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RESEARCH ARTICLE

Runway assignment optimisation model for Istanbul Airport considering multiple parallel runway operations

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Abstract

The aviation industry has rapidly developed in recent years. Due to the increased number of flight operations, managing air traffic has become essential. The air traffic management system aims to reduce the air traffic control workload and use existing resources more efficiently. This study proposed a new mixed integer linear programming model to minimise the total fuel consumption during taxi operations for the runway assignment problem, comparing the actual Istanbul Airport runway assignment data. The average taxi times are calculated using the 30,000-flight operations data for each arrival and departure taxi route. Also, 47 different aircraft types are obtained using the data for the fuel consumption calculation. The International Civil. Aviation Organisation (IACO) aircraft engine emissions databank provides the fuel consumption values for each aircraft according to engine type. This approach allows our model to calculate more realistic fuel consumption for taxi operations, as each aircraft engine type has a different fuel consumption value. The proposed model is implemented at Istanbul Airport, the busiest airport in Turkey, where multiple parallel runway operations are applied. The results showed that the proposed model reduced total fuel consumption for taxi operations between 6.6% and 14.4% compared to the actual Istanbul Airport runway assignment data.

Nomenclature

ADP	aircraft departure problem
ALP	aircraft landing problem
ASSP	aircraft sequencing and scheduling problem
MILP	mixed integer linear programming
MIP	mixed integer programming
NM	nautical miles
PMS	point merge system
RSP	runway assignment problem
TMA	terminal manoeuvring area

1.0 Introduction

According to EUROCONTROL's forecasts, in 2040, flight mobility in Europe will increase by 53%, 19 airports in Europe will be completely congested, 1.5 m flights that cannot be accepted at airports will not be operated, 160 m passengers will not be able to fly due to this reason, and this will have an economic impact of 88 billion euros [1]. Congestion in air traffic management due to increased traffic is not a new challenge for studies to manage the air traffic management system in an optimum operation for increasing capacity and reducing delay and costs. In these studies, the most economical solution is to investigate how existing resources can be used more efficiently. New runways, taxiways and airports are built where existing resources are insufficient to meet the expected demand [2]. One example is Istanbul Airport, which was constructed to meet the increasing demand at Istanbul Atatürk Airport. The construction of large and complex airports introduces more difficult problems for the air traffic system. Optimal use of existing or newly constructed facilities is always critical for improving fuel economy, increasing passenger satisfaction and reducing environmental impacts.

The primary constraint of the air traffic system is the runway [3]. Efficient use of the runway ensures maximum efficiency for ground operations. Runway capacity is defined as the hourly rate of aircraft operations on a single runway or combination of runways that can reasonably be expected to be met by system capacity under certain conditions [4]. Capacity depends on runway occupancy time, the sequence of aircraft types using the runway, the position and condition of taxiways, aircraft type and performance, the distance between parallel runways, whether the runways intersect, the mode of operation, the air traffic management system, weather conditions (low visibility, snow, etc.) and noise limitations [5]. To increase the efficiency of the air traffic system, efficient use of the runway, one of the main constraints, should be ensured. Many studies show that multiple parallel runways significantly increase airport efficiency [6]. Airports in busy cities around the world have multiple parallel runways. Paris Charles de Gaulle International Airport, Shanghai Pudong International Airport, Amsterdam Schiphol International Airport, Jeddah King Abdul Aziz International Airport, Hartsfield-Jackson Atlanta International Airport, Detroit Metropolitan Airport, Dallas Fort Worth International Airport, Denver International Airport and Chicago O'hare International Airport are some examples. Istanbul Airport, which has multiple parallel runways, was opened for use in anticipation of the insufficient capacity of Atatürk Airport in Istanbul, one of Turkey's cities with the highest air traffic. Since the effective use of multiple parallel runways is of great importance in terms of capacity, this study presents a solution by examining the runway assignment model with the actual data of Istanbul Airport, which is an important centre at the intersection of Asia, Europe and the Middle East and has multiple parallel runways.

This study presents a mixed integer linear programming (MILP) model to minimise the total fuel consumption for runway assignment problems (RSP) during taxi operations. This study investigates how much fuel consumption the model can reduce in taxi operations, comparing the fixed runway assignment approach, which is stuck to the gate assignments in the actual data. The study aims to provide a runway assignment for each aircraft regarding the parking position and runway availability. Also, our model utilises actual taxi duration obtained from real traffic data. After analysing the 30,000 aircraft operations at Istanbul Airport in September 2021, the average taxi times from each parking position to each runway were calculated. Besides, previous studies generally selected three different aircraft types to represent the aircraft mix. Unlike them, this proposed model used 47 different aircraft types to accurately describe air traffic obtained using actual data. In this way, the intensity of ground movements is improved and fuel consumption is presented more rationally, providing economic and environmental benefits. The fuel consumption values of the engine types in taxi operations are extracted from the ICAO Engine Emission Data Bank. The maximum and minimum fuel consumption values are listed for each aircraft type [7]. This model aims to minimise fuel consumption in ground operations for multi-parallel runway operations, considering the actual data of taxi duration for both departure aircraft and arrival aircraft separately.

