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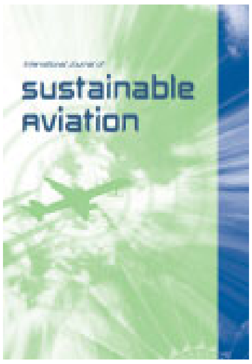

International Journal of Sustainable Aviation

ISSN online: 2050-0475 - ISSN print: 2050-0467

https://www.inderscience.com/jhome.php?jcode=ijsa

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DOI: 10.1504/IJSA.2022.120612

Article History:

Received:	18 June 2021
Last revised:	01 October 2021
Accepted:	20 October 2021
Published online:	28 January 2022

The fuel consumption impact of the turning point location for the point merge system

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Abstract: This study considers the impact of the turning point location on fuel consumption for aircraft landing problem by using the point merge system. A mixed-integer linear programming model is applied for this problem. Also, vector manoeuvre is added to the model to solve any conflict before entering sequencing legs. Two different methods are compared. First, no fixed turning point is placed, allowing aircraft to make a turn anywhere on the sequencing legs. However, the problem is that it is not very applicable neither for air traffic controllers nor pilots regarding the instruction time. The second method uses constant turning points with a pre-defined distance between two successive points. The results for the second method displayed that when we increased the distance between the two following turning points, the total fuel consumption also increased by 7.35% compared to the no-fixed turning point method.

Keywords: aircraft landing problem; ALP; point merge system; PMS; fuel consumption; mixed-integer linear programming; MILP.

Reference to this paper should be made as follows: Cecen, R.K. (2022) ‘The fuel consumption impact of the turning point location for the point merge system’, *Int. J. Sustainable Aviation*, Vol. 8, No. 1, pp.75–90.

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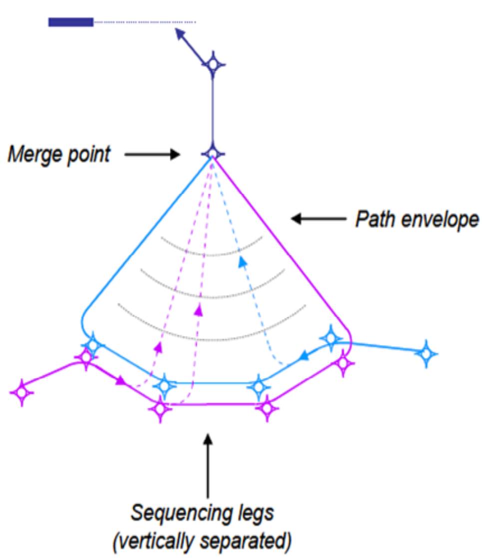
This paper is a revised and expanded version of a paper entitled ‘The effect of turning point placement in the point merge system on total fuel consumption’ presented at International Symposium on Aircraft Technology, MRO & Operations (ISATECH21), Budapest University of Technology & Economics, Budapest, Hungary, 28–30 June 2021.

1 Introduction

The aviation sector provides significant contributions to the spread of trade in the world. However, COVID-19 pandemic has negatively affected the air transportation system. The worldwide COVID-19 pandemic reduced global passenger numbers by 60% in 2020 compared to the previous year. In addition, according to the predictions for 2021, there will be a slight increase in the number of passengers compared to 2020 (Bureau, 2020). EUROCONTROL (2020) predicts that the aviation industry can only reach 2019 in 2024. With the increase in air traffic, it will become inevitable to experience congestion in the airspaces. These congestions will increase aircraft delays and total fuel consumption, especially in terminal manoeuvring areas (TMAs), a transition between airports and the en-route phase. However, TMAs have a smaller volume than the en-route phase, and they provide both separation and sequencing services. It causes an increase in the workload of air traffic controllers (ATCos). Therefore, aircraft separation and sequencing manoeuvres are essential operations for both airlines and ATCos. These operations are generally defined as the aircraft sequencing and scheduling problem (ASSP) considering both departure and arrival aircraft. In addition, scheduling and sequencing for arrival aircraft are classified as aircraft landing problem (ALP), a sub-problem of ASSP. Arrival and departure manager systems are utilised to manage the air traffic efficiently, and they advise ATCos to obtain conflict-free aircraft sequencing. In addition, ATCos use several separations and sequencing techniques such as vector manoeuvre, speed adjustment, holding point, ground holding, and point merge system (PMS). EUROCONTROL Experimental Centre presented the PMS to regulate air traffic more effectively. This system allows considerable reductions in vector manoeuvres applied by ATCos. The PMS approach aims to manage arrival aircraft with closed-loop instructions. In addition, the PMS is designed to handle traffic even under heavy traffic demand, and its specific route structure is presented in Figure 1.

