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INVESTIGATION OF THE IMPACT OF THE AIR TRAFFIC ROUTE CONFIGURATIONS ON SECTOR CAPACITY

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ABSTRACT

Airspace constraints such as the network structure of the routes are among the limiting factors of the airspace capacity. The network structure of the routes is related to the configuration of routes, the presence of intersecting routes or conflict points, and the intersection angles. Improved sector capacity can be achieved through air route network development which allows to obtain an appropriate intersection angle and optimal configuration of the routes. Accordingly, two different route structures including single conflict point and three conflict points have been developed through the fast time simulation to measure the effect of different number of conflict points on the sector capacity. The study is conducted to different intersection angles including 15°, 30°, 45° and 60°. It is found that the capacity of the route structure including the single conflict point is lower compared to the route structure including three conflict points. Besides, as the intersection angle increases, the capacity gap between the investigated route structures decreases.

Keywords: Intersecting routes, Sector capacity, Fast time simulation, Air traffic management

1. INTRODUCTION

Airspace can be divided into subdivisions called sector to ensure aircraft which are separated safely, to achieve an efficient traffic flow and a more manageable airspace. However, the presence of intersecting routes, intersection angle, the location of the routes, and the distance among them may prevent the airspace from partitioning efficiently. Thus, a number of changes may be needed for a more efficient sectorisation, such as changing the positions of existing routes, reducing the number of intersections, or merging the routes intersecting at different points into a single point. Accordingly, in the European Organization for the Safety of Air Navigation (EUROCONTROL)'s report called "European Route Network Improvement Plan (ERNIP)", it is stated that unidirectional routes at the same level (odd and even) can be grouped at two different points so that two different sectors can be established. This method is called "roundabout" by EUROCONTROL [1].

In Figure 1a, there are 6 conflict points where direct routes are used, and in Figure 1b, which is structured with roundabout, there is only one conflict point per sector.

It can be said that the implementation of the roundabout method reduces the complexity of the sector as it reduces the number of conflict points. However, rearranging the flight routes to reduce the number of intersections or to change the angle of intersection may require extra maneuvering by the aircraft. On the other hand, it may be possible to increase the capacity of the airspace and to perform safe operations in intense traffic in return for extra maneuvers and operational costs. Besides, tactical interventions can be carried out by air traffic controllers with radar vectors in non-intensive traffic conditions.

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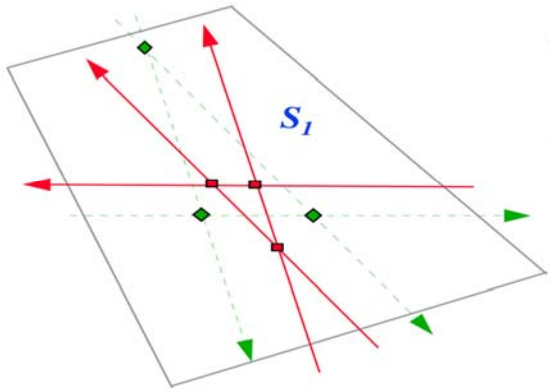


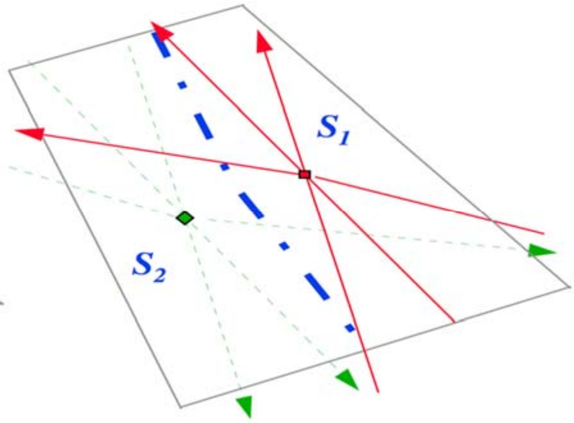


Figure 1: (a) Direct routes in a single sector (S1); (b) Routes in two different sectors (S1, S2) structured by roundabout [1].

