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CONFLICT RESOLUTION ALGORITHMS FOR THE INTEGRATION OF CONTINUOUS CLIMB OPERATIONS IN A TERMINAL MANEUVER AREA

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Abstract

This work presents a design approach and the algorithms for a future air traffic control tool which allow the operation of Continuous Climb Operations free of conflicts. This tool is designed for a tactical scenario where controllers can allow or prevent from an optimal departure of an aircraft taking into account several factors – type of aircraft, arrival and departing aircraft performances and airspace design. Thus, the aim of this tool is to generate a blocking area on some arrival or departing standard routes to ease the decision of air traffic controllers to permit or forbid the operation. Henceforward, controllers have two options – or to favor the arrival aircraft preventing the departure aircraft from taking-off until the blocking area is free or to opt for the opposite action, in which the arrival aircraft has to modify its route in order to avoid a conflict. This effect is analyzed in a real and high-density scenario Palma de Mallorca (Spain). The traffic of Palma is assessed and simulated with fast-time simulations in order to shape the blocking areas. Lastly a real instance is presented in order to validate the algorithm.

1 Introduction

Nowadays, air transport is undergoing one of the major evolutions of its history with the development of the macro-programs SESAR and NextGen in EUROPE and USA respectively. IATA forecasts that air traffic will double its number of operations in 20 years as well as expect to increase the footprint over the environment. To manage this dramatic impact in the environment, SESAR and NextGen are applying novel actions which expect to contribute to pollutant reduction.

Continuous Climb Operations (CCO) are based on these research lines [1]. ICAO [2] defines CCO as a “technical flight operation which allows the aircraft for the execution of a flight profile optimized to the performance of the aircraft without the interaction of Air Traffic Control (ATC) clearances”. Several studies corroborated the benefits contributed by performing CCO as optimal trajectories: Marais et al. [3] developed an in-depth study about mitigating measures which will help aviation to reduce their environmental impact. Herein, CCO procedure was selected as one of the potential operational changes that could bring more advantages. Torres et al. [4] proposed a method considering the environmental impact as a compound of noise nuisance, local air quality and global warming. Visser and Hartjes [5] assessed the impact of optimized trajectories in terms of fuel consumption, noise and emissions highlighting the impact of CCO in the vicinity of airports.

Nonetheless, the individual improvement which supposes the operation of these procedures can be worsened by the difficulty of their implementation in a generic way at a high-density scenario. From this point of view, few works have been carried out previously. Weitz et al. [6] performed an analysis about the uncertainties associated with continuous descent approaches in a Terminal Maneuver Area (TMA) and their effect on the capacity. Vempati [7] analyzed the impact of traffic and weather on the likelihood of executing continuous operations in a high-density TMA. Vempati concluded that the influence of the demand on the capacity negatively impacts the integration of continuous operations.

Moreover, the implementation of CCO supposes the appearance of new conflicts inside the TMA. These new conflicts must be analyzed in-depth because can prevent the performance of CCO. According to Roach and Robinson [8] route geometry, flow direction and arrival streams are the main factors which limit the integration of CCO and an exhaustive study of conflict detection should be done upfront.

Therefore, it is necessary to improve the automation level with different tools in order to ease the air traffic management by Air Traffic Controllers (ATCOs). Based on this concept, Jung and Isaacson [9] developed a conflict-free tool for unrestricted climbs at a TMA in order to detect conflicts between departures and arrivals. They concluded that to execute CCO were advisable but with under several capacity restrictions. According to Erzberger et al. [10], the tactical control maneuvers in a TMA should include speed, horizontal and altitude changes. In addition, knowing the predominant types of aircraft improves results and reduces uncertainty. Lastly, the blocking area is not a novel concept because it was dealt by others authors but more focused on collision risk studies than as an ATC tool [11].