Figure 1 Example of PMS with two entry points (see online version for colours)



Source: Favennec et al. (2009)

Table 1 The review of related literature

Reference	*Objective function*	*Solution approach*
Faye (2015)	Cost	Mixed-integer programming (MIP) and dynamic constraint generation algorithm
Lieder et al. (2015)	Cost due delay	MIP, dynamic programming (DP)
Murça and Müller (2015)	Cost due to delay	MIP, DP
Vadlamani and Hosseini (2014)	Cost due to delay	ALNS algorithm
Cecen et al. (2020)	Delay	Simulated annealing (SA) algorithm
D'Ariano et al. (2012)	Delay	Branch and bound algorithm
Hancerliogullari et al. (2013)	Delay	MIP, heuristic algorithm
Rodríguez-Díaz et al. (2018)	Delay	Simulated annealing algorithm
Samà et al. (2013)	Delay	Branch and bound algorithm
Samà et al. (2014)	Delay	MIP, branch and bound algorithm and Tabu search
Cecen and Çetek (2020)	Delay, conflict resolution time	CPLEX algorithm
Bennell et al. (2017)	Delay, fuel consumption, throughput, cost due to delay	DP
Samà et al. (2015)	Delay, makespan	MIP
Liang et al. (2018)	Delay, operation interval, total position shift	SA
Cecen (2021)	Delay, the total number of conflict resolution instruction	CPLEX algorithm
Balakrishnan and Chandran (2010)	Makespan	DP
Hong et al. (2017)	Makespan	MIP
Hong et al. (2018)	Makespan	Particle swarm optimisation
Kaplan and Çetek (2020)	Makespan	Clonal selection algorithm
Kwasiborska (2017)	Makespan	Heuristic algorithm
Ng et al. (2017)	Makespan	Artificial bee colony algorithm
Ng et al. (2021)	Makespan	Benders decomposition
Sölveling and Clarke (2014)	Makespan	Branch and bound algorithm
Furini et al. (2015)	Runway capacity	Iterative rolling horizon algorithm
		Tabu search algorithm
Khassiba et al. (2020)	Runway sequence length	Enhanced benders decomposition
Dönmez et al. (2021)	Fuel consumption, delay	CPLEX algorithm

In addition, the PMS offers many advantages, including a more efficient air traffic flow, reduction in holding circles, a continuous descent approach support, reduction in fuel consumption, and alleviation of the workload of controllers. Several studies have been introduced in the literature about the PMS, such as Boursier et al. (2007), Ivanescu et al. (2009), Favennec et al. (2009), Sahin Meric and Usanmaz (2013), Sahin et al. (2018), Liang et al. (2018), Cecen et al. (2020) and Cecen (2021). Detailed literature reviews on the ASSP topic are as follows: Bianco et al. (2006), Bennell et al. (2011), Samà et al. (2017), Ng et al. (2021) and Dönmez et al. (2021). Various studies about ASSP are shown in Table 1.

Studies using the PMS approach for ASSP are also available in the literature. Boursier et al. (2007) proposed a model that allows ATCos to regulate aircraft traffic for high-density traffic without the need for vector manoeuvres. In another study, Ivanescu et al. (2009) tested their proposed PMS model and vector manoeuvre methods with fast-time simulation. It showed that PMS reduced fuel consumption, task load and instructions. Favennec et al. (2009) introduced another PMS simulation. The outputs displayed that the PMS could perform flight movements and enhanced continuous descent operations more effectively. Sahin Meric and Usanmaz (2013) suggested a PMS for the intersecting runways without applying the head angle change instruction for Istanbul Atatürk Airport. Sahin et al. (2018) proposed another novel destination route model for three major airports in Istanbul TMA using the PMS approach to decrease fuel consumption and carbon emissions. They compared the PMS with the Standard Terminal Arrival (STAR), a design which is simply the arrival route structure for aircraft that follow instrument flight rules (FAA) in terms of CO_2 emission, flight time, and fuel consumption. The results demonstrated that the CO_2 emission, flight time and fuel consumption reduced by 17%, 24.5%, and 26%, respectively. Liang et al. (2018) presented a MIP model approach to generate efficient trajectories for aircraft. The model utilises the PMS structure with sequencing legs at four different flight levels for parallel runway operations. Cecen et al. (2020) presented a stochastic mixed-integer linear programming (MILP) model for ASSP considering the wind direction uncertainties. They applied SA algorithm to reach near optimum solutions in short time. Cecen (2021) also introduced multi-objective MILP model using PMS approach. The total aircraft delay and the number of conflict resolution manoeuvre were selected as the objective functions.