Roundabout is a term used mostly in urban traffic, while it is also used for multiple intersecting routes in a number of air traffic management studies [2-5]. There is no turning maneuver in the method mentioned in the paper as on the highways. However, in such route networks, a turn maneuver may be required to prevent aircraft from conflicting, and it may be carried out by a controller via vectoring technique. Ramamoorthy et al., developed a conflict detection and resolution algorithm and presented a proposal using the roundabout method for 8 aircraft flying from different points to the same point. They stated that it is possible to avoid the conflict by a counter clockwise reversal, instead of changing the level of the aircraft [6]. Chatteri and Sridhar pointed out that the number of intersecting routes has significant influence on sector complexity. They also noted that it is easier to separate aircraft approaching at 90°, while it is more difficult at small angles [7].

The study is carried out through SIMMOD (The Airport and Airspace Delay and Consumption Simulation Model), which is a discrete-event fast-time simulation model, and especially used for capacity and delay analysis in air traffic operations. SIMMOD is based on detailed representation of airport and airspace structures using nodes and links. Traffic flows through the network of node-links where each node or link can accommodate a single flight at one time. When two aircraft meet on the same node or link, it is decided to which of them pass first and which is delayed by programming strategies of the model. The separation is provided by reducing or increasing the speed, a vector delay or holding the aircraft at a node. Some of the inputs required to design airspace structures in SIMMOD are the determination of the lengths and altitudes of the routes, the definition of the aircraft flying in the route network, aircraft speeds and separation minimums. The major outputs are travel time, traffic flow, capacity, delays and fuel consumption [8, 9]. SIMMOD is used for various problems such as congestion, delay and capacity analysis [10-12], analysis of different runway configurations [13], infrastructure changes such as runway, taxiway and gates [14], and fuel, emissions and their effects [15, 16]. In this study, the effects of the route configurations such as intersecting routes and the intersection angle on the average delay time, the sector capacity and occupancy, are examined.

2. MATERIALS AND METHODS

The air traffic control (ATC) sector capacity is the maximum number of aircraft that enters a specified sector and can be handled, directed or serviced safely in a given period of time, according to the international rules [17, 18]. The factors affecting sector capacity can be divided into two groups as traffic and sector conditions. Traffic conditions are the total number of aircraft in the sector, aircraft types and performance characteristics, traffic mix, the number of climbing/descending aircraft, aircraft speeds, horizontal and vertical separation standards, flight direction, the number of potential conflicts, level, heading and speed changes. Factors related to the sector can be listed as sector size and shape, the position of sector boundaries, the number of flight levels in the sector, the number of sector entry-exit points, the configuration of routes, the number of unidirectional routes, the number of air traffic facilities and wind [1, 18-21]. In the study, some of these factors (such as aircraft speeds for the same category) are assumed as equal and some are ignored (such as level change and wind) in order to calculate the sector capacity which is affected by many factors.

2.1. Separation Minimums

There are two types of separation as vertical and horizontal that must be applied in the airspace to allow the aircraft to fly safely [20]. In Turkish airspace, the vertical separation minimum is applied 1000 ft up to FL410 and 2000 ft above FL410, and the minimum horizontal (lateral and longitudinal) radar separation is 5 nautical miles (NM) [22].

For intersecting routes or the routes located closer than the minimum lateral separation distance (S_y), a lateral separation must also be provided together with the longitudinal separation. International Civil Aviation Organization (ICAO) states that an aircraft traveling on a route intersecting the course of another aircraft is laterally separated until it reaches the lateral separation point. After crossing the intersection point, the aircraft has been separated laterally by the other aircraft after passing the lateral separation point, which is located at a certain distance measured perpendicularly from the course of the other aircraft [20]. In the study, the horizontal separation between intersecting routes is established in accordance with these rules, and the conflict area for two intersecting routes is shown in Figure 2.