2.0 Literature Review

Increasing traffic and congestion in the air traffic system have led to various solutions and tools to improve efficiency. Decision support mechanisms such as the arrival manager and departure manager, models aimed to prevent traffic conflicts, the design of standard instrument departures and standard terminal arrival routes that provide procedural separation, the collection point system established by

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eurocontrol in 2009, etc., are some examples. While some studies examine ground movements and terminal manoeuvring area (TMA) operations separately, some studies aim to optimise ground movements by considering ground movements and TMA operations. These studies include aircraft sequencing, runway assignment, and gate assignment. In the literature, solutions to these problems are commonly sought through mathematical modelling. Mathematical models provide solutions by considering the constraints in line with the specified objective. In aircraft sequencing and scheduling, attention to runway and gate assignments allows more aircraft to be served per unit time. Aircraft sequencing and scheduling problem (ASSP) is generally divided into aircraft landing problem (ALP) and aircraft take-off problem (ATP), which consider unique physical constraints involving arrival or departure operations. If both landing and take-off traffic is analysed in the study, it is called the ASSP. Since ASSP evaluates both landing and take-off aircraft, it reflects the reality more. ALP and ATP aim to determine the optimal arrival and departure sequencing to optimise the objective function given the operational constraints. The constraints used for the mathematical formulation of ALP and ATP are the separation values between two consecutive aircraft required for a safe landing, the maximum time constraint for the aircraft to land due to fuel, and priority constraints. The objective function used varies depending on the decision maker. The decision maker can set different objective functions by considering the various stakeholders of the airport system. However, there are differences between what is in theory and what is realised due to the human factor [8].

Flow optimisation in air traffic management has been the subject of many studies from different perspectives. These studies address conflict resolution, sequencing and scheduling issues to achieve flow optimisation in the airspace. In contrast to previous studies, Hong et al. presented a single and multi-objective optimisation model for the ASSP with a limited number of sequence changes by considering the working principle of an actual air traffic controller. This study paved the way for studies that will take more into account the human factor [9]. Cecen presented a single and multi-objective optimisation model that minimises the total delay and number of conflict resolution manoeuvres by identifying that sequencing and conflict resolution is the most time-consuming task for air traffic controllers. A solution to the ASSP was presented with mixed integer programming (MIP) [10]. Cecen et al. proposed a multi-objective optimisation model for the ALP to minimise emissions and total flight time. They used the GAMS CPLEX solver, which gives exact solutions. Their study obtained Pareto-optimal solutions for each air traffic situation [11].

In other studies, Ma et al. presented a model that handles airspace and ground operations together, aiming at both traffic flow optimisation and the proper functioning of ground operations, with the idea that the air traffic system, airspace operations and airport operations should be considered. With the presented model, a solution for resolving conflicts in the airspace was offered, while at the same time, runway assignment was proposed [12]. Cecen et al. proposed a stochastic MILP model to solve ASSP using the simulated annealing algorithm. The model, which aims to minimise the total aircraft delay for an airport runway serving mixed operations, provided an appropriate aircraft sequencing considering the wind direction uncertainties, which are critical in the decision-making process [13]. Ghoniem et al. addressed the static aircraft sequencing problem for single runway or closely interacting parallel runways with mixed operation modes. The model utilised the basic structure of the time window asymmetric peddler problem, and its effectiveness was demonstrated with simulated examples using real data from Doha International Airport [14]. Cecen presented a mathematical model to minimise the total fuel consumption for ALP. The path stretching method and the point merge system (PMS) were compared using vector manoeuvre and speed reduction techniques. The results showed that the path-stretching approach increases the number of continuous descent operations and reduces fuel consumption [15]. Some studies provided various solutions to RSP using single and multi-objective models. Runway assignment studies aim to provide a more efficient traffic flow by assigning landing and take-off aircraft to the most suitable runway. When runway assignment is considered from the perspective of the airline carrier, the parking position taxi time between the runway and the parking position is included in the objective function. In contrast, safety, shorter flight time, and less workload are considered from the air traffic controller's

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perspective. Liu et al. introduced a mathematical model for the TMA operations using a tailored selective simulated annealing algorithm. They compared the trombone procedure and the PMS system. Their outputs showed that the PMS system improved the performance of arrival air traffic [16]. Salehipour mentioned that the ALP is a problem that includes both the landing sequence of aircraft and the runway assignment. For this reason, he presented a heuristic model that can provide a solution to the ALP in a short time. He tested his algorithm on 124 examples. According to the results, the presented model produced a satisfactory solution quickly [17]. Dönmez et al. discussed the importance of landing sequencing in a collection point system and the reassignment of runways to ensure maximum efficiency in landing sequencing. They showed that assigning aircraft to a different runway can significantly reduce delays and fuel consumption due to the difference in taxi entry/exit times. The study proposed single and multi-objective programming models for a TMA with multiple collection point merge systems to minimise total fuel consumption, flight time and delay, including taxi entry/exit times. According to the results obtained from applying the proposed model with Istanbul Airport data, it reduced delays by 77.5% and fuel consumption by 8.7% due to the difference in taxi entry/exit times [18]. Dönmez et al. presented deterministic single-objective, deterministic multi-objective, stochastic single-objective and stochastic multi-objective mathematical models for parallel runway airports with multiple collection point systems considering wind uncertainty and taxi times, respectively. The model, which aims to minimise total fuel consumption, total flight time, and total delays, provides arrival-departure sequencing, scheduling and runway assignments and shows how wind and taxi times affect fuel consumption, flight times, delays and runway preferences [19].

Guépet et al. presented a model to resolve terminal airspace conflicts, reduce airside capacity overload and reduce delays, as airspace and ground operations were considered the main bottlenecks affecting capacity. In this study, an optimisation model was produced by using speed, arrival time, departure time and runway assignment, and then the optimisation model is tested with data from Paris Charles De Gaulle Airport using the simulation annealing method. A four-hour period was considered for the test during one of the airport's peak days, and runway assignments were made for landings and take-offs. As a result, a 37% improvement in landing delays and a 36% in take-off delays were achieved. The presented model showed that balanced use of runways and reduced delays can be achieved [20]. Rodríguez-Sanz et al. introduced the integration of runway scheduling for arrival and departure operations with a mathematical model to minimise delays in the tactical phase while maximising runway utilisation. The presented model was tested with data from Alicante-Elche airport. The results showed that the presented model reduces the delays by 50% on average [21].