This current study investigates the effect of the turning point location throughout the sequencing legs used in the PMS on fuel consumption. A MILP model is used to solve this problem. Furthermore, the model utilises vector manoeuvre with PMS to avoid any aircraft conflict. Two different placement approaches are compared. In the first approach, no fixed turning point is specified for the turning point. The second approach presents a constant distance between two consecutive turning points. To the best of our knowledge, this study is the first one that investigates the turning point placement effect on fuel consumption. Because most of the previous studies using PMS in the TMAs (Hong et al., 2017, 2018; Liang et al., 2018; Lee et al., 2020; Tian et al., 2021) determined turning decisions assigning the flight duration on the sequencing legs. However, this approach creates a problem for both ATCos and pilots in terms of instruction. Therefore, in this study, evaluating the effect of turning points on fuel will provide a different perspective to further studies on PMS.

The rest of this paper is organised as follows: problem description and mathematical model are explained in Section 2, and Section 3 presents the results and discussion. Lastly, the conclusions and further research are described in Section 4.

2 Problem description

2.1 Air traffic control

This study examines the ALP for the Istanbul Sabiha Gökçen Airport (LTFJ) for a single-runway airport. ATCos are responsible for handling aircraft traffic for conflict-free operations using suitable altitude, speed, and heading angle changes. It is assumed that radar separation is applied as three nautical miles (NM) and 1,000 feet in the selected TMA. Each aircraft has an expected time of arrival and a pre-defined TMA entry point. Aircraft use sequencing legs, merge point (MP) and final approach point (FAP) in the PMS. In this model, the altitudes of the sequencing legs are defined as 8,000 feet and 9,000 feet. These legs are divided into east arrivals and west arrivals, respectively. The distances between two sequencing legs and the FAP are 24 NM and 26 NM, respectively. The sequencing legs' distances are 29.5 NM and 26.5 NM, and the distances between the MP and the two sequencing legs are determined as 18 NM and 20 NM, respectively (DHMI, 2019). The separation between two successive aircraft operations on the runway is maintained using vortex separation as presented in Table 2.

Table 2 Time separations, in sec

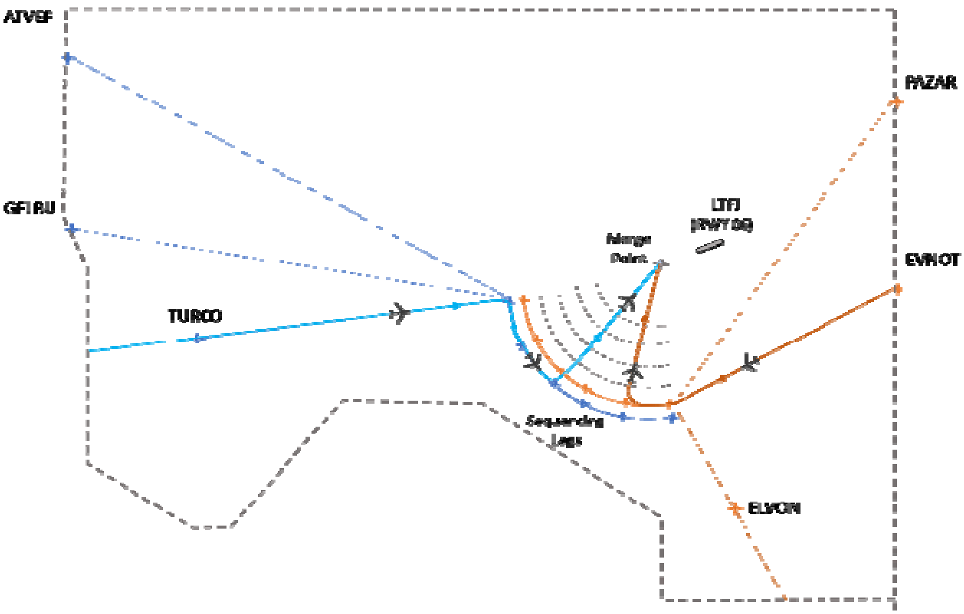
Leading/trailing	*Arrival-arrival*	*Arrival-departure*	*Departure-arrival*	*Departure-departure*
Heavy-heavy	96	75	60	90
Heavy-medium	157	75	60	120
Medium-heavy	60	75	60	60
Medium-medium	69	75	60	60

Source: Balakrishnan and Chandran (2010)

In Table 2, heavy and medium aircraft performance categories (APCs) are determined according to maximum take-off mass to maintain vortex separation minima. Heavy aircraft mass is between 136 and 560 tons. Similarly, medium aircraft mass is between 7 and 136 tons (ICAO Doc, 2018). In this study, vector manoeuvre with PMS is used to provide separation between aircraft pairs. It is assumed that the aircraft perform their vector manoeuvre before entering the TMA presented in Figure 2.

