Fuel Efficient Flight Level Assignments Under Wind Uncertainties for the Conflict Resolution Problem at the En-Route Phase

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Nomenclature

3D	3-Dimensional
ATM	Air Traffic Management
CDP	Conflict Detection Problem
CRP	Conflict Resolution Problem
EV	Expected Value Solution
FLC	Flight Level Change
GAMS	The General Algebraic Modeling System
HAC	Heading Angle Change
NA	Not Available
NM	Nautical Miles
RP	Here and Now Solution
SC	Speed Change
WSC	Wind Speed Coefficients

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1 Introduction

Conflict resolution problem (CRP) can be solved using three different approaches: speed change (SC), heading angle change (HAC), and flight level change (FLC). SC and HAC do not affect the vertical position of aircraft. However, changing the flight level of an aircraft causes an interaction between different levels (Cecen & Cetek, 2020). Also, weather conditions may change between the levels, which can affect the ground speeds of aircraft. Even though FLC is performed with a single instruction, conflict resolution using this approach creates follow-up difficulties for the controllers due to the above-mentioned issues. Weather conditions must be considered to provide efficient and safe solutions for the CRP using FLC.

In general, the weather affects the predicted arrival or departure times of aircraft in two ways. The first one is bad weather conditions that affect the air traffic management (ATM) at a network level by causing no-fly zones, and the second one is atmospheric issues such as wind which may affect the individual routes of flights (Hernández-Romero et al., 2017). In such a situation, controllers may need to intervene to ensure minimum separations between aircraft. The wind is a weather component that significantly affects flight trajectories. It affects the trajectories through its speed element (Chaloulos & Lygeros, 2007). However, considering the uncertainties of both wind components (i.e., direction and speed) may provide more efficient and safe air traffic management (Dönmez, 2022).

In the literature, many studies handle conflict detection problem (CDP) and CRP, considering the wind uncertainties. Vela et al. provided a two-stage stochastic programming model for the CRP considering the wind uncertainties. They allowed only SC in their model to resolve the conflict (Vela et al., 2009). In addition, Matsuno et al. (2016) developed a stochastic near-optimal control method considering several uncertainties, including wind prediction errors, airspeed measurement errors, etc. Their model presented near-optimal heading maneuvers considering a two-dimensional horizontal plane (Matsuno et al., 2016). Matsuno et al. (2015) provided an optimal control model for determining three-dimensional conflict-free aircraft trajectories under wind uncertainty (Matsuno et al., 2015). Romero et al. presented a probabilistic approach for CDP and CRP considering the uncertainty of wind forecast. They assumed that the operations are realized with constant speed and flight level (Hernández-Romero et al., 2020). Most of the above-mentioned studies showed that robust and efficient conflict resolutions could provide considering the wind uncertainties.

The current study develops a two-stage stochastic mathematical model for the CRP for the en-route phase at a three-dimensional (3D) plane. Both wind direction and speed uncertainties are integrated into the model to validate the previous efforts. It is compared to the deterministic and expected value approaches to find out the possible gains of the developed stochastic programming model. Wind data from İZMİR (17220) station was added to a mathematical model to quantify the results, and various traffic samples were solved using GAMS (The General Algebraic Modeling System).

2 Method

We developed a two-stage stochastic programming model in a 3D plane for the CRP. FLC is used as the solution method. It is compared with the deterministic and expected solution approaches to find out possible gains of the presented model. The deterministic approach does not consider any wind uncertainty in the system while assigning the aircraft to the flight levels in the first stage of the problem. In the second stage, these assignment decisions are run under any uncertainty in the deterministic model. In the expected value solution (EV), on the other hand, the assignment decisions obtained from the first stage are applied under uncertainties. The first stage decisions of the deterministic and expected value solution are the same. The developed stochastic model considers the wind speed and direction uncertainties when assigning the aircraft to the FLs. Solutions of the stochastic model are obtained directly and referred to "as here and now solution" (RP). The methodology of the study is summarized in Fig. 1.

For all strategies, we assume that assignments are decided before sector entry points. Aircraft enter the system from the assigned flight levels. Figure 2 represents the operational concept of the models.

Generic airspace includes five different fight levels and two routes. For each flight level, there is one conflict point. The routes, entry and exit points, and flight level information are integrated to the mathematical model as parameters. The length of all air routes was determined as 100 nautical miles (NM) and the distance to the intersection point as 50 NM. The safe separation between the aircraft is specified as 5 NM and included in the mathematical model as time-based separations based on the aircraft velocities for each flight level. The aircraft speeds are constants for each flight level, and no speed change is allowed. In addition, deviation from the predetermined routes in the horizontal plane is not permitted after the sector entry points.