In short, the aim of this work is to develop a methodology to detect conflicts between CCO and arrival flows in a TMA and work them out by generating an ATC tool which will define new blocking areas. The remainder of this paper is structured as follows: in section 2 it is detailed the operational concept of CCO, the methodology developed to detect possible conflicts and how to shape blocking areas. In section 3, Palma TMA scenario is introduced and CCO and arrival traffic patterns are characterized. Afterwards, this methodology is applied on Palma TMA, results are discussed and future works are commented. Finally, the concluding section remarks the steps taken to solve this problem and the key points attained in this work.

2 Methodology

In this section authors presents the methodology developed to obtain the blocking area. The aim of this blocking area is to provide an ATC tool which will help ATCOs to manage the air traffic more efficiently. This tool will ensure the fulfillment of the separation minima inside the TMA between arrival and departing traffic. In this way, the algorithm permits to the ATC to detect and avoid in advance a potential conflict.

The blocking area represents the route tract where the controller must take the appropriate steps to avoid a future conflict if an aircraft is within. Based on this concept, there exist two types of problems:

1. First, the situation where arrival has preference over departure, namely, the arrival path influence departing aircraft, preventing them from taking-off.
2. Second, the departing aircraft have preference over arriving ones. In this case, ATC must take the necessary actions for the arriving aircraft in order to avoid conflict.

Obviously, both solutions have a remarkable effect on the capacity of the TMA. Therefore, the methodology defines three principal subsections: the geographical detection of the potential conflict points in a TMA and the modelling of the conflict resolution algorithm to obtain the blocking area for each situation.

2.1 Strategical detection of crossing points

The goal of this subsection is to detect the potential conflict points that could arise by the integration of CCO in a TMA. Three steps have been detected as necessary steps to proceed:

Firstly, establishing the blocking area is required to identify the geographical position of the potential conflict points, i.e., such crossing points between the Standard Instrument

Departures (SIDs) and the Standard Terminal Arrival Routes (STARs). The detection of these crossing points is made over a bidimensional map. Thus, a violation of the separation minima may exist in these crossing points. Because of the nature of this medium of transport, if two aircraft are at the beginning of a conflict, it cannot be possible to stop and wait. Consequently, these conflicts must be assessed prior to the tactical stage although the tool will be used at tactical one.

The separation minima which are applied in a TMA are defined by the air navigation service provider. This separation depends on the radar surveillance capacities and the aircraft distant to the radar. In Spain, the longitudinal separation minima in all TMA are 3 Nautical Miles (NM) under normal situations [12].

Secondly, once the crossing point is detected on the map, the possibility of separation minima violation in altitude is analyzed. In this case, the vertical separation minimum in a TMA is 1000 ft. and therefore, a previous analysis of the real vertical profiles for arrivals and the simulated vertical profiles for CCO must be carried out. Having done this, we erase false conflict points from the potential conflict points selected before. These false points respond to those where the departing aircraft are operating at a different level from that of the arrivals. In other words, there is no difference whether arrivals are flying higher or lower than departures. Later on, this analysis is particularized to the Palma TMA in section 3.

In the course of the definition of the conflict point, Fig. 1 represents the safety area which is colored in orange around the conflict point. Thus, the safety area is defined as the limits imposed by the separation minima between SIDs and STARs, is equal to all the conflict points in a TMA, and its size at each direction is 3 NM.

Finally, those points detected as conflict-point candidates are selected in order to apply on them the algorithms of the next subsection.

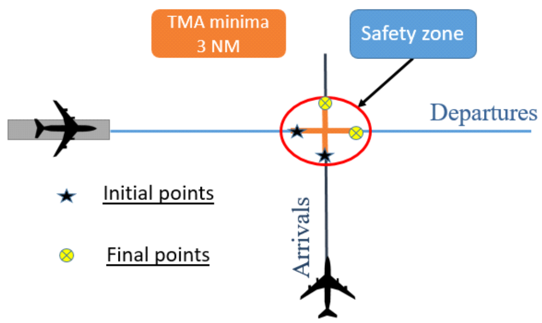

Fig. 1, Definition of the safety area, 3 NM for both routes and directions.