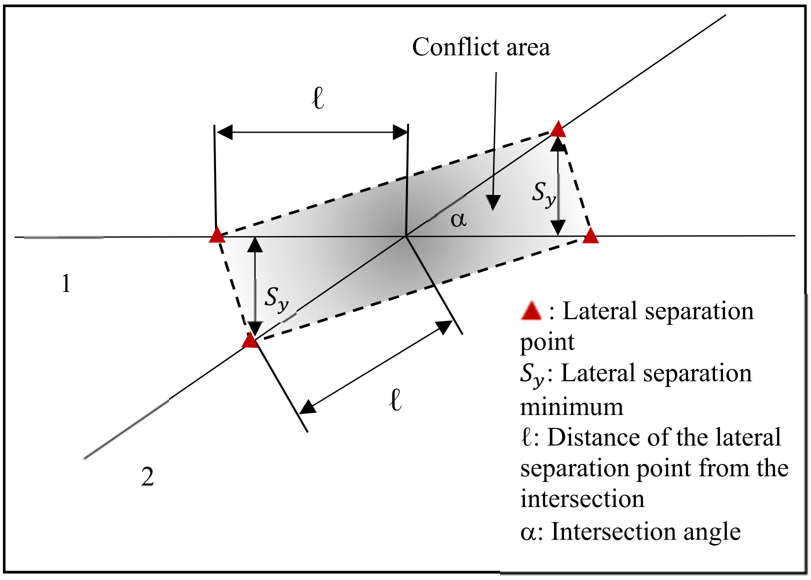


Figure 2: Lateral separation points and conflict area in intersecting routes [19].

2.2. Intersection Angle

In addition to the number of conflict points in the airspace, the size of the conflict area, which is the region that aircraft should not occupy at the same time, is also among the factors affecting the airspace capacity. The conflict area between ATS routes must be kept in minimum so that aircraft can be safely separated horizontally [1].

The size of the conflict area varies depending on the intersection angle. The reduction in the intersection angle requires an increase in the distance (ℓ) from the intersection point to the lateral separation point so that the minimum lateral separation distance (S_y) can be provided. For this reason, the area of the conflict region at the small angels is higher than larger angles, and this is a limiting factor for capacity as it increases airspace complexity. At 90°, the complexity and conflict area are the least for two intersecting routes [7]. For the three intersecting routes, the smallest conflict area is obtained for 60°, on condition that the angles between the route pairs are equal. For this reason, the largest angle of intersection used in the study is 60°.

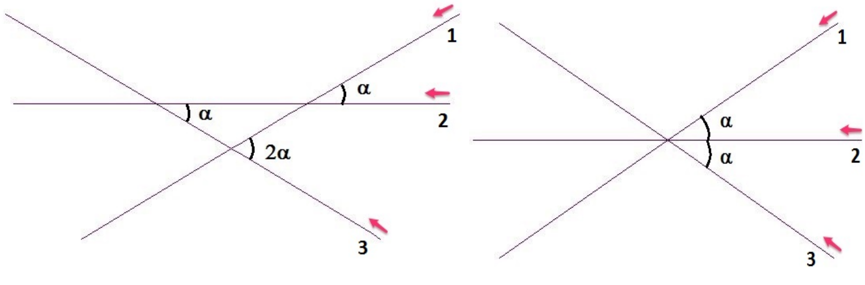
2.3. Simulation Model

Aircraft in intersecting routes can be separated by a level change. However, it is assumed that only horizontal separation procedures are executed in the study to analyze the angle of intersection. Besides, vertical separation is not always possible especially in intense traffic conditions. Considering this, the effects of proposed airspace route structures with different intersection angles are analyzed by applying a horizontal separation procedure for the aircraft maintaining the same level.

A sector can include many routes of different lengths. However, its size and shape are mostly based on the factors such as the traffic load and flow direction. They are usually determined to cover traffic flow and critical merge points to give controllers enough time to ensure safe separation [23]. In the study, route lengths are established to allow the proposed route structure to be designed, and the conflict points are located in a sufficient distance to the sector boundaries. Taking into account all of these, the lengths of each route are set equal to 200 NM in all scenarios.