It has been observed that environmental factors have been ignored in the studies conducted for runway efficiency. Sölveling et al. presented an integrated approach to ensure efficient runway use and minimisation of environmental impact with a first-come, first-served (FCFS) logic. The study aimed to minimise cost and environmental factors while introducing runway scheduling and aircraft sequencing. Instead of including environmental factors directly, they were included in the objective function in the form of fuel consumption. The presented model was analysed at Detroit Metropolitan Wayne County Airport, which has two parallel runways with intersecting taxiways. The results showed that optimisation-based scheduling that considers environmental costs significantly saves airlines and society. Furthermore, even if environmental components are not directly included in the optimisation but a fuel consumption-based target is used, ecological savings through a FCFS policy are still significant [22]. Lieder et al. presented an optimisation model for the ASSP based on generic runway configurations. The dynamic programming heuristic model minimised the delay-related costs of aircraft and generated a runway assignment solution by considering the minimum diagonal separation between dependent runways. The model's validity was tested on the runway configurations currently used at Frankfurt Airport, which has four runways [23]. Ng et al. presented a model that provided solutions to dynamic runway configuration planning, aircraft sequencing, and scheduling problems by considering the criteria considered by the air traffic controller in determining the runway configuration to ensure efficient and balanced use of runways during peak and off-peak periods of landing or take-off air traffic. The model, which provides a systematic approach to runway operations, was tested at Hong Kong International Airport and reduced

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delays by 71.6% and 37.08% for the two modes of using the separated runway system, respectively [24]. Cecen presented a mathematical model for a terminal traffic flow problem. Extended TMA boundary and conventional TMA boundary with PMS were compared using vector manoeuvre, the PMS and speed reduction techniques. The result revealed that extended TMA operations using speed reduction reduced fuel consumption [25].

Weiszer et al. presented an optimisation model to provide solutions to airport ground movements and runway scheduling problems, emphasising the efficient use of time and the consideration of fuel consumption and related emission values while investigating the optimisation of airport surface operations. To evaluate the performance of this model, experimental studies using data from Doha, Manchester and Beijing Capital International airports showed that the model could be used as a decision support mechanism [26]. Fritzsche et al. studied the dynamic assignment of runways to landing aircraft, recognising that flexible and demand-driven use of runways could be vital to meeting future capacity, efficiency and environmental sustainability. The study aims at balanced runway utilisation to reduce landing and take-off delays and taxi times, which cause fuel consumption and emissions. The results showed that providing a balanced runway assignment impacts delays, taxi times and fuel consumption [27]. Delsen examined the problem of RSP for landing and take-off aircraft at Amsterdam Schiphol International Airport from a different perspective. Since he observed a trade-off between reducing noise and increasing capacity in the current runway assignment but that fuel consumption and resulting emissions were not taken into account in the runway assignment, he presented a model using MIP that aims to optimise for fuel and noise [2].

3.0 Model description

To test the validity of the mathematical model developed in this study, which provides a solution to the runway assignment problem, actual data from Istanbul Airport was utilised.

3.1. İstanbul airport structure

On October 31, 2018, shortly after the first commercial flight was launched, Istanbul Airport became the busiest airport in Europe, surpassing Paris Charles de Gaulle, Amsterdam Schiphol, Frankfurt and London Heathrow airports, which are the busiest airports in the world [28]. Istanbul Airport served 200 m passengers with 262 destinations in 2021. Istanbul Airport, where the first phase has been completed [29], has 5 parallel runways (34L, 34R, 35L, 35R and 36) and 186 taxiways. While runways pairs 34L-34R and 35L-35R, are dependent parallel runways, 34-35-36 runways are operated independently. For instance, runways 34R and 35L are used as independent parallel runways while 34L is used for arrival and 34R is used for departure operations. Depending on the wind direction and different variables, aircraft generally use two different configurations: North and South. The North and South configuration is shown in Fig. 1.

Only the North configuration and its operation modes were studied in this study. It assumed that 34L and 35R serve for landing, 34R and 35L serve for take-off, and runway 36 serves for both landing and take-off.

3.2. Istanbul airport traffic demand

According to the State Airports Authority's annual report for 2021, traffic volume in 2021 increased by 39% compared to 2020 but remained below the traffic volume in 2019 due to the travel restrictions imposed during the pandemic. In 2021, the number of passengers carried increased by 57.1% compared to 2020, reaching approximately 128 m passengers. The Covid-19 crisis has also significantly affected airports in Turkey. Although it took a long time for many airports to recover from this impact, Istanbul, Sabiha Gökçen and Antalya Airports were close to their previous performance in a short time. Among these, Istanbul Airport became the second airport in Europe in terms of average daily movements [30].