2.1 Conflict detection algorithm for arrival preference

Continuing with the methodology, the logic followed by the algorithm for arrival preference is detailed here. In this case, the blocking area is located in the arrival route because if some arrival aircraft is within the blocking area, the departing aircraft must wait as long as it takes the arrival aircraft to leave.

There exist two critical situations based on if the arrival is at the initial point (3NM before the conflict point) or at the final point (3 NM after the conflict point) of the safety area.

- Initial critical situation: in this situation, the time expended by the departing aircraft (A_1) to fly the distance until its final point (d_{F1}) shall be equal to the time of the arrival aircraft (A_2) to reach its initial point (d_{I2}). Thus, the algorithm ensures that both aircraft maintain the separation minimum of 3 NM throughout the safety zone. Fig. 2 depicts a draft of the operational characteristics of this situation.

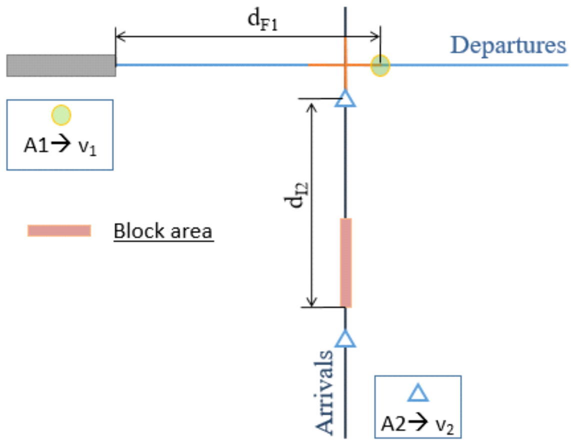

Fig. 2. Initial critical situation: definition of the initial point of the blocking area for arrival preference.

- Final critical situation: this situation is similar to the previous one with the difference that, in this case, the time spent by A_1 to fly up to the initial point d_{I1} must be the same time which is needed by A_2 to fly the distance d_{F2}. Fig. 3 outlines this situation.

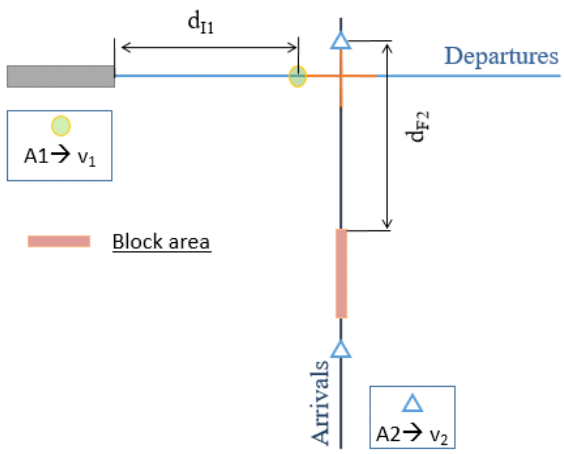

Fig. 3. Final critical situation: characterization of the final point of the blocking area for arrival preference.

The length of the blocking area is defined by the relative movement of both aircraft, namely, the speed of both aircraft. To simply the calculation, authors approached the motion of both aircraft as a continuous movement in which the speed was constant. This constant speed is estimated based on real data from arrivals and simulations for CCO. Henceforward, the movement of the aircraft is considered a mean of a statistical sample. The characterization of the length of the blocking area requires the following values for each aircraft:

- Mean of speed up to the conflict point $\overline{v_1}$ and $\overline{v_2}$.
- Distance between the runway until the conflict point d_{C1}.
- Distance between the entry point of the STAR and the conflict point d_{C2}.