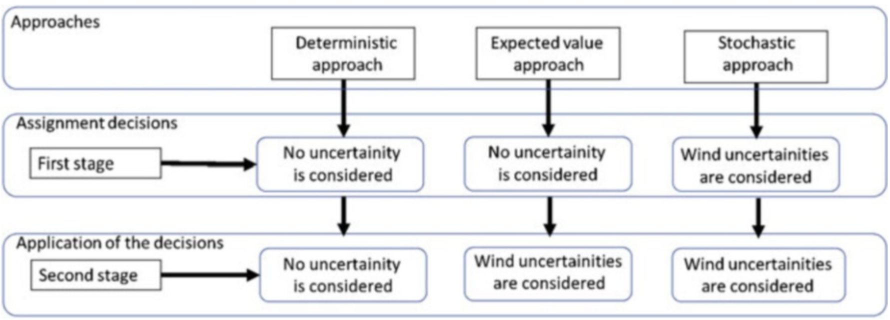

Fig. 1 Methodology

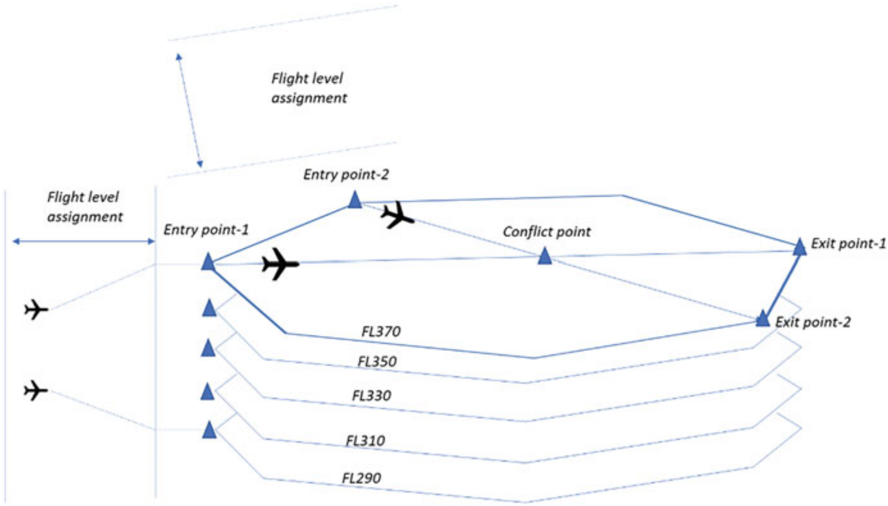

Fig. 2 Generic airspace and flight level assignments

2.1 Data Analysis

Wind data is obtained from the weather sound database of Wyoming University (Weatherdata, 2021). İzmir station (17220) data is used in this study. While the wind directions are considered at 60-degree intervals, wind speeds are considered at 20 kts intervals. A cross table of the wind speeds and directions that are observed together is given in Table 1.

As seen in Table 1, the frequency of some of the cells is equal to 0. This means no observation is found for these direction and speed intervals. Therefore, these scenarios were eliminated, and a total of 21 scenarios were included in the model. To represent all intervals and to generate reasonable scenarios for the mathematical model, medians and means of the wind directions and speeds are considered, respectively. Table 2 presents the wind scenarios with the probabilities.

As seen in Table 2, the highest probability is 15%, while the lowest probability is 0.013% among the scenarios. The highest wind speed is 121.63 kts, and the lowest is 13.05 kts. The above-mentioned scenarios are generated using the data for FL350 which is chosen as reference FL for wind scenarios. In addition, the flight levels' differences in wind speed are reflected in the model using the wind speed coefficients. These coefficients are obtained by comparing each flight level with the reference flight level regarding wind characteristics. Hence, we could extend the scenarios for all flight levels. Table 3 shows the differences between flight levels regarding wind direction and wind speeds.