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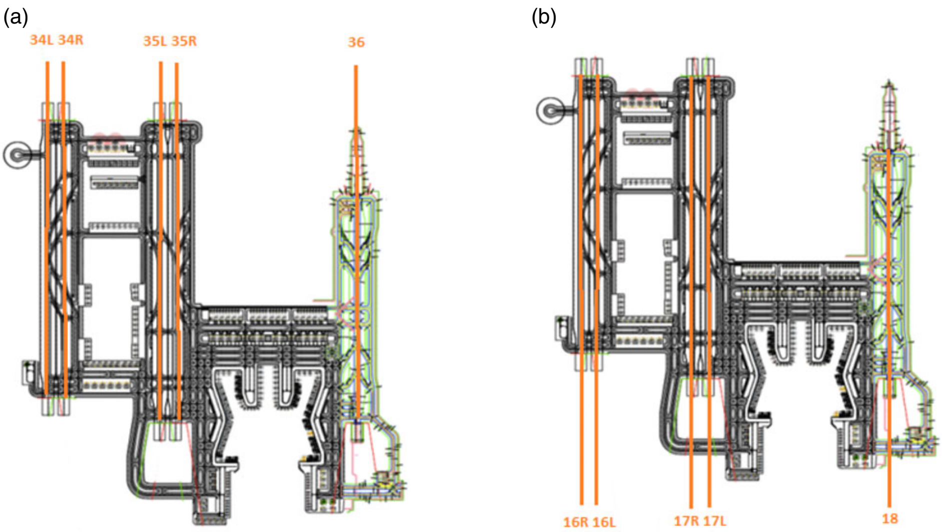

North Configuration

South Configuration

Figure 1. *Configuration of the parallel runways at Istanbul Airport.*

Istanbul Airport served 280,108 traffic in 2021. While 94% of the aircraft served are passenger aircraft, cargo aircraft are the second most common type, with a rate of 4%. State, military and other aviation aircraft accounted for 1% of the aircraft served. In September 2021, 29,818 aircraft (14,955 landings and 14,863 take-offs) used Istanbul Airport. In September 2021, a daily average of 499 landings and 496 take-offs, and a daily average of 993 traffic was served, according to the data obtained from the State Airports Authority, the airport, which is mainly used by passenger planes, cargo planes, military planes and private jets, which constitute the majority of the traffic, served an average of 985 passenger planes per day in September. While 30% of these passenger flights were domestic, 70% were international. It was figured out that there were 304 domestic flights and 681 international flights on a daily average.

For the analysis mentioned above, the aircraft types used at Istanbul Airport in September 2021 and the average taxi time between each parking position and each runway were obtained. The aircraft types are obtained using the one-month traffic data of Istanbul Airport. Since the engine types directly affect the fuel consumption value, the engine types used for 1 jumbo category, 20 heavy categories and 27 medium categories of aircraft types in the table were obtained from Eurocontrol data and examined in detail. Fuel consumption data for the alternative engine types listed for each aircraft type were obtained from the ICAO Engine Emission Data Bank [7]. Listing all possible engine types was essential to see the differences in fuel consumption. If more than two engines exist for an aircraft type, the engine that provides less fuel consumption values was used for an aircraft type.

Since Istanbul Airport covers a large area, taxi times vary considerably depending on the runway and the gate assignments. To calculate the average taxi time between Istanbul Airport runways and parking positions, the taxi times of the aircraft landing and taking off from the airport in one month, the data of five runways and 364 parking positions used were analysed carefully, and the average taxi time between each runway and parking position was obtained.

According to the analysis of the average taxi time of landing traffic for each runway in a previous academic study, an aircraft landing on runway 34L has an average taxi time of 17.97 minutes, an aircraft landing on runway 35R has an average taxi time of 10.20 minutes and an aircraft landing on runway 36 has an average taxi time of 10.45 minutes. According to this analysis, an Airbus 300-600 aircraft landing on runway 35R instead of 34L can taxi 7.77 minutes less on average and save 191kg of fuel, provided the assigned gate remains the same. For this reason, the study examines the improvement that

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Table 1. The amount of traffic in the scenarios

Date	Arrival	Departure	Total
03.09.2021	519	527	1,046
04.09.2021	513	509	1,022
05.09.2021	516	517	1,033
10.09.2021	516	527	1,043
11.09.2021	514	509	1,023
12.09.2021	515	514	1,029
13.09.2021	512	505	1,017
26.09.2021	509	509	1,018
Average	514	515	1,029

can be achieved by the runway assignment through fuel savings [31]. According to the data, in September 2021, it had an average of 1,006 daily traffic. In September, eight different days with higher-than-average September traffic are selected. In the model, six-hour traffic operations are considered. The amount of traffic in the scenarios is shown in Table 1.

3.3 Mathematical model

This section introduces the sets, parameters, decision variables, constraintsand objective function equation used in the proposed mathematical model (PMM). This problem aims to minimise the total fuel consumed in ground movements for the RSP. Equations (1b), (2)–(13) are used for the fixed runway assignment approach (FRAA) regarding actual data, and Equations (1a), (2)–(13) are used without FRAA.

Sets:

$I = \{1, 2, \ldots., n\}$ the aircraft set

$J = \{1, 2, \ldots., r\}$ the runway set

$K = \{1, 2, \ldots., s\}$ the park position set

Indices:

$i, i_1, i_2 \in I$ are indices to donate aircraft

j, j_1, j_2 are indices to donate runway

$k \in K$ is indices to donate the park position

Parameters:

ox_i	The operation type of aircraft i where arrival =1 and departure=2
$ra_{ox_i,j}$	$\begin{cases} 1, & \text{if } ox_i \text{ can use runway } j \\ 0, & \text{otherwise} \end{cases}$
dpr_{j,j_2}	$\begin{cases} 1, & \text{if the runway } j \text{ and } j_2 \text{ are the same or parallel dependent} \\ 0, & \text{otherwise} \end{cases}$
$taxiin_{j,k}$	The taxi duration for arrival aircraft using runway j and park position k
$taxiout_{j,k}$	The taxi duration for departure aircraft using runway j and park position k