Once this values are defined, the size of the blocking area is determined by the location of the initial and final point of the safety area:

$$d_{I2} = d_{F1} * \frac{\overline{v_2}}{\overline{v_1}} \tag{1}$$

$$d_{F2} = d_{I1} * \frac{\overline{v_2}}{\overline{v_1}} \tag{2}$$

The length of the blocking area I and the time t_2 spent by A_2 to fly I are:

$$I = 2 * \mathrm{D}_{\min sep} + d_{I2} - d_{F2} \tag{3}$$

$$t_2 = \frac{I}{\overline{v_2}} = \frac{2 * \mathrm{D}_{\min sep} + d_{I2} - d_{F2}}{\overline{v_2}} \tag{4}$$

Thus, the time needed to wait at the runway by A_1 depends on the time that took to leave the blocking area by A_2. This extra time, which the departure must spend on the runway, affects directly to the capacity of the TMA because the departure flow is blocked.

Moreover, the methodology took into consideration different aircraft types (Light, Medium and Heavy). Distinct blocking area will be generated based on the number of aircraft models chosen for the simulation. This discrimination is because each aircraft type or model has diverse operational performances, which means that different blocking areas are obtained. Afterwards, the final blocking area must encompass all the previous areas encompassing the minor and the major boundaries.

2.2 Conflict detection algorithm for departing preference

In this case the logic is fairly similar to the previous one with the difference that now it is the departure which influences the arrival. In that way, if the departure is located in the blocking area, ATCO must perform some actions – such as vectoring, level-off or holding pattern – to ensure the arrival avoids the conflict. Besides, the same aircraft types or models selected in the previous case are chosen to assess their individual influence on the blocking-area length. In Fig. 4, a draft of the initial and final critical situations are depicted:

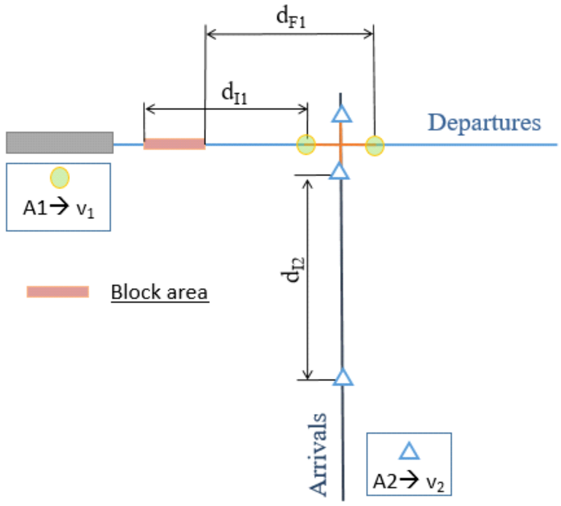

Fig. 4. Initial and final critical situation: characterization of the blocking area for departure preference.

- Initial critical situation: the time spent by A_2 to reach its final point of the safety area (d_{F2}) shall be equal to the time needed by A_1 to fly up to its initial point (d_{I1}).
- Final critical situation: the time spent by A_1 to fly the distance to its final point (d_{F1}) shall be equal to the time spent by A_2 to fly the distance up to its initial point (d_{I2}).

Thus, the characterization of the blocking area is obtained from the following equations:

$$d_{I1} = d_{F2} * \frac{\overline{v_1}}{\overline{v_2}} \qquad (5)$$

$$d_{F1} = d_{F2} * \frac{\overline{v_1}}{\overline{v_2}} \qquad (6)$$

Where the length of the blocking area I and the time t_1 spent to fly all the blocking area by A_1 are:

$$I = 2 * D_{\min sep} + d_{I1} - d_{F1} \qquad (7)$$

$$t_1 = \frac{I}{\overline{v_1}} = \frac{2 * D_{\min sep} + d_{I1} - d_{F1}}{\overline{v_1}} \qquad (8)$$

Thus, the time that A_2 must wait performing some avoiding maneuver is the time the departing aircraft need to leave the blocking area.

3 Case-study Palma TMA

This section explains the reasons why Palma TMA were chosen as the target scenario to implement CCO, how vertical profile of arrivals and departures were calculated and which were the real conflict points in Palma TMA.