As seen in Table 3, there are no significant differences between the flight levels regarding wind direction. Significant differences, however, are observed for wind speed. As a result, these differences are reflected in the mathematical model using

Table 1 Cross table of wind speeds and directions

İZMİR (17220)								
			Speed intervals (kts)					Total
			0–20	20–40	40–60	60–80	80+	
Direction intervals (degree)	0–60	Count	4	3	1	1	0	9
		%	5.0	3.8	1.3	1.3	0.0	11.3
	61–120	Count	1	0	0	0	0	1
		%	1.3	0.0	0.0	0.0	0.0	1.3
	121–180	Count	0	1	0	0	0	1
		%	0.0	1.3	0.0	0.0	0.0	1.3
	181–240	Count	5	4	3	2	3	17
		%	6.3	5.0	3.8	2.5	3.8	21.3
	241–300	Count	7	11	12	8	4	42
		%	8.8	13.8	15.0	10.0	5.0	52.5
	301–360	Count	3	4	1	1	1	10
		%	3.8	5.0	1.3	1.3	1.3	12.5
Total		Count	20	23	17	12	8	80
		%	25.0	28.8	21.3	15.0	10.0	100.0

Table 2 Wind scenarios

Scenario number	Probability	Direction	Speed
Scenario 1	0.050	30	13.05
Scenario 2	0.038	30	28.83
Scenario 3	0.013	30	48.82
Scenario 4	0.013	30	68.08
Scenario 5	0.013	90	13.05
Scenario 6	0.013	150	28.83
Scenario 7	0.063	210	13.05
Scenario 8	0.050	210	28.83
Scenario 9	0.038	210	48.82
Scenario 10	0.025	210	68.08
Scenario 11	0.038	210	121.63
Scenario 12	0.088	270	13.05
Scenario 13	0.138	270	28.83
Scenario 14	0.150	270	48.82
Scenario 15	0.100	270	68.08
Scenario 16	0.050	270	121.63
Scenario 17	0.038	330	13.05
Scenario 18	0.050	330	28.83
Scenario 19	0.013	330	48.82
Scenario 20	0.013	330	68.08
Scenario 21	0.013	330	121.63

Table 3 Wind differences between the flight levels

	Median of wind direction	Mean of wind speed	Wind speed coefficient (WSC)
FL290	269.00	25.58	0.58
FL310	259.50	29.71	0.67
FL330	271.50	33.66	0.76
FL350	275.00	44.30	1.00
FL370	275.00	46.22	1.04
Range	15.50	20.65	

wind speed coefficients (WSC). Including the differences in the model using coefficients decreases the computational load of the model compared to the additional scenarios (Dönmez et al., 2022).

2.2 *Two-Stage Stochastic Model*

The deterministic model developed by Dönmez and Cecen (2022) is enhanced to a stochastic model in this study (Dönmez & Cecen, 2022). They used SC and VM techniques with a deterministic approach in the model. They also considered a two-dimensional plane in the model. Their model is based on Cecen (2021); however, they enhanced the model by integrating improved speed restrictions and fuel calculations.

In the current model, FLC is considered a conflict resolution method. Also, 3D interactions between the aircraft are considered. The model's objective function is determined as the minimization of the total fuel consumption of aircraft. The fuel calculation regression model presented by Dönmez and Cecen 2022 is integrated to the mathematical modeling (Dönmez & Cecen, 2022). Additional speed and fuel calculations presented in previous study is maintained in the model. The fuel calculations using the regression models generated based on BADA 3.11 provide more realistic estimates than the only time-dependent ones. In the time-dependent calculation approach, fuel has a linear relationship with flight time. Provided regression models, however, consider the speed and altitude effect and flight time. The full form of the model is not presented here, but the deterministic version of the model can be reached from Cecen (2021), and extended speed and fuel calculations can be found in Dönmez and Cecen (2022).

3 Results

In this section, we first compared RP, deterministic, and EV strategies in fuel consumption. Then, we solved ten test problems to find out possible savings of the stochastic approach. Finally, Table 4 shows the models' total fuel consumption (kg) results.

As seen in Table 4, EV did not provide any feasible solution for the test problems. This means that the assignment decisions provided in the deterministic model in the first stage of the problem are not feasible when uncertainties occur. If we compare the results of the deterministic and RP solutions, we observed that RP provides an average improvement by 4.17% compared to deterministic in terms of fuel consumption. Table 5 shows the savings of the RP compared to the deterministic approach.