Since the simulation model is designed on a horizontal plane, there are no climbing and descending aircraft. Therefore, there is no need to apply vertical separation minima. The minimum horizontal separation is 5 NM as in Turkish airspace. The study is carried out in the en-route phase of flight and created with the assumption of a radar-based airspace, and designed on a single sector. In addition, aircraft are considered to be flying in calm wind conditions.

The models created in SIMMOD environment are shown in Figure 3. Model 1 is formed by intersection of three routes, while model 2 is formed by using the roundabout method. In fact, model 2 is created geometrically by shifting route 2 to the intersection point of route 1 and route 3 in model 1. Also, the intersection angles between the routes (route 1 and route 2, route 2 and route 3) are equal (α). In this regard, it is aimed that the effect of both models on sector capacity can be compared under equal conditions. The aircraft's entry points and directions are shown by the arrows. The number of aircraft following each route is 30. A flight arriving from any routes follows and exits from the same route.



(a) **(b)**

Figure 3: (a) model 1 - routes intersecting at three points (b); model 2 - routes intersecting at one point by roundabout method

The study is carried out for each model at 15°, 30°, 45° and 60° to measure the effect of different intersection angles (α), and the created scenarios are shown in Table 1. The first three aircraft enter the simulation at 10:00 and the last ones at 12:25. In this period, the aircraft enter the simulations at the same time by 5 minutes interval from the routes numbered 1, 2 and 3.

Table 1. Scenarios created in SIMMOD for different angles.

Models	Intersection angle	Scenarios
Model 1	$\alpha=15°$	scenario 1
	$\alpha=30°$	scenario 2
	$\alpha=45°$	scenario 3
	$\alpha=60°$	scenario 4
Model 2	$\alpha=15°$	scenario 5
	$\alpha=30°$	scenario 6
	$\alpha=45°$	scenario 7
	$\alpha=60°$	scenario 8

The distribution of the aircraft type and wake turbulence category is based on the top 50 aircraft types using the European airspace between July 2014 and June 2015 [24]. In the study, a total of 90 aircraft are used, and their types and categories are given in Table 2.

Table 2. Aircraft used in simulations

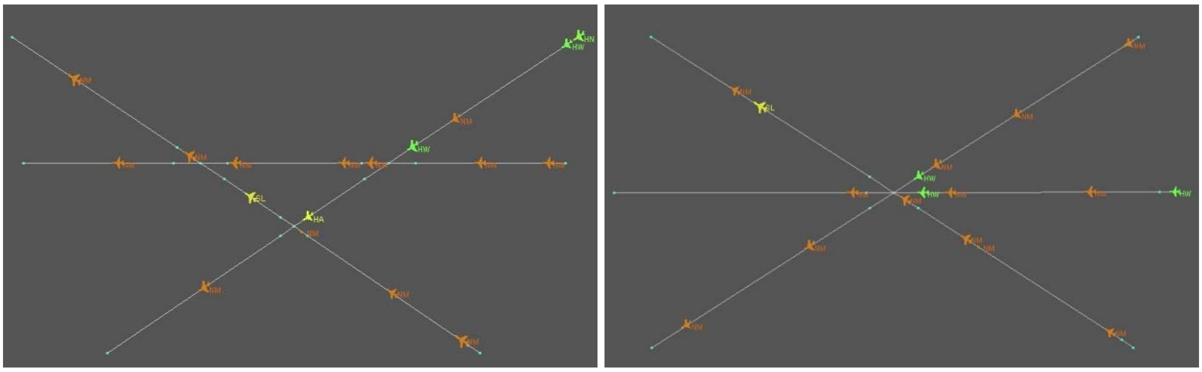
Order	Aircraft type	Category
1	B738	medium
2	A320	medium
3	A319	medium
4	A321	medium
5	B737	medium
6	B763	heavy
7	B733	medium
8	B752	medium
9	A333	heavy
10	E145	medium
11	B734	medium
12	B736	medium
13	B735	medium
14	F70	medium
15	H25B	medium