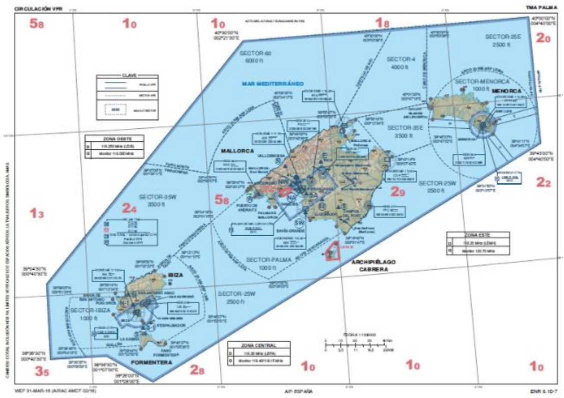

Fig. 5. Palma TMA draft [13].

Palma TMA (Spain), Fig. 5, is located in Barcelona FIR at the Mediterranean Sea and is adjacent to Marseilles FIR. Palma TMA comprises three airports – Palma de Mallorca, Menorca e Ibiza – where Palma is the major airport and the scenario of this work. Whereby this case-study, only East configuration is considered. The reasons why Palma TMA was selected were:

- Existence of three airports in a reduced space.
- Complexity in the design of departure and arrival procedures (SID and STAR) which generates a high number of potential conflicts.
- High-density scenario where tactical management of air traffic is fairly complex for ATC.

Once the location were selected, a previous analysis were carried out to detect the initial conflicts which existed in Palma TMA. Firstly geographical crossing points were detected among SIDs and STARs of the three airports. Fig. 6 outlines an example of these potential conflicts between Palma SIDs and Menorca STARs.

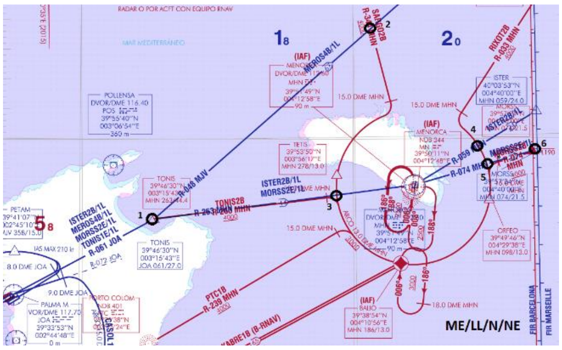

Fig. 6. Draft of geographical crossing points between Palma SIDs and Menorca STARs.

These geographical crossing points were assessed with vertical profiles in order to check whether arrivals and departures really operated at adjacent levels. On the contrary, if the vertical profiles did not fulfill the prior condition, these were false conflict points.

Finally, talking about the float distribution which operated at Palma TMA the results were clear: 2,5% Light (PRM1), 33% B737 family (Medium), 40% A320 family (Medium), 4,5% E190 (Medium) and 2,5% Heavy (A332). The 95% of the float which operated at Palma were Medium and specifically B737 and A320 families tackled together the 73%.

3.1 Vertical profile of CCO

The departure considered in this work is not a "standard departure" (with level-offs) but is a CCO in which the ATCO cannot take any action over the aircraft throughout the climb. This is an innovative factor because the integration of CCO in a TMA has not been studied in-depth so far. Thus, having detected a set of crossing points, authors assessed whether they fulfilled or not the condition of flying at adjacent flight levels. As commented in section 2, it was required to define the blocking area to obtain d_{C1} and the speed profile of CCO.

A set of simulations were run depending on the type and models previously selected with the aim to obtain real CCO trajectories [14]. These paths served as basic trajectories to assess the vertical profile, distance and speed.

Then, the corresponding SID to analyze was selected and the distance d_{C1} was obtained with the help of NEST tool [15]. NEST permits to evaluate a great number of performances and trajectory data from real flights. In order to attain an accurate value for the distance d_{C1}, a set of real samples for the SID considered were analyzed, regarding distinct aircraft types. During this process, authors ascertained that different aircraft models flied roughly the same distance up to the conflict point, which meant that the influence on the aircraft type disappeared. Once the distance d_{C1} is known, the time spent by departing aircraft flying this distance is obtained from CCO simulations. Finally, the average speed $\overline{v_1}$of the departure was simple to obtain, but special attention was paid to the particular speed corresponding to each aircraft.