As seen in Table 5, an average of 1962.17 kg of fuel saving is provided in the stochastic model. This corresponds to approximately 39 kg fuel savings per aircraft. Note that this is not a clear comparison because the second stage of the problem is

Table 4 The results in terms of total fuel consumption (kg)

	Fuel consumption		
Test problems	Deterministic	RP	EV
1	39477.11	37829.27	NA
2	42732.87	40937.05	NA
3	45890.12	43998.91	NA
4	47258.73	45295.68	NA
5	50013.8	47918.41	NA
6	45734.51	43826.01	NA
7	51844.74	49690.98	NA
8	47512.18	45518.58	NA
9	50861.11	48750.74	NA
10	49384.46	47322.35	NA

NA Not available

Table 5 Savings of the stochastic approach

Test problems	kg	%
1	1647.83	4.17
2	1795.83	4.20
3	1891.21	4.12
4	1963.04	4.15
5	2095.39	4.19
6	1908.50	4.17
7	2153.77	4.15
8	1993.60	4.20
9	2110.37	4.15
10	2062.11	4.18
Average	1962.17	4.17

Table 6 Number of aircraft that provided non-conflicted routes in the EV model

Test problems	Feasible solutions for EV	
	Aircraft count	%
1	34	68
2	41	82
3	43	86
4	37	74
5	36	72
6	37	74
7	41	82
8	42	84
9	38	76
10	36	72
Average	38.50	77.00

not having any uncertainty in the deterministic model. Since no results were obtained in the EV model, the results of the stochastic model were directly compared with the deterministic approach.

We also examined the unfeasible solutions of the EV model in detail. Table 6 shows the number of aircraft that provided non-conflicted routes in the EV model for each scenario.

As seen in Table 6, the EV model provided non-conflicted routes for an average of 38.5 aircraft in each scenario. This means that approximately 12 aircraft's conflicts cannot solve by applying the first stage assignment decisions obtained from the deterministic model when the uncertainties are realized. Therefore, only delaying some of these 12 aircraft can solve the problem. However, we did not allow any delay in all strategies. Namely, suppose the deterministic assignment decisions obtained for the first stage of the problem are applied under the uncertainties. In that case, non-conflicted routes are provided for 77% of aircraft, while the others have a potential conflict that may be resolved by delaying some aircraft. However, in the RP model, feasible and better solutions are provided for all scenarios compared to deterministic and EV approaches. We also compared the deterministic and RP solutions regarding the number of aircraft assigned to the same altitude (Table 7).

Table 7 indicates that 65.2% of the aircraft is assigned to the same altitude in RP and deterministic approaches, and 34.8% of aircraft are assigned to different levels for these models. We also examined how many aircraft were assigned to each flight level for each test problem. Figure 3 shows the average number of aircraft assigned to each flight level for all test problems.

As seen in Fig. 3, 33.4 aircraft were assigned to FL370 in the deterministic model, while 28.6 aircraft were assigned to this flight level in the stochastic model. Although both models assigned most aircraft to higher flight levels because of fuel efficiency, the stochastic model used lower flight levels more than the deterministic approach. This is because wind speed increases as the flight level increases. Although the wind speed affects the aircraft positively or negatively according to the direction of wind and arrival, lower levels are preferable to higher flight levels

Table 7 Number of aircraft assigned to the same altitude in deterministic and stochastic models

Test problem	Count	%
1	35	70
2	29	58
3	37	74
4	35	70
5	29	58
6	29	58
7	33	66
8	33	66
9	34	68
10	32	64
Average	32.60	65.20

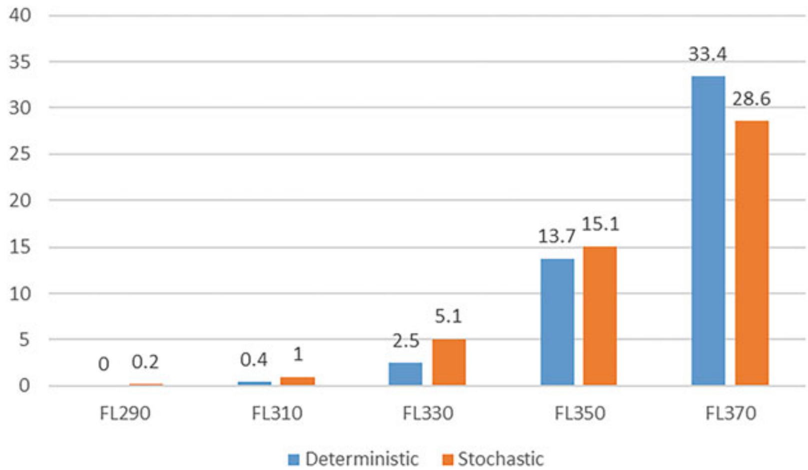

Fig. 3 Average flight level assignments

when the wind is involved in the problem because of uncertainty. Note that the stochastic model still prefers higher levels. The above statements are valid for comparisons made with the deterministic approach. Figures 4 and 5 show the rates of flight level assignments for stochastic and deterministic methods, respectively.