In Figure 2, blue-coloured and orange-coloured arrival routes help to understand the approach side of an aircraft, which can be either westbound (blue-coloured) or eastbound (orange-coloured) traffic. In addition, the TMA has six different entry points (ATVEP, GELBU, TURCO, PAZAR, EVNOT and ELVON), two sequencing legs with a MP. Sequencing legs are placed at the altitude of 9,000 (blue-coloured) and 8,000 (orange-coloured) feet. An aircraft starts descending operation after entering the TMA until reaching the assigned sequencing leg. Furthermore, turning points were placed on the sequencing legs with no fixed point, 1 NM, 2 NM, and 3 NM for the arrival operations. In the TMA, 3 NM radar separation and vortex separation were applied for the TMA and runway operations, respectively. It is assumed that aircraft fly with the standard atmospheric conditions. Wind speed does not affect the operations. All aircraft use the specific entry points of the TMA. While calculating the fuel consumption, two different aircraft fleet types are selected to represent heavy and medium APCs. The average traffic rates are determined as 10% and 90% for heavy and medium APCs, respectively. Also, this situation can represent the air traffic. Also, two main aircraft fleet types use LTFJ as a medium performance category, and their airspeed and fuel consumption values are similar for the specific flight levels. Therefore, one type of fleet for each APC was selected for this study.

Figure 2 TMA route configurations (see online version for colours)



Source: TMA route configurations (Cecen et al., 2020)

Then, the speed information is received from BADA 3.11 (2013), and the fuel data corresponding to these speed values are also considered. It is assumed that the aircraft started their descent movement right after entering the TMA. Therefore, they can also perform straight flight movements on the sequencing legs and TMA entrance level at two different altitudes. The parameters used in the fuel calculation are presented in Table 3 for equations (1), (2), (3) and (4).

Table 3 The parameters used in the fuel calculation

C_{f_1}	Thrust specific fuel consumption coefficient (kg/(min·kN))
C_{f_2}	Thrust specific fuel consumption coefficient (knot)
V_{TAS}	True airspeed (knot)
η	Thrust specific fuel consumption
Thr	Thrust
C_{fcr}	Cruise fuel flow factor
D	Drag
C_D	Drag coefficient
ρ	The air density
S	The wing area

It is necessary to calculate the thrust-specific fuel consumption value (η) [kg/(min·kN)] for the nominal fuel flow value. This value can be obtained using the following equation:

$$\eta = C_{f1} \times \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \quad (1)$$

The nominal fuel flow, f_{nom} [kg/min], can then be calculated using the thrust, *Thr*:

$$f_{nom} = \eta \times Thr \quad (2)$$

The cruise fuel flow, f_{cr} [kg/min], is calculated using the thrust specific fuel consumption η, the thrust *Thr*, and a cruise fuel flow factor, C_{fcr}:

$$f_{cr} = C_{fcr} \times \eta \times Thr \quad (3)$$

The required thrust *Thr* is assumed to be equal to aerodynamic drag for en route operations and depends on the drag coefficient, the air density, the wing reference area, and the true airspeed.

$$D = \frac{C_D \cdot \rho \cdot V_{TAS}^2 \cdot S}{2}. \quad (4)$$

2.2 Mathematical model

The MILP model aims to minimise total fuel consumption for the PMS operations and compare the turning point placement with regard to using no fixed turning point and fixed turning point approaches. The first approach uses equations (5)–(9) and (11)–(14), and the second one utilises equations (5)–(8) and (10)–(14). The entire model is presented below.

Indices

I set of aircraft i, i_1, $i_2 \in I$

K set of turning points $k \in K$.

Parameters

g_i the expected time of TMA entry (sec) for the aircraft i

d_{r_i} the distance (NM) from the entry point r_i to sequencing legs

s_i the approach side of the aircraft i for the sequencing leg

p_i the performance category of the aircraft i

fh_i the fuel consumption (kg) per second of an aircraft i for TMA entry level

fl_i the fuel consumption (kg) per second of an aircraft i for sequencing leg

k_i the fuel consumption (kg) value for the descent operations of an aircraft i

v_{r_i} the average airspeed (knot) from the entry point r_i to sequencing legs *dl* the distance (NM) from sequencing legs to the runway

v_l the average airspeed (knot) from sequencing legs to the runway

u the distance (NM) between two consecutive turning points.