Henceforward, this was the point where authors made the hypothesis that the movement of CCO were supposed as continuous uniform movement, as explained in section 2. Fig. 6 schematizes the process followed to obtain all the data required.

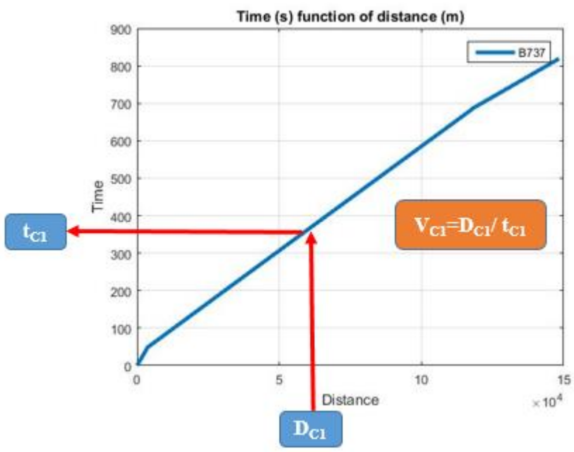

Fig. 7. Time (s) function of distance (m) of a B737 (Medium) CCO.

3.2 Vertical profile of arrivals

Subsequently, once the required data for CCO was calculated, the step for obtaining the arrival data was performed with NEST and the draft was quite similar to the CCO process.

At the beginning, the STAR which belonged the analyzed conflict were chosen, selecting a set of real samples of different aircraft types. A high number of samples are extremely recommended to obtain the precise accuracy of the correct average, Fig 8. After that, the distance between the entry point of the STAR and the conflict were determined. As in the CCO case, the dependency of the aircraft type on the distance flied disappeared.

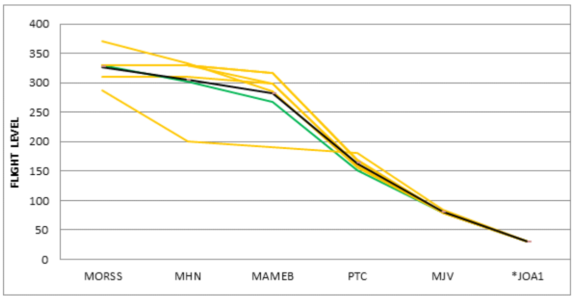

Fig. 8. Set of approach trajectories to Palma TMA, highlighted in black the average trajectory and in green the closest trajectory.

Lastly, medium values were obtained to characterize the average speed $\overline{v_2}$ based on the vertical profile of different arrivals.

3.3 Selection of real conflict points at Palma TMA

The final step were to contrast the vertical profile of CCO and the arrivals in the conflict points. The condition to confirm that a possible conflict were a real conflict were that the vertical separation between CCO and arrivals did violate the vertical minima.

Thus, for arrival routes authors considered the profiles provided by NEST and for CCO simulated profiles. Fig. 9 depicts an instance of the comparison among CCO and arrivals. In this case, Light and Heavy models of CCO determined a conflict with the arrivals although medium CCO no. Because the tool could not be aware of the aircraft type during tactical stage, the algorithm considered that if only one aircraft type could generate a real conflict, every aircraft must be considered throughout the process.

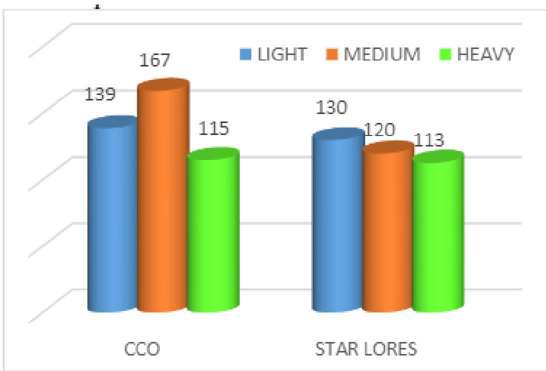

Fig. 9. Breakdown of the FL for each aircraft type at a conflict point depending on the route.

