadrotor will receive more tail wind in DQRP flights, the wind effect is positively utilized. Therefore, when the DQRP and SQRP created for the locations determined in the WEDQRP application are compared, the total flight time decreases in DQRP although the flight distance generally increases. Energy consumption will decrease with the shortening of the Quadrotor flight time. The effects of wind speed and wind angle on the quadrotor cannot be evaluated in SQRP. With the DQRP study conducted, the effect of wind was taken into account in route planning. Thus, the optimal QRP was dynamically created depending on changing weather conditions.

In order to create a DQRP, the flight times between locations are updated according to changes in weather conditions and a DQRP is created using up-to-date flight times. When flying along the route plan created according to DQRP, the actual flight time and the calculated flight time will be close to each other. In this way, the problems caused by changes in weather conditions can be minimized. In addition to this, with the DQRP created taking into account the effect of wind, safer and more stable flights will be provided compared to the SQRP created without taking the wind effect into account. Thus, it is predicted that the overall operating cost of the system will decrease and the vehicle / cargo safety will increase even more.

With DQRP, the actual flight time will be prevented from taking longer than the calculated flight time and the battery consumption calculated according to the flight time will be made more realistic. Moreover, the wind speed and wind angle ranges that may be dangerous for the locations determined in future studies can be determined and suggestions can be made to prevent flight at wind values in this range.

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