The categories, maximum altitudes and speeds of the aircraft have been obtained from EUROCONTROL's User Manual for the Base of Aircraft Data (BADA) [25]. Aircraft are assumed flying at flight level (FL) 360 by considering the most frequently used flight levels for en-route operations [24] and maximum altitudes of aircraft. In the situation of a potential conflict, the maximum and minimum speeds at which the speed of the aircraft can be increased or decreased are determined according to the categories based on the BADA data for the FL360. The reference speed refers to the travel speed of the aircraft under normal circumstances. These speeds are given in Table 3 in terms of true airspeed (TAS).

Table 3. Flight speeds according to aircraft categories (knots)

	Minimum	Reference	Maximum
Heavy	377	441	504
Medium	350	415	481

Figure 4 represents the screenshots of the models showing traffic flow for 30° angle of intersection.



(a) (b)

Figure 4: (a) Traffic flow of Model 1; (b) Traffic flow of Model 2

3. RESULTS

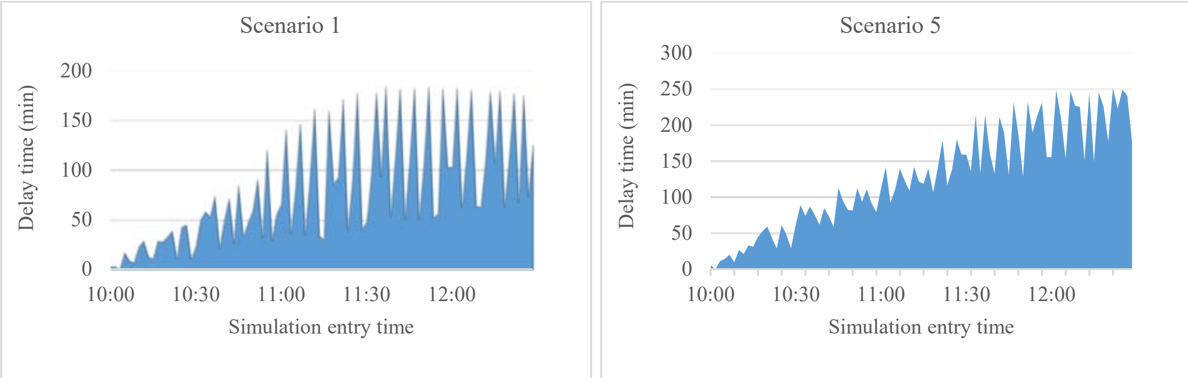
In the study, the capacity is calculated by counting the number of aircraft serviced within one hour time period. The simulation results of the scenarios are listed in Table 4 as simulation time, average delay and hourly aircraft capacity.

Table 4. Simulation results

Scenarios	Simulation time (min)	Average delay (min)	Capacity (aircraft/hour)
scenario 1	348	80	10
scenario 2	219	18	21
scenario 3	208	13	23
scenario 4	193	10	24
scenario 5	423	128	3
scenario 6	279	50	13
scenario 7	247	25	20
scenario 8	220	18	21

The delay times of the aircraft for the scenario 1 and 5 are given in Figure 5 depending on the simulation entry time. As it is seen, the delay times of the aircraft increase continuously throughout the simulation period. The difference in scenario 1 is that the aircraft are generally less delayed than scenario 5. On the basis of the aircraft, the longest delay times for the scenario 1 and 5 are about 180 and 250 minutes, respectively. On the other hand, it is seen that the delay times for both scenarios are very long, even though the delay time in scenario 1 is relatively lower. The reasons for this are that the traffic intensity is high for these two configurations, and the intersection angles are very small.