$T_{p_{i1}p_{i2}}$ the separation time (sec) between APC of p_{i_1} and p_{i_2}

vs the airspeed on the sequencing legs

B the required separation (sec) time while entering the sequencing legs.

Decision variables

wh_i the vector manoeuvre duration (sec) for aircraft *i*

wl_i the travel duration (sec) along with the sequencing leg for aircraft *i*

e_i the entry time (sec) of sequencing leg for the aircraft *i*

q_i the arrival time (sec) of the aircraft *i* for runway

y_{i_1,i_2} 0–1 variable that gets a value of 1 if aircraft i_1 uses the runway before aircraft i_2; otherwise, it is zero

$c_{i,k}$ 0–1 variable that gets a value of 1 if aircraft *i* uses the turn point *k*; otherwise, it is zero.

$$\text{Min} \sum_i wh_i \cdot fh_i + wl_i \cdot fl_i + k_i \tag{5}$$

$$e_i = g_i + wh_i + \frac{d_{r_i}}{v_{r_i}} \qquad \forall i \tag{6}$$

$$e_{i_1} - e_{i_2} \ge B - \left(y_{i_1,i_2}\right) \cdot M \qquad \forall i_1, i_2 \,\middle|\, i_1 \ne i_2, s_{i_1} = s_{i_2} \tag{7}$$

$$e_{i_2} - e_{i_1} \ge B - \left(1 - y_{i_1,i_2}\right) \cdot M \qquad \forall i_1, i_2 \,\middle|\, i_1 \ne i_2, s_{i_1} = s_{i_2} \tag{8}$$

$$q_i = e_i + wl_i + \frac{dl}{vl} \qquad \forall i \tag{9}$$

$$q_i = e_i + \frac{\left(\sum_k c_{i,k} \cdot k\right)}{vs} \cdot u + \frac{dl}{vl} \qquad \forall i \tag{10}$$

$$q_{i_1} - q_{i_2} \ge T_{p_{i2}p_{i1}} - \left(y_{i_1,i_2}\right) \cdot M \qquad \forall i_1, i_2 \,\middle|\, i_1 \ne i_2 \tag{11}$$

$$q_{i_2} - q_{i_1} \ge T_{p_{i_1}p_{i_2}} - \left(1 - y_{i_1,i_2}\right) \cdot M \qquad \forall i_1, i_2 \,\middle|\, i_1 \ne i_2 \tag{12}$$

$$e_i, q_i, wh_i, wl_i \ge 0 \qquad \forall i \in I \tag{13}$$

$$c_{i,k}, y_{i_1,i_2} \in \{0, 1\} \qquad \forall i_1, i_2 \in I \; \forall k \in K \tag{14}$$

The objective function aims to minimise the total fuel consumption due to vector manoeuvre, flight on the sequencing legs and descent operations given in equation (5).

Constraint (6) calculates the entry time of the sequencing leg using the parameter expected entry time of the TMA, vector manoeuvre duration and flight time from the TMA entry point to the sequencing leg. Moreover, constraints (7) and (8) maintain the collision avoidance on the sequencing leg if the aircraft i_1 and aircraft i_2 use the same one. Also, separation is assured by the B value calculated using both the radar separation distance (3 NM) and airspeed value (approximately 280 knot) for the given flight level. Therefore, B value is determined as 40 seconds for both type of APCs since they both use the same airspeed in the same flight level according to the BADA 3.11 (2013) document. Constraints (9) and (10) calculate the landing time for each aircraft using the entry time of the sequencing legs, travel time on the sequencing and flight time from sequencing leg to the runway for no fixed turning point approach and pre-defined turning points, respectively. Constraints (11) and (12) check each aircraft pair's vortex separations minima on the runway according to their APCs. Constraints (13) and (14) are sign constraints.

3 Results and discussion

The mathematical model was implemented in GAMS/CPLEX program. Also, 18 different independent scenarios were generated, including different route, entry time, entry point, APC and aircraft operation type information for each test problem. Each scenario had a traffic situation for 20 arrival aircraft per 30 minutes. While the TMA entry time of each aircraft was obtained using an exponential distribution, the APC was generated through historical data as it is mentioned in Section 2. In addition, entry point assignments were determined via uniform distribution. Therefore, aircraft do not enter the TMA at the same time. In addition, each scenario had a unique traffic situation in terms of aircraft route assignments and TMA entry times due to the distributions mentioned above. The number of aircraft using entry point (count), the number of APC (count), and the number of aircraft for each time interval (count) is presented for each scenario in Table 4.