4 Results

The aim of this work were to develop an ATC tool which generated blocking areas to detect and avoid possible conflicts among CCO and arrivals. After overlapping SID and STAR routes and analyzing the vertical profiles of CCO and arrivals, the study concluded that only 16 points from the 64 possible were considered as real conflicts. Fig. 9 represents the conflict point selected to illustrate the methodology.

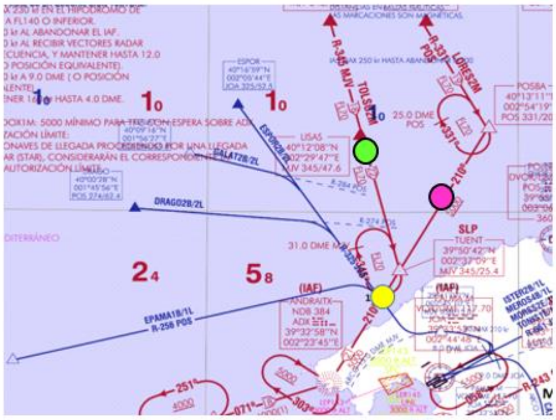

Fig. 10. Location of conflict point (yellow) between CCO and arrival flow at Palma TMA. The green and pink circles indicate the new initial points for arrivals with departing preference.

In terms of the arrival flow, two STARs were affected by the conflict point, LORES2M and TOLSO2M, and up to four SIDs were affected, EPAMA1B/1L, DRAGO2B/2L, GALAT2B/2L and ESPOR2B/2L.

Once a conflict point was selected and the airspace design assessed, the methodology developed in section 2 was implemented for shaping the blocking area.

4.1 Arrivals preference

In this case ATCOs will prevent take-offs depending on the location of arrivals. The methodology was applied for the five aircraft models selected in section 3 and obtained the respective blocking areas, Fig. 11, where the top blocking area is the total one which encompasses the rest.

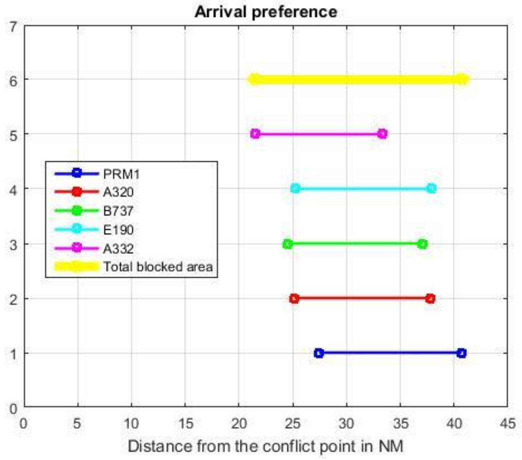

Fig. 11. Blocking areas for arrival preference function of aircraft models.

The total blocking area has a total length of 19.15 NM and in Fig. 12 it is represented the blocking area for LORES2M.

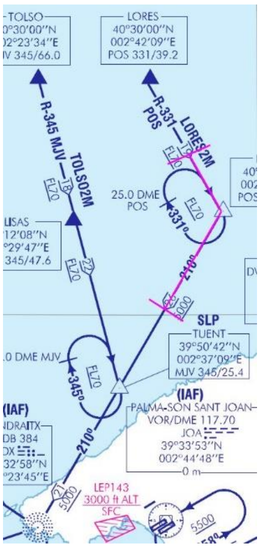

Fig. 12. Location of the total blocking area for LORES2M STAR.