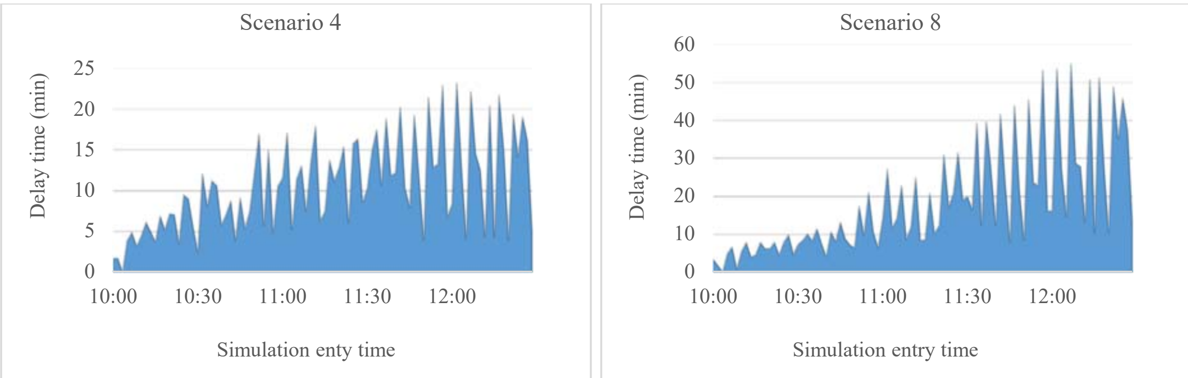
Moreover, the lack of level change in the study requires the conflict to be solved only by speed reduction/increase, vectoring and holding methods, which caused the delay times to increase. It can be concluded that the intersection angles of 15° and below for this traffic density can cause congestion and inefficiencies in the airspace.



(a) **(b)**

Figure 5: (a) Delay distribution of scenario 1 (α=15°); (b) Delay distribution of scenario 5 (α=15°)

When the intersection angle is increased to 60°, it is observed that the delay times have decreased considerably compared to 15°, as shown in Figure 6. On the basis of the aircraft, the longest delay times for scenario 4 and 8 are about 23 and 55 minutes, respectively. Besides, in scenario 4, the delay times are less than scenario 8. It can be stated that scenario 4 provides a more manageable traffic flow in terms of air traffic, as the increase in delay times is limited.



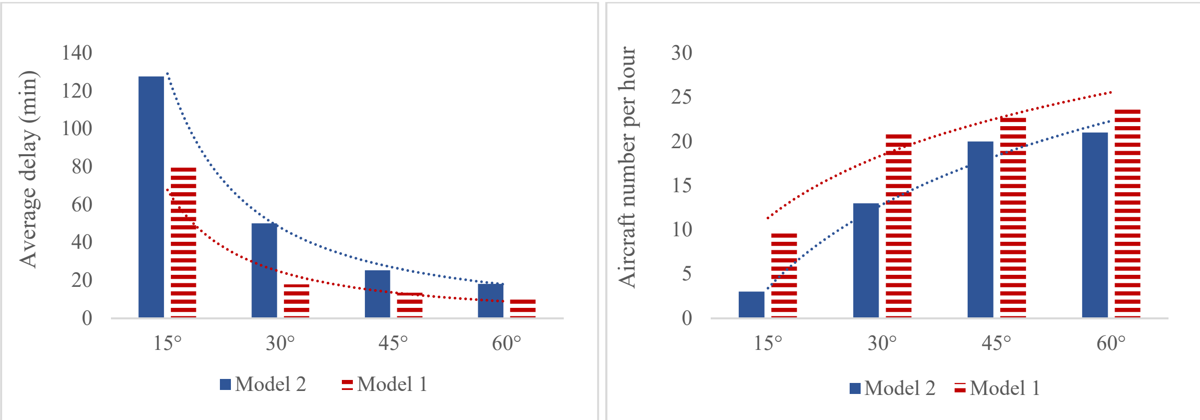
(a) **(b)**

Figure 6: (a) Delay distribution of scenario 4 (α=60°); (b) Delay distribution of scenario 8 (α=60°)

Figure 7a shows the change of the average delay times of the models depending on the intersection angle. The average delay time for model 1 and model 2 at 15° is 80 and 128 minutes, respectively. It is seen that as the intersection angle increases, there is a significant decrease in the average delay time. Furthermore, in model 2 formed by intersection angles of 15°, 30°, 45° and 60°, the average delay time is higher than the values corresponding to the same angle of model 1. This is because the aircraft have to go through a single point, and at this point, the congestion occurs over time.