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M	A big number enough $$M = \left(\left(rt_{i_2}\right) - \left(rt_{i_1}\right)\right) \cdot 2$$ where i_1 and i_2 are the first and the last aircraft entering the TMA, respectively
p_i	The aircraft performance category
r_i	The runway assignment for aircraft *i,* in actual data
B	Time separation between two aircraft using the same parking position
t_i	The taxi duration of aircraft *i,* in actual data
g_i	The park position of aircraft *i,* in actual data
f_i	The fuel flow rate for aircraft *i* during taxi operations
rt_i	The runway use time for aircraft *i* in actual data
$tsep_{j,p_{i_1},p_{i_2},ox_{i_1},ox_{i_2}}$	The wake turbulence separation for the aircraft pairs using the same or parallel dependent runways according to their performance categories and operation types

Decision Variables:

$x_{i,j}$	$\begin{cases} 1, & \text{if the aircraft } i \text{ is assinged to the runway } j \\ 0, & \text{otherwise} \end{cases}$
e_{1i_1,i_2}	$\begin{cases} 1, & \text{if the aircraft } i_1 \text{ uses the runway before aircraft } i_2 \\ 0, & \text{otherwise} \end{cases}$
e_{2i_1,i_2}	$\begin{cases} 1, & \text{if the aircraft } i_1 \text{ uses the park position before aircraft } i_2 \\ 0, & \text{otherwise} \end{cases}$
aw_i	The parking position waiting time for aircraft *i*
gw_i	The departure queue waiting time for aircraft *i*
rut_i	The departure/arrival time of aircraft *i*
gut_i	The reach or leave time for parking position of aircraft *i*
$taxia_i$	The taxi duration for aircraft *i* to reach the arrival park position
$taxid_i$	The taxi duration for aircraft *i* to reach the departure runway

Constraints

$$\sum_{j|ra_{ox_i,j}=1} x_{i,j} = 1 \qquad \forall\, i \in I \tag{1a}$$

$$\sum_{j|j=r_i} x_{i,j} = 1 \qquad \forall\, i \in I \tag{1b}$$

$$rut_i = rt_i \qquad \forall\, i \in I, ox_i = 1 \tag{2}$$

$$gut_i = rt_i - t_i \qquad \forall\, i \in I, ox_i = 2 \tag{3}$$

$$rut_i = rt_i - t_i + \sum_j x_{i,j} \cdot taxiout_{j,k} + gw_i \qquad \forall\, i \in I\,, \forall\, k \in K,\ ox_i = 2,\ k = g_i \tag{4}$$

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Table 2. *Runway separation minima in nautical miles (NM)*

Arrival runway	Departure runway	Separation minima
34L-36	34R-35L	34L: 8NM 36: 4NM
35R-36	34R-35L	35R: 5NM 36: 4NM
34L-35R	34R-36	34L: 8NM 35R: 4NM
35R-36	34R-36	35R: 4NM 36: 8NM
34L-35R	35L-36	34L: 4NM 35R: 5NM
34L-36	35L-36	34L: 4NM 36: 8NM

$$gut_i = rut_i + \sum_j x_{i,j} \cdot taxiin_{j,k} + aw_i \qquad \forall\, i \in I\,, \forall\, k \in K,\; ox_i = 1,\; k = g_i \tag{5}$$

$$rut_{i_2} - rut_{i_1} \geq tsep_{j,p_{i_1},p_{i_2},ox_{i_1},ox_{i_2}} - \left(1 - e_{1_{i_1,i_2}}\right) \cdot M - \left(2 - x_{i_1,j_1} - x_{i_2,j_2}\right) \cdot M \qquad \forall\, i_1, i_2 \in I, \forall\, j_1, j_2 \in J,\; i_1 \neq i_2, dpr_{j_1,j_2} = 1 \tag{6}$$

$$rut_{i_1} - rut_{i_2} \geq tsep_{j,p_{i_2},p_{i_1},ox_{i_2},ox_{i_1}} - \left(e_{1_{i_1,i_2}}\right) \cdot M - \left(2 - x_{i_1,j_1} - x_{i_2,j_2}\right) \cdot M \qquad \forall\, i_1, i_2 \in I, \forall\, j_1, j_2 \in J,\; i_1 \neq i_2, dpr_{j_1,j_2} = 1 \tag{7}$$

$$gut_{i_2} - gut_{i_1} \geq B - \left(1 - e_{2_{i_1,i_2}}\right) \cdot M \qquad \forall\, i_1, i_2 \in I,\; g_{i_1} = g_{i_2} \tag{8}$$

$$gut_{i_1} - gut_{i_2} \geq B - \left(e_{1_{i_1,i_2}}\right) \cdot M \qquad \forall\, i_1, i_2 \in I,\; g_{i_1} = g_{i_2} \tag{9}$$

$$taxia_i = \sum_j x_{i,j} \cdot taxiin_{j,k} \qquad \forall\, i \in I\,, \forall\, k \in K,\; ox_i = 1,\; k = g_i \tag{10}$$

$$taxid_i = \sum_j x_{i,j} \cdot taxiout_{j,k} \qquad \forall\, i \in I\,, \forall\, k \in K,\; ox_i = 2,\; k = g_i \tag{11}$$

$$min \sum_i (taxia_i + taxid_i + aw_i + gw_i) \cdot f_i \tag{12}$$

Equation (1a) ensures that each aircraft is assigned to a suitable runway according to the type of operation. In contrast, Equation (1b) ensures that each aircraft is given to the runway, considering the actual data. According to real data, Equation (2) provides the runway use time for each aircraft that arrives. Similarly, Equation (3) calculates each departure aircraft's parking position leaving time. Equation (4) calculates the runway use times of the aircraft relative to taxi duration, using the parking position leaving time while considering the departure waiting time of each departure aircraft. Likewise, Equation (5) calculates the parking position reaching time for each landing aircraft using landing time, taxi duration and parking position waiting time durations. Equations (6) and (7) maintain wake turbulence separations between two consecutive aircraft using the same runway or two parallel dependent runways. Similarly, Equations (8) and (9) provide the time separation between pairs of aircraft using the same park position. Equations (10) and (11) calculate the taxi times obtained in ground operations for each landing and departing aircraft. Equation (12) minimises the total fuel consumption, considering taxi duration and waiting times. The parameters in Equations (6) and (7) were obtained using the minimum separation values published in Turkey by DHMI Aviation Information Publication [32]. These values are presented in Table 2. In addition to these published values, the wake turbulence separation criteria between the aircraft in the ICAO Procedures for Air Navigation Services - Air Traffic Management document were also considered [33]. Wake turbulence separation values are given in Table 3.