4.2 Departing preference

Here, results are quite similar to the case of arrival preference but a modification in the design must be done. Due to the operational characteristics of the airspace design, the location of the initial point of the arrival flow had had to be modified. This is because the calculation of the blocking area threw its position before the runway. Thus, the resolution of the algorithm was not feasible with the actual entry point of the STARs and the initial points had to be changed. Valid points were defined throughout the tract between the entry and the conflict point (green points in Fig. 10). After that, the calculation of the blocking area was simple, Fig. 13.

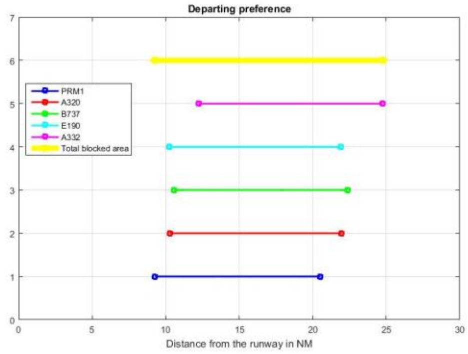

Fig. 13. Blocking areas for departing preference function of aircraft models.

The total blocking area measured 15.5 NM for LORES2M and 14.95 NM for TOLSO2M which were smaller than arrival preference once. Finally, Fig. 14 represents the location of the total blocking areas depending on the STAR which they affect (LORES2M pink and TOLSO2M green).

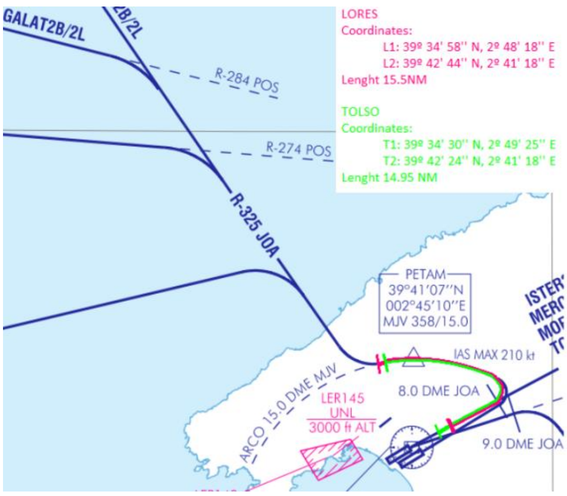

Fig. 14. Location of the total blocking area for SIDs EPAMA1B/1L, DRAGO2B/2L, GALAT2B/2L and ESPOR2B/2L.

4.3 Future works

With this example, authors validated the methodology proposed due to the fact that real blocking areas were obtained. The major characteristics of Palma TMA – i.e., speed profiles, aircraft models, airspace features – were assessed and correctly integrated. After that, the remainder of SIDs and STARs should be analyzed and the rest of blocking areas calculated. Thus, ATCOs will have a tactical tool which will ease the CCO integration, which was the goal of this work.

However, there exist some improvements that should be applied in future works. The algorithm only considered a static case in which uncertainties were out of the scope. Some typical uncertainties that should be considered are – wind (which at the TMA has a strong variability), speed changes, performance variabilities and studies about how ATCOs work with this kind of tools.

Lastly, the systematic implementation of blocking areas in the TMA tactical management will generate a negative impact on the capacity (as commented in section 2) and will be the major task of future research.

5 Conclusions

In this work authors present the definition, development and validation of an ATC tool. The tool's goal is to help ATCOs to manage efficiently the air traffic in a TMA and detect possible conflicts which will arise because of the integration of the novel operational concept (CCO). The algorithm permits to choose what flow to favor among CCO or arrivals. On one hand, ATC can choose to benefit arrivals over the departing flow, so, CCO will wait at the runway until an ATCO clearance. On the other hand, ATCOs must carry out some maneuvers for arrivals in order to avoid a conflict. Thus, in order to give an adequate size to blocking areas, the traffic patterns of Palma TMA are evaluated: real arrival paths are assessed and diverse CCO are simulated based on their aircraft type. The algorithm concludes with the detection of true conflicts inside the TMA. At the end, the methodology is applied to a real conflict point detected in Palma TMA and authors obtain the size and location of particular blocking areas.

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