In Figs. 4 and 5, the highest rate of assignments was FL370 for both models. While assignments to FL330 and FL350 constituted approximately 40% of the aircraft in the stochastic model, this ratio remained at approximately 32% in the deterministic model. Table 8 examines the flight level assignments for each test problem given below.

As seen in Table 8, some of the test problems resulted in more different FL assignments. For example, for test problem 10, 35 aircraft were assigned to FL370 in the deterministic model, while 28 were assigned to this level in the stochastic model. For all test problems, it is observed that the lower levels are not preferred much in both models.

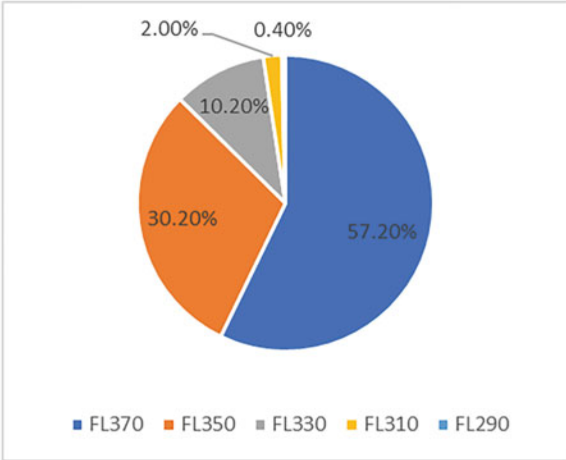

Fig. 4 Flight level assignment rates for stochastic model

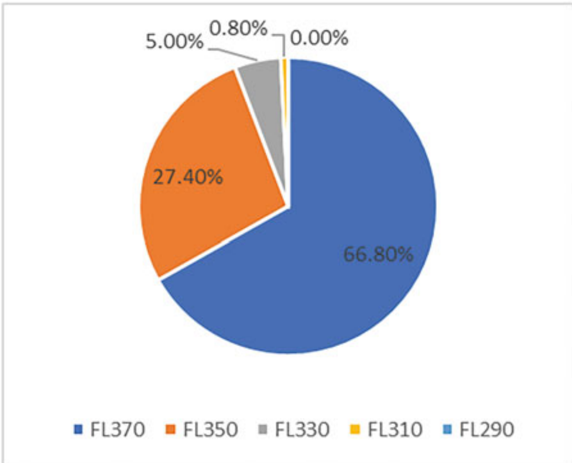

Fig. 5 Flight level assignment rates for deterministic model

4 Discussion and Conclusion

This study develops a two-stage stochastic model for the conflict resolution problem in the en-route phase. Also, flight level assignment is used as a conflict resolution technique, and wind direction and speed uncertainties are reflected in the model. In addition, the mathematical model uses real wind data to reflect wind speed differences between the levels. The developed model then, compared to deterministic and expected value approaches in terms of fuel efficiency and the assignment decisions of the stochastic and deterministic approaches, is examined in detail. As a result, it is observed that the stochastic model provides an average of 4.17% fuel savings compared to the deterministic model. In addition, it was observed that none of the deterministic assignment decisions were applicable when the uncertainties occurred.

Table 8 Flight level assignments for each test problem

Model	Test problem	FL290	FL310	FL330	FL350	FL370
Stochastic	1	1	1	4	18	26
	2	0	2	5	17	26
	3	0	0	4	16	30
	4	1	2	6	12	29
	5	0	2	4	15	29
	6	0	2	6	14	28
	7	0	0	2	15	33
	8	0	0	6	15	29
	9	0	1	8	13	28
	10	0	0	6	16	28
Deterministic	1	0	1	1	16	32
	2	0	1	5	12	32
	3	0	0	2	13	35
	4	0	0	4	12	34
	5	0	1	1	13	35
	6	0	1	4	14	31
	7	0	0	0	12	38
	8	0	0	3	16	31
	9	0	0	4	15	31
	10	0	0	1	14	35

Therefore, any feasible solution for the EV model is not obtained, including applying the deterministic assignment decisions under uncertainties. The EV model provided non-conflicted routes for approximately 77% of aircraft. However, 23% of the conflicts were not solved without aircraft delays. On the other hand, the stochastic model solved all conflicts by flight level assignments without delay.

The assignment decisions of the models were examined in detail. It was observed that although both models assigned aircraft to higher flight levels because of fuel efficiency, it is seen that the stochastic model used lower flight levels more than the deterministic approach. This is because wind speed increases as the flight level increases. In future work, we will test the model efficiency for different wind characteristics by obtaining various data from other stations. In addition, flight level assignments after the sector entry points in the tactical phase will also be integrated into the model by using a dynamic model.

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