Turning points were placed with no fixed point, 1 NM, 2 NM, and 3NM, respectively, and their fuel consumptions were analysed. The distance for two consecutive turning points (TPD) (NM), total fuel consumption (FC) (kg), total flight time (FT) (min), and total airborne delay (D) (sec) of aircraft are provided in Table 5.

According to Table 1, the outputs presented in Figure 3 showed that the average total fuel consumptions were calculated as 2,922.1, 2,994.7, 3,025, and 3,137.5 kg for no fixed point, 1NM, 2NM, and 3 NM for the distance of two consecutive turning points, respectively. Also, the maximum total fuel consumptions were calculated as 3,230.8, 3,319.8, 3,452.5 and 3,534.6 kg, respectively. Similarly, the minimum total fuel consumptions were calculated as 2,645.7, 2,673.8, 2,703 and 2,731.4 kg, respectively.

Besides, the outputs introduced in Figure 4 showed that the average total flight times were calculated as 244.7, 246.7, 247.5, and 250.6 min for no fixed point, 1 NM, 2 NM, and 3 NM for the distance of two consecutive turning points, respectively. Also, the maximum total flight times were calculated as 252.5, 255, 258.7, and 261 min, respectively. Similarly, the minimum total flight times were calculated as 237.3, 238.1, 238.8 and 239.6 min, respectively.

Figure 3 Total fuel consumption values for different turning point distances (see online version for colours)

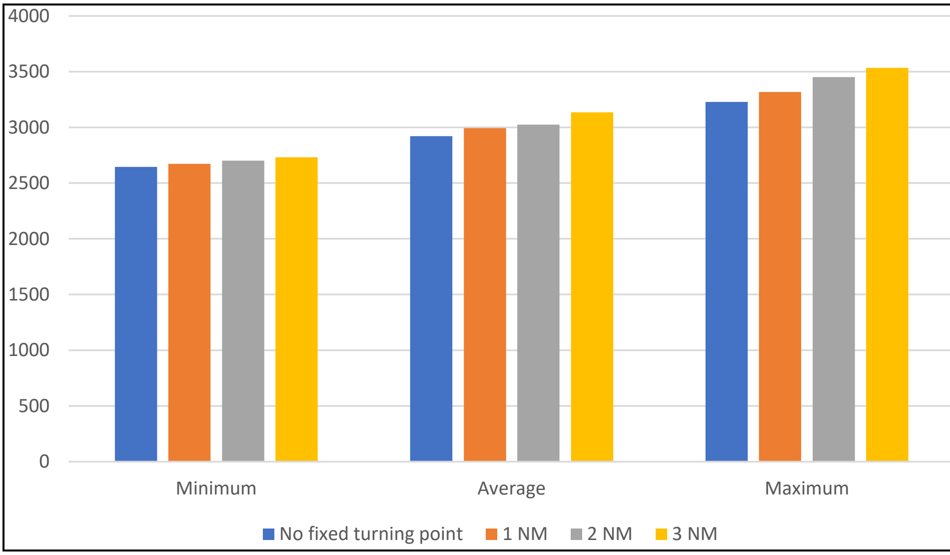


Table 4 Scenarios' details regarding entry point, APC and entry time distributions

Scenario	*Entry point distributions*						*APC*		*Entry time*			
	1	*2*	*3*	*4*	*5*	*6*	*Heavy*	*Medium*	*0–450*	*450–900*	*900–1,350*	*1,350–1,800*
1	2	1	3	5	3	6	2	18	6	3	5	6
2	2	2	4	1	3	8	2	18	3	5	4	8
3	5	1	4	4	1	5	0	20	6	3	6	5
4	5	3	3	5	3	1	4	16	5	4	5	6
5	5	3	4	3	2	3	0	20	4	5	3	8
6	3	1	5	6	2	3	1	19	5	3	4	8
7	0	6	5	4	2	3	1	19	3	6	6	5
8	6	5	4	3	1	1	2	18	6	4	4	6
9	3	2	4	4	2	5	0	20	3	6	4	7
10	4	3	4	4	3	2	1	19	4	3	4	9
11	2	7	4	2	1	4	1	19	5	6	4	5
12	3	3	7	2	3	2	3	17	6	5	4	5
13	3	2	2	4	5	4	0	20	6	5	5	4
14	3	2	1	8	3	3	2	18	6	6	6	2
15	8	6	0	1	0	5	1	19	6	4	3	7
16	6	0	7	1	3	3	2	18	4	3	6	7
17	4	2	6	2	4	2	0	20	3	3	3	11
18	4	4	3	3	2	4	0	20	4	5	3	8

