Impact of continuous climb operations on airport capacity

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ABSTRACT

The full benefits of Continuous Climb Operations (CCO) are realised when CCO are performed without interruption. However, CCO require safe departures that necessarily implies a reduction in capacity at high density traffic airports. This paper quantifies the capacity impact due to the integration of CCO (conflict-free with other departures and arrivals) in a high density traffic airport. The methodology develops a scheduling algorithm, a conflict-detection and resolution algorithm, and Monte Carlo simulations. The scheduling algorithm calculates two schedules, one for departures and another for arrivals, considering the CCO Rate. The conflict-detection and resolution algorithm compares CCO and arrival trajectories to detect which aircraft pairs are in conflict. The Air Traffic Control (ATC) intervention required to solve the conflict is modelled by delaying the CCO take-off. Numerical simulations based on Monte Carlo techniques are used to analyse scheduling combinations that are statistically significant in terms of conflict, ATC interventions, total delay and capacity. The results show a 32% reduction in the maximum theoretical capacity with a CCO Rate of 100%. Despite the reduction, the number of CCO departures is above the maximum operational capacity (50% of the maximum theoretical capacity). This implies that with optimised scheduling it is possible for all departures to be CCO.

1. Introduction & motivation

The number of movements handled by the current Air Transportation System is expected to seamlessly increase over the coming years. This increase cannot be managed without research and development, and the implementation of new technologies and procedures for the future Air Transportation System (Janc, 2014). Efforts such as Continuous Climb Operations (CCO), Continuous Cruise Climb and Continuous Descent Approach (CDA) provide fuel, environmental and economic benefits in specific stages of the flight (Marais et al., 2013). However, these optimised procedures usually have a negative impact on air traffic capacity due to the high uncertainty associated with vertical profiles and speed profiles, and overfly times at waypoints (Johnson, 2011; Murdoch et al., 2009; Xu et al., 2016).

The International Civil Aviation Organization (ICAO) defines CCO (ICAO, 2012) as “an aircraft operating technique enabled by airspace design, procedure design and facilitation by Air Traffic Control (ATC), allowing for the execution of a flight profile optimised to the performance of the aircraft...”. The operation of CCO constitutes a progress for the future of trajectory management because the goal is to execute optimised profiles adapted to airspace design (McEnteggart and Whidborne, 2015; Mitchell et al., 2012; Zhang et al., 2018). ATC’s primary concern is safety, and the improvement of the efficiency arises once safety is ensured. The integration of CCO requires that ATC should adapt the airspace and air traffic flows to provide ideal conditions to favour the operation of CCO.
However, the integration of CCO in a Terminal Control Area (TMA) requires structured analysis of their impact on capacity. This is the crucial operational factor because a high-capacity reduction can imply the inhibition of the CCO integration. The implementation of CCO in isolated airports with low density traffic is straightforward because the likelihood of their being factors that could inhibit their use is extremely low. In high density traffic airports or TMA the situation is significantly different. The high level of ATC intervention required to manage interactions between arrivals and departures limits the potential benefits of CCO (Hebly and Visser, 2009; Jacquillat et al., 2017; Janic, 2014; Lehouillier et al., 2017).

Therefore, this paper tackles an innovative aspect of the CCO because it quantifies the capacity impact due to the integration of CCO in high traffic density airports. A further novelty is that CCO are conflict-free of other departures and arrivals. This allows an optimal and continuous departure free of ATC interactions once the aircraft takes off. From the best authors' knowledge, no previous studies have dealt with this problem. The paper is organised as follows. Sections 2 gives a literature review and Section 3 the conceptual framework. Section 4 presents the methodology. Each subsection of the methodology explains the different processes used to build the model. Section 5 discusses the capacity simulation method developed to assess the impact of CCO on airport capacity. Section 6 describes the scenario – Palma airport (Spain) – and its operational features. Section 7 presents the results and discusses the variation in capacity due to the implementation of CCO. Finally, the concluding remarks are given in Section 8.