The minimum radar separation in Istanbul Terminal Airspace is 3NM. However, the minimum separation value that reduces for runways is 4NM. It has been applied in a way that meets the requirements

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Table 3. *Wake turbulence separation*

Leading aircraft	Trailing aircraft		
	Heavy	Medium	Light
Heavy	4NM	5NM	6NM
Medium	Minimum radar separation	Minimum radar separation	5NM
Light	Minimum radar separation	Minimum radar separation	Minimum radar separation

Table 4. *Arrival and departure aircraft number for scenarios*

Scenario	Arrival	Departure	Total
1	194	219	413
2	241	224	465
3	237	241	478
4	224	248	472
5	233	217	450
6	233	239	472
7	230	221	451
8	235	239	473

of Table 3. The model assumes that the engine consumes fuel in the idle configuration during the taxi movements and the gate waiting periods, the landing aircraft can only wait when approaching right before the park position, and the departure aircraft can wait just before entering the runway. The wind speed is assumed to be calm at 0kt.

4.0 Computational results

To test the proposed MILP model, scenarios were created using the busiest six-hour part of the eight-day traffic data of Istanbul Airport for September 2021. These scenarios were analysed according to the runway assignments presented in the actual traffic data and the runway assignments made by the mathematical model. The number of arrival and departure aircraft and the total number of aircraft in the traffic data used are shown in Table 4.

While a minimum of 194 and a maximum of 241 arrival aircraft occur in the scenarios, the number of departure aircraft is at least 217 and at most 248. The maximum traffic in scenarios with the busiest six hours of a day's traffic is 478. The results of the study can be evaluated in two criteria. In comparison, the first part evaluates the examination of operation types of aircraft in terms of taxi times and fuel consumption values. The second one assesses taxi times and fuel consumption, considering their performance categories. The average taxi times and enhancement rates (%) for aircraft operation types comparing runway use for the FRAA and PMM are presented in Table 5.

In the scenarios for arrival traffic using FRAA, the average taxi time of the landing traffic varies between 9.5 minutes and 12.4 minutes, while the average taxi time varies between 8.1 and 10.1 minutes in the PMM. The PMM provided a minimum of 11.3% and a maximum of 23.1% improvement in the average taxi time of landing traffic in eight scenarios. While the average taxi time of departure traffic varies between 13.5 and 16.7 minutes in the FRAA, the average taxi time varies between 13.3 and 14.9 minutes in the PMM. It is seen that the proposed model provides a minimum of 0.8% and a maximum of 10.8% improvement in the average taxi time of arrival traffic in a total of eight scenarios. According to the results, departure air traffic takes longer in taxis. It has been observed that waiting on the ground is preferred since arriving aircraft have priority in landing. In addition, the difference in the taxi routes

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Table 5. *Average taxi times of arrival and departure traffic (min.)*

	Arrival traffic			Departure traffic		
Scenario	FRAA	PMM	(%)	FRAA	PMM	(%)
1	12.4	10.1	18.6	16.7	14.9	10.8
2	11.1	8.8	20.6	13.9	13.8	0.8
3	10.3	8.2	20.2	13.5	13.3	1.0
4	11.0	8.5	23.1	13.7	13.5	1.4
5	10.7	9.1	15.1	14.1	13.9	1.7
6	9.5	8.4	11.3	13.8	13.7	1.3
7	11.2	9.1	18.9	14.2	13.9	2.0
8	10.1	8.1	19.9	14.6	13.7	6.2

Table 6. *Average fuel consumption of arrival and departure traffic during taxi operations (kg)*

	Arrival traffic			Departure traffic		
Scenario	FRAA	PMM	(%)	FRAA	PMM	(%)
1	307.1	249.3	18.8	431.4	383.7	11.1
2	271.5	213.1	21.5	345.7	342.3	1.0
3	249.3	193.6	22.3	337.6	334.6	0.9
4	262.9	198.1	24.7	355.2	351.0	1.2
5	280.6	235.8	16.0	347.0	338.9	2.3
6	241.8	208.6	13.7	360.2	354.1	1.7
7	305.3	233.7	23.4	383.6	370.5	3.4
8	247.2	200.9	18.7	376.7	355.5	5.6

used by the arrival and departure aircraft on the ground directly affected the taxi times. This situation can be seen in Table 5. The average fuel consumption values of the arrival and departure traffic in the taxi operations are given in Table 6.

Arrival traffic consumed a minimum of 241.8 and 307.1kg of fuel during the taxi duration. The improvement rates offered by the PMM, which significantly reduces the average fuel consumption of the arrival traffic in the taxi, vary between 13.7% and 24.7%. In four scenarios, it is seen that the average amount of fuel consumed by the landing traffic in the taxi has improved by over 24%. Departure traffic consumes a minimum of 337.6kg and a maximum of 431.4kg of fuel during the taxi duration. It is seen that the model's departure traffic improves the average fuel consumption in the taxi between 0.9% and 11.1%. Scenario 1 has the highest enhancement rate. Considering the traffic distribution in the scenarios, it is seen in Table 7 that the aircraft in the heavy category do not exceed 30% of the total traffic. For this reason, exploring fuel consumption according to the aircraft performance categories is necessary to understand the study's importance.