Table 5 Experimental results

Scenario	*TPD*	*FC*	*FT*	*D*
1	0	2,708.0	238.9	322.9
	1	2,742.2	239.9	379.8
	2	2,771.5	240.7	428.9
	3	2,831.1	242.3	528.1
2	0	2,751.8	239.9	383.6
	1	2,818.4	241.8	494.6
	2	2,788.8	241.0	445.2
	3	2,865.3	243.1	571.9
3	0	2,992.5	247.0	806.8
	1	3,076.7	249.3	946.2
	2	3,094.2	249.8	974.4
	3	3,283.8	255.0	1,289.0
4	0	3,078.1	249.3	947.8
	1	3,160.6	251.6	1,085.2
	2	3,213.8	253.1	1,173.4
	3	3,279.8	254.9	1,283.8
5	0	2,931.5	245.0	685.8
	1	3,102.1	249.7	970.1
	2	3,099.6	249.6	964.0
	3	3,397.9	257.9	1,461.1
6	0	2,858.8	243.0	565.5
	1	2,891.3	243.9	619.6
	2	2,944.1	245.3	707.4
	3	2,988.8	246.6	781.9
7	0	3,044.8	247.6	841.3
	1	3,137.0	250.1	994.8
	2	3,187.9	251.5	1,077.3
	3	3,329.4	255.4	1,313.1
8	0	2,879.3	243.6	604.4
	1	2,975.8	246.3	765.3
	2	3,038.4	248.0	868.4
	3	3,057.1	248.5	895.2
9	0	2,789.4	241.0	448.6
	1	2,835.1	242.3	524.6
	2	2,842.5	242.5	537.0
	3	2,969.1	246.0	748.0
10	0	3,013.9	247.0	805.1
	1	3,097.3	249.3	943.9
	2	3,126.5	250.1	992.8
	3	3,305.3	255.1	1,290.7

Table 5 Experimental results (continued)

Scenario	*TPD*	*FC*	*FT*	*D*
11	0	2,645.7	237.3	225.2
	1	2,673.8	238.1	272.1
	2	2,703.0	238.8	318.1
	3	2,731.4	239.6	365.9
12	0	3,062.7	248.5	897.3
	1	3,129.7	250.4	1,008.4
	2	3,159.5	251.2	1,058.1
	3	3,238.2	253.3	1,187.6
13	0	3,057.7	248.3	884.9
	1	3,131.2	250.3	1,007.4
	2	3,138.7	250.5	1,019.9
	3	3,332.3	255.9	1,342.6
14	0	2,746.0	240.1	393.5
	1	2,775.8	240.9	442.9
	2	2,798.2	241.5	480.2
	3	2,815.2	242.0	507.7
15	0	2,859.8	243.0	566.4
	1	2,902.0	244.2	636.3
	2	2,931.4	245.0	685.4
	3	2,968.4	246.0	747.1
16	0	3,230.8	252.5	1,139.1
	1	3,319.8	255.0	1,286.4
	2	3,452.5	258.7	1,508.1
	3	3,534.6	261.0	1,644.9
17	0	2,916.7	244.8	673.5
	1	3,010.4	247.4	829.6
	2	3,078.5	249.3	942.7
	3	3,226.4	253.4	1,189.6
18	0	3,029.4	247.4	834.1
	1	3,125.9	250.1	994.8
	2	3,081.0	248.8	917.3
	3	3,320.6	255.5	1,319.1

Furthermore, the outputs in Figure 5 showed that the average total delays were calculated as 668.1, 789, 838.8, and 1,026 sec for no fixed point, 1 NM, 2 NM, and 3 NM for the distance of two consecutive turning points, respectively. Also, the maximum total delays were calculated as 1,139.1, 1,286.4, 1,508.1 and 1,644.9 sec, respectively. Similarly, the minimum total delays were calculated as 225.2, 272.1, 318.1 and 365.9 sec, respectively.