2. Literature review

The environmental and operational benefits of continuous trajectories have been already demonstrated (Alam et al., 2010; Dalmau and Prats, 2015; Errico and Di Vito, 2017; Kim et al., 2013; Prats et al., 2010). IFATCA (IFATCA, 2012) summarised the potential benefits of the systematic introduction of CCO with respect to delays, fuel consumption and the emission of pollutants. Extensive research into the benefits of CCO concluded that the average potential fuel savings are between 6 and 19 kg per departure, with annual CO₂ savings of around 5000 kg per high density traffic airport (McConnachie et al., 2015). Different authors (Hartjes et al., 2009; Prats et al., 2010; Visser and Hartjes, 2014) analysed the impact of optimised departures on fuel consumption, noise and emissions. All these studies agreed on the need to implement CCO due to the economic and environmental benefits.

Although other authors have worked on the optimisation of departure trajectories, the crucial issue is the impact of CCO on capacity in high density traffic airports. The main issues for the integration of new procedures are capacity and safety (Jacquillat et al., 2017; Simialakis and Balakrishnan, 2016). Previous studies showed that the integration of CDA in high density traffic airports was feasible, but it led to a significant reduction in capacity (Alam et al., 2010; Ren et al., 2003; Weitz et al., 2005). The main reasons are that the uncertainties associated with CDAs and the overfly times at different waypoints are so high that the separation minima must be enlarged to encompass every feasible path (Coppenbarger et al., 2012; Dalmau and Prats, 2017). Ren and Clarke (2007) developed a theoretical framework based on a separation analysis methodology to introduce RNAV procedures in airports. They concluded that distance-based separation was not efficient. Furthermore, issues related to the probability of separation were crucial.
to the introduction of new procedures. Several studies have analysed the introduction of CDAs in peak and off-peak periods (Roach and Robinson III, 2016; Tong et al., 2007). However, recent studies (Copenbarger et al., 2012; Errico and Di Vito, 2017) have shown that efficient management of 4D optimised descent profiles coupled with time-based separation have reduced path uncertainty and improved the accuracy with which aircraft arrive at waypoints as per the schedule. Apparently, the implementation of CCO could also reduce the capacity of airports (Hebly and Visser, 2009; Pérez-Castán et al., 2016). However, the integration of CCO cannot progress without a thorough analysis of the impact of CCO on capacity in high density traffic airports.

The impact on safety is a key issue in the introduction of new procedures. In a TMA, there are arrival and departure air traffic flows whose paths constantly cross, leading to conflicts. ATC resolves these conflicts by performing level-offs, headings or velocity changes (Erzberger et al., 2016; Païelli and Erzberger, 2017). However, the interaction of ATC with airborne aircraft leads to increased fuel consumption and emissions. Different authors have studied the issue of Conflict-Detection and Resolution (CD&R) in a complex airspace (Calvo-Fernández et al., 2017; Chen et al., 2016; Erzberger et al., 2012; Erzberger and Heere, 2010; Païelli et al., 2009). As with previous studies into CDA (Errico and Di Vito, 2017; Murdoch et al., 2009), the systematic introduction of CCO means that: (1) ATC should avoid acting on CCO and (2) CCO will fly vertical profiles that are different to current (standard) departures (Mitchell et al., 2012; Torres et al., 2011). This second point means that new conflicts may arise while others will disappear (Lehouillier et al., 2017; Meyn et al., 2011; Mitchell et al., 2012; Vilardaga and Prats, 2014). The reason for this is that currently, departures are prevented from climbing to a specific Flight Level (FL) unless ATC issues a clearance. As a result, aircraft fly at lower altitudes than their operational capacities. As we are concerned that CCO will have an impact on ATC, the aim is to arrive at the safest solution which minimal ATC intervention. In other words, high levels of ATC workload could prevent the safe implementation of CCO.