On the other hand, at the intersections of 45° and 60°, the average delay time for model 2 is 25 and 18 minutes respectively, while for model 1, the average delay time for the same angles is 13 and 10 minutes. This demonstrates that increasing the intersection angle from 45° to 60° does not significantly reduce the average delay, especially for model 1.

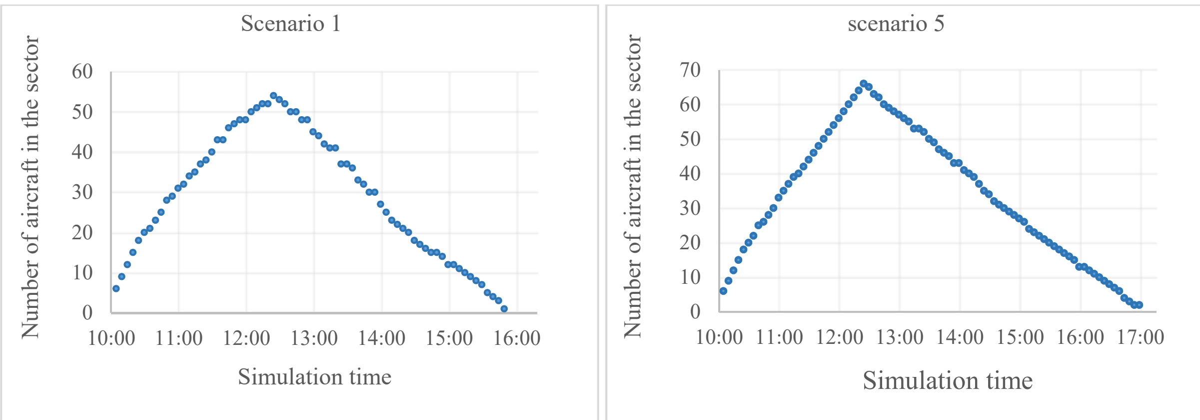
The effect of the different intersection angles on the capacity is shown in Figure 7b. At the small angles, the capacities are low, while they are significantly increased when the intersection angle increases. It is also seen that the average delay and the capacity graph change inversely. This indicates that the decrease in average delay increases the capacity. The capacity increase is only 1 flight/hour for both models as the intersection angle increases from 45° to 60°. The decrease in the increase of the capacity after a certain angle shows that using an angle value close to the optimal angle (60° in this case) in designing route may be sufficient to achieve an almost maximum capacity. Besides, at 15°, the difference between the capacities for model 1 and model 2 is 7, while this difference is only 3 for 60°. That is, approaching to the optimal intersection angle has also reduced the capacity differences between the models as it is also understood from the trend lines approaching each other in Figure 7b. In this context, if it is desired to merge the routes, it is important to select an optimal or close to optimal intersection angle in order to achive the maximum capacity.



(a) **(b)**

Figure 7: (a) Average delay time for different angles; (b) Capacity for different angles