Table 8 shows the average taxi times of aircraft set in the medium performance category (MPC) and heavy performance category (HPC) aircraft for each scenario.

The average taxi time for medium category traffic in FRAA is at least 11.5 and at most 14.5 minutes. In the PMM, this value is at least 10.7 minutes and, at most, 12.5 minutes. With the PMM, the minor improvement was in Scenario 6, with 3.7%. In this scenario, the average taxi time was reduced from 11.5 to 11.1 minutes. The highest improvement rate was 14% in the first scenario. In this scenario, the average taxi time was reduced from 14.5 to 12.5 minutes. It is seen that the average taxi time for heavy category traffic is at least 12.2 minutes and at most 15.1 minutes in essential scenarios. In the PMM, it is seen that this value is at least 10.9 minutes and, at most, 13 minutes. The highest improvement rate was

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Table 7. *Number of traffic according to performance categories (count)*

Scenario	Medium	Heavy	Total
1	294	119	413
2	345	120	465
3	348	130	478
4	354	118	472
5	333	117	450
6	341	131	472
7	351	100	451
8	339	134	473

Table 8. *Average taxi times for medium and heavy performance categories traffic (min.)*

	MPC			HPC		
Scenario	FRAA	PMM	(%)	FRAA	PMM	(%)
1	14.5	12.5	14.0	15.1	13.0	13.6
2	12.3	11.0	10.8	12.7	11.7	7.5
3	11.7	10.7	8.4	12.3	10.9	11.4
4	12.2	10.9	10.4	13.0	11.6	10.9
5	12.2	11.4	6.1	12.9	11.4	12.1
6	11.5	11.1	3.7	12.2	11.1	9.1
7	12.3	11.3	8.1	13.8	11.9	14.3
8	12.1	10.8	10.4	13.1	11.1	15.0

Table 9. *Average fuel consumption of medium and heavy category traffic (kg)*

	MPC			HPC		
Scenario	FRAA	PMM	(%)	FRAA	PMM	(%)
1	324.7	278.0	14.4	492.4	425.7	13.6
2	268.8	236.6	12.0	417.9	386.7	7.5
3	252.5	230.0	8.9	404.4	357.4	11.6
4	270.9	242.8	10.4	433.0	385.2	11.0
5	273.5	254.9	6.8	424.0	372.6	12.1
6	268.4	254.5	5.2	388.4	354.6	8.7
7	308.8	273.0	11.6	466.2	398.1	14.6
8	269.1	247.3	8.1	424.4	360.4	15.1

observed in the eighth scenario, with 15%. In Scenario 8, the proposed model reduced the average taxi time from 13.1 to 11.1 minutes. The amount of fuel consumed by medium and heavy category traffic in a taxi is given in Table 9.

It was observed that a minimum of 5.2% and a maximum of 14.4% improvements were achieved for MPC. For the first scenario, which showed a gain of 14.4%, it is seen that the average fuel consumption values were reduced from 324.7 to 278kg. In Scenario 6, where the lowest recovery rate is seen, fuel consumption in the average taxi decreased from 268.4 to 254.5kg. While the average amount of fuel consumed by HPC traffic in a taxi was at least 388.4kg in Scenario 6, the average fuel consumption

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Table 10. *The distribution of the number of aircraft using the runways (count)*

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Runway	FRAA	PMM	FRAA	PMM	FRAA	PMM	FRAA	PMM
34L	9	55	13	69	8	65	13	72
34R	6	0	5	0	4	0	5	0
35L	87	178	98	130	97	104	95	83
35R	121	29	144	171	159	166	128	146
36	190	151	205	95	210	140	228	171
	Scenario 5		Scenario 6		Scenario 7		Scenario 8	
Runway	FRAA	PMM	FRAA	PMM	FRAA	PMM	FRAA	PMM
34L	14	38	7	28	8	60	5	50
34R	3	0	2	0	2	0	4	0
35L	84	121	95	134	87	128	105	160
35R	144	138	147	88	137	48	152	132
36	205	153	221	222	217	215	208	132

was reduced to 354.6kg with the proposed model. A minimum of 7.5% and a maximum of 15.1% improvement has been demonstrated. In Scenario 8, with the highest recovery rate, it is seen that there are 134 heavy-category aircraft, and the average fuel consumption values have been reduced from 424.4 to 360.4kg. These values saved more than 8 tons of fuel with the model proposed for the eighth basic scenario. When the changes in the taxi times for MPC and HPC aircraft and the decrease in total taxi fuel consumption are examined with the model presented, it reduces at least 4.5 tons, at most 13.7 tons in medium category scenarios. In comparison, it decreases to at least 3.7 tons and, at most, to about 8.5 tons in the heavy category. The average fuel consumption enhancements among all scenarios are 9.18% and 6.15% for the MPC and HPC, respectively. The distribution of the number of aircraft using the runways in the scenarios is given in Table 10.