Figure 4 Flight time durations for different turning point distances (see online version for colours)

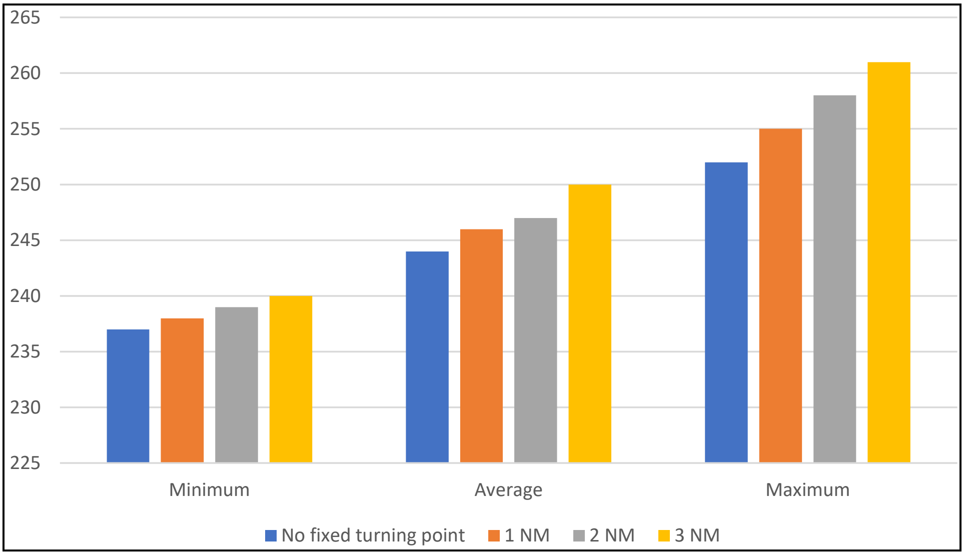
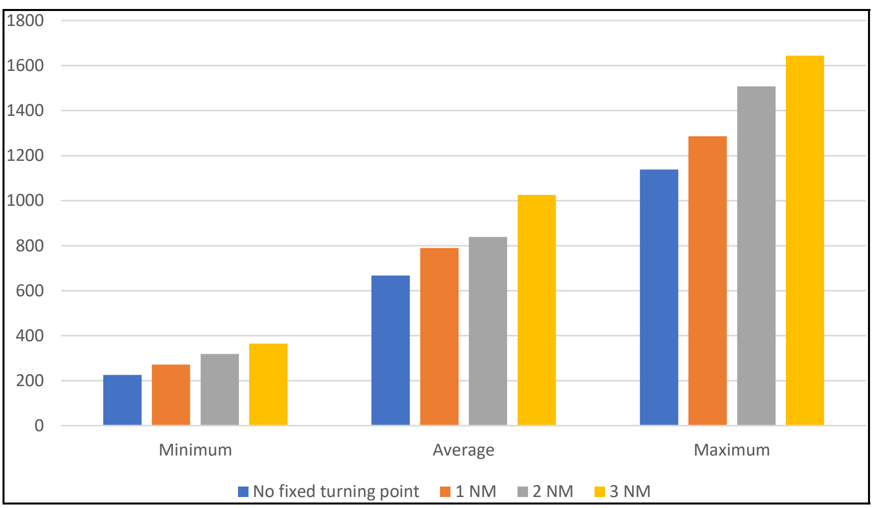


Figure 5 Total delay durations for different turning point distances (see online version for colours)



The results demonstrated that as the distance between the consecutive turning point increased, the average total fuel consumption increased 2.48%, 3.52% and 7.37%, respectively. Similarly, the increase also occurred in both total delay and total flight time. The average total flight time increased 0.82%, 1.15%, 2.41%, respectively. The average total delay time accounted for 4.55%, 5.33%, 5.64% and 6.82% of the total flight time, respectively.

4 Conclusions

This study considers the turning point location impact on aircraft fuel consumption throughout the sequencing legs on the PMS. Also, the model utilises vector manoeuvre with PMS to avoid any aircraft conflict. Two different methods are presented. No fixed turning point is specified for the turning point in the first one, and aircraft can turn anywhere. The second one presents a constant distance between two consecutive turning points. The result demonstrated that as we increased the distance between the two successive turning points, total fuel consumption also increased by 7.35% compared to the no fixed turning point placement. Moreover, the results showed that turning point placement affects fuel consumption directly. While the most common methods use no fixed turning point approach for this problem, applying this approach is difficult for ATCos or pilots. Determining constant turning points helps to decrease the workload of ATCos because they give simple instructions about which turning point are assigned for each arrival aircraft. Thus it is more applicable for decision support systems. Furthermore, the turning point decision must be provided as a specific turning point instead of time duration. In future studies, real-time application of this model can be implemented. Furthermore, a stochastic version of the model can be presented and tested for further studies.

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