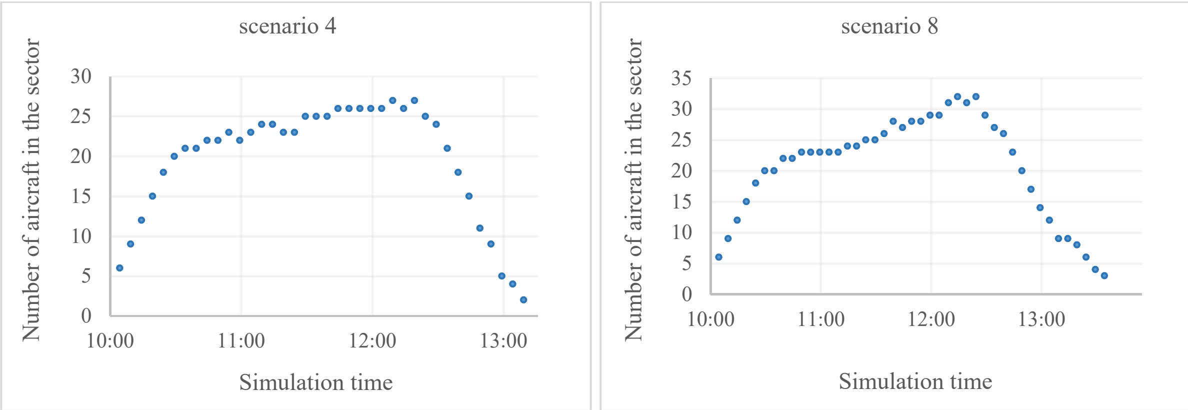
The distributions of the aircraft number in the sector during the simulation period for scenario 1 and 5 are given in Figure 8. As the aircraft continue to enter, sector occupancy increases steadily and at 12:25 rises to 54 for scenario 1 and 66 for scenario 5 due to the low capacity. The aircraft at the peak time (12:25) in scenario 1 is lower because the capacity is higher. However, in both cases, the increase in the number of aircraft until the last aircraft entry time indicates that the 15° intersection angle is not sustainable and causes the sectors to overload.



(a) **(b)**

Figure 8: (a) Sector occupancy for scenario 1 (α=15°); (b) Sector occupancy for scenario 5 (α=15°)

The distributions of the aircraft number in the sector during the simulation period for scenario 4 and 8 are given in Figure 9. In scenario 4, the number of aircraft in the sector changes from 23 to 27 between 11:10 and 12:30, and this change is limited compared to other scenarios. Also, the aircraft number at peak hour is 27, and this is less than all the other scenarios. The number of aircraft at 12.25, which is the peak time of other scenarios, is 25. This indicates that the number of aircraft in the sector is not in an increasing trend. On the other hand, for scenario 8, the number of aircraft in the sector increases continuously and reaches 32 at 12:25. If new aircraft enter the sector, it is expected that the number of aircraft in the sector will continue to increase.



(a) **(b)**

Figure 9: (a) Sector occupancy for scenario 4 (α=60°); (b) Sector occupancy for scenario 8 (α=60°)

4. DISCUSSION AND CONCLUSION

Factors such as airspace constraints, number of ATS routes and intersection points, interactions of routes and separation minima may limit sector capacity. In order to increase the efficiency of air traffic services and for a more manageable airspace, it can be divided into subdivisions called sectors. However, dividing some sectors into sub-sectors may be required to merge the ATS routes into a single point, and in the study, the effects of these arrangements are evaluated. The simulation results show that the increase of intersection angle reduces average delay time and sector occupancy, and enhances capacity. In the scenarios created for 15°, the number of aircraft in the sector rapidly increases to a certain point and afterwards decreases, however, this transition phase spreads over a wider time for 60°. Based on the investigated scenarios, it can be concluded that 60° of intersection angle and model 1 provide much better results in terms of airspace efficiency (sector capacity and occupancy, and delay).

Huang et al. and Treleaven and Mao suggest that the intersecting routes at one point can be transformed into a structure intersecting in pairs so that the conflict problem can be solved more easily [26, 27]. This proposed arrangement matches the findings obtained in the study. The results of the study and the existing studies in the literature show that the merger of more than two routes at the same level at a single point makes it difficult to resolve the conflicts as well as decreasing sector capacity. Merging the routes in a single point can allow the sectors to divide into sub-sectors, however, the limitation of the airspace capacity and the risk of increasing route lengths are the handicaps. In such conditions, it is useful to consider possible benefits and limitations and make an overall assessment of the air traffic system.

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