When all scenarios are examined, when the 34L runway is used only for arrival operations, it is seen that the utilisation rate has increased in all proposed scenarios. It is seen that an assignment has yet to be made to runway 34R, which is used only as a take-off runway. It is understood from the tables that assigning departures to the 35L runway, which is used only as the take-off runway, reduces taxi time and, accordingly, fuel consumption. When the usage frequency and usage rates of the 35L runway are examined, the usage rate of the 35L runway has increased in all scenarios except the fourth scenario. Considering the use frequency and usage rates of the 35R runway, which is used only for arrivals, the use rate was increased in the three scenarios suggested. In comparison, it was decreased in five scenarios. While the usage rate of the 36 runways used as landing and take-off runways decreased in seven scenarios, the usage rate was increased in one scenario. When the tables of runway usage frequency and rates are examined, the proposed model makes suggestions to improve the use of runway 34L, which is used only for landing, to eliminate the use of runway 34R, which is used only for take-off, to increase the use of runway 35L, which is used only for take-off, and to reduce the use of runway 36, which is used for both landing and take-off. It is seen that the use of the 34L runway more for landing and the more preferred use of the 35L runway for take-off will improve fuel consumption. The total fuel consumption of landing and take-off aircraft and the total fuel consumption values in each scenario are given in Table 11.

The proposed model reduced overall fuel consumption in all scenarios. The improvement in the total fuel consumption of the landing traffic is relatively higher than the improvement in the total fuel consumption of the departure traffic. The presented model showed an improvement between 6.6% and 14.4%. The table shows that the most significant improvement was achieved in the first scenario, with 14.4%.

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Table 11. *Total fuel consumption values*

Scenario		Arrival (kg)	Departure (kg)	Total (kg)
1	FRAA	71,409.2	96,937.9	168,347.2
	PMM	59,600.1	84,509.7	144,109.8
	(%)	16.5	12.8	14.4
2	FRAA	84,159.2	77,891.9	162,051.0
	PMM	74,531.8	76,896.7	151,428.6
	(%)	11.4	1.3	6.6
3	FRAA	67,950.6	81,959.3	149,909.9
	PMM	57,337.2	80,982.7	138,320.0
	(%)	15.6	1.2	7.7
4	FRAA	70,367.4	88,964.6	159,332.0
	PMM	57,068.4	87,598.7	144,667.1
	(%)	18.9	1.5	9.2
5	FRAA	79,618.5	76,657.4	156,275.9
	PMM	68,860.6	73,744.1	142,604.7
	(%)	13.5	3.8	8.7
6	FRAA	74,352.2	87,977.9	162,330.1
	PMM	66,546.5	84,935.6	151,482.1
	(%)	10.5	3.5	6.7
7	FRAA	82,775.8	86,192.1	168,967.9
	PMM	67,731.3	82,058.9	149,790.1
	(%)	18.2	4.8	11.3
8	FRAA	70,083.7	91,181.1	161,264.8
	PMM	60,170.6	85,230.1	145,400.7
	(%)	14.1	6.5	9.8

5.0 Conclusion

This study proposes a MILP model to solve the RSP in multiple parallel runway operations. The model aims to minimise the total fuel consumption spent on taxi operations. To test the model's validity, the actual traffic data of Istanbul Airport were used, and the types of aircraft using the airport and the average taxi times from each parking position to each runway were determined. The engine types used in each aircraft type and their fuel consumption values are determined to calculate the fuel consumption of the specified aircraft types. Unlike previous studies, all aircraft types and fuel consumptions served at the airport were realistically examined in detail. Also, the proposed model aims to minimise the total amount of fuel consumed during taxi operations without assigning a new gate, only re-assigning the runway, and has been tested with scenarios created with Istanbul Airport data. The scenarios implemented by taking the six-hour parts of the eight-day traffic data of Istanbul Airport were compared with the FRAA, and the improvements were evaluated. When the experimental results were obtained, the eight scenarios discussed with the proposed model presented a minimum of 6.6% and a maximum of 14.4% improvement in total fuel consumption compared to the FRAA. It is seen that the total fuel of the landing traffic is reduced by 16.5%, and the total fuel of the take-offs is reduced by 12.8% in the case where the maximum improvement was seen in the total fuel consumption. When the assignment rates of the model, which offers a runway assignment proposal, are examined, it is seen that it assigns the landing traffic to the 34L runway and the take-off traffic to the 35L runway to increase the use of these runways and to avoid the use of this runway by not assigning the 34R runway.

The solutions presented to the runway assignment problem include reducing fuel consumption by assigning the runway close to the parking position and minimising the waiting duration. Besides, as the proposed mathematical model can minimise total fuel consumption on busy days, it can reduce both

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taxi duration and fuel consumption values on non-peak days more efficiently since there would be more options for runway assignments. Furthermore, the arrival sequence is maintained by ATCOs considering safety and efficient flight operations. However, as the fuel consumption values during ground operations were considered, a significant reduction for the fuel consumption can be provided. Runway assignment, which is not easy to solve, is a complex problem for the air traffic controller to solve in the current workload.

For this reason, mechanisms are needed to assist the air traffic controller in deciding on runway assignment. With this model presented, dealing with the required real-life situation is desired. There is no such decision support mechanism in practice. The use of such a decision support mechanism is critical in terms of speeding up the decision-making process of the approach controller, reducing the workload as a result of more efficient ground movements for which the tower controller is responsible, providing less cost for the airline operator and causing less pollution in terms of the environment. The mathematical model needs additional constraints to integrate the approach and tower operations. When the model can provide conflict-free TMA operations before the entire TMA, fast and feasible solutions obtained by the proposed mathematical model can be presented on one of the screens of air traffic controllers. This way, ATCOs can consider these arrival sequencing before the final sequencing. The runway assignment significantly affects the total fuel consumption of the aircraft. If even changing the tracks without changing the doors makes such a difference, it is thought that systematically assigning doors and tracks can significantly affect fuel consumption. The study can be more comprehensive by combining approach control and tower control. The study did not examine the environmental impact of reducing fuel consumption. Still, reduced fuel consumption will reduce exhaust emissions and the spread of carbon footprints to the environment. The environmental effects of runway designation can be examined in further studies.

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