In this article, the authors bring to the light how the theoretical airport capacity is affected by the integration of different CCO rates. Theoretical airport capacity is the maximum number of aircraft that can depart or land in a given time. This does not take the impact on ATC into account and assumes that ATC can handle all this traffic. We consider that CCO trajectories are fuel-optimised paths that are free of ATC segregation requirements with respect to arrival flows. Arrival flows are modelled based on statistical analysis of real traffic. The aim is to obtain a departure schedule, that takes the CCO Rate into consideration, in which CCO are conflict-free. The methodology does not innovate with new solving techniques, but it takes advantage of known methods. The scheduling algorithm generates two initial schedules, one for departures and another for arrivals. The conflict-detection algorithm generates and compares random trajectories of arrivals and CCO to detect conflicts between them. The conflict-resolution algorithm proposes modifications to the initial schedule to avoid conflicts in the air by delaying CCO on the runway. The methodology is applied to a high density traffic airport using Monte Carlo simulations. To the best of our knowledge, no complete studies have previously been published on the impact of CCO on airport capacity. Similarly, there has been no prior research into the implementation of CCO that are intended to be entirely conflict-free.

3. Conceptual framework

3.1. Conventional or standard operations

In a conventional departure or arrival, ATC tactically intervenes to manage the movement of aircraft, thereby ensuring a safe operation. ATC provides speed, heading and ad-hoc altitude commands to ensure safe and seamless air traffic flow. At the same time, Standard Instrumental Departures (SIDs) and Standard ARivals (STARs) define segregation requirements to facilitate the work of ATC. The primary advantage of segregation requirements is that they provide ATC with the flexibility required to manage air traffic flows freely, maximising runway throughput that is crucial to minimising delays in periods of high traffic. However, when ATC intervenes to resolve a conflict this results in increased fuel burn, flight time, emissions and noise values (Ren et al., 2003; Torres et al., 2011). If aircraft could use CCO, then ATC intervention and environmental impact would be reduced.

3.2. Continuous Climb Operations

Optimised trajectories would help to resolve several issues with the current Air Transport System. ATC tries not to intervene in flights using CCO. Ideally, ATC would prepare the airspace for the efficient implementation of CCO while retaining the option to take control of the flight if the situation deteriorates. Therefore, a CCO would follow an optimised profile. Fig. 1 shows a CCO and a standard departure.

3.3. Proposed Operational Concept

Previous studies (Alam et al., 2010; Gomez Comendador et al., 2009; Hebly and Visser, 2009; Ren and Clarke, 2007) analysed the impact of different optimised-trajectory techniques in high density traffic scenarios. Capacity studies showed that the implementation of optimised-landing procedures led to an increase in separation minima with a consequent reduction in capacity. The reason for this is that consecutive aircraft needs larger separations due to the uncertainty associated with vertical profiles.

This paper sets out a methodology for assessing the impact of CCO on airport capacity. The first issue is how ATC deals with CCO. This paper assumes that every arrival or departure can be managed by ATC. This means that ATC is able to manage conflicts between CCO and standard departures and arrivals. The goal is twofold: to facilitate conflict-free optimised departures, and to minimise the impact on ATC workload. By defining new separation minima between CCO we ensure that the runway separation between
consecutive CCO is sufficiently large to make ATC intervention with other CCO unnecessary until the en-route phase. This means that many of the environmental and operational benefits are realised. However, airspace design cannot avoid conflicts between departure and arrival flows because the airspace is reduced and therefore needs to be used optimally.

The second issue is about the capacity impact. ATC uses different strategies to manage air traffic such as leveling-off, vectoring, or speed changes. Each strategy has an impact on ATC workload and aircraft performance. In this paper the solution we propose is to delay the departure time of the CCO until we are sure that there will be no infringement of separation minima with arrivals in the air. In other words, a CCO will depart only if ATC does not have to intervene during the climbing phase. The worst possible situation is when we delay CCO on the runway because this scenario has the greatest impact on capacity. In the future it would be interesting to look at alternative solutions to conflict resolution perhaps involving multi-objective optimisation. It is important to bear in mind that, due to the specific definition of separation used in this paper, the results of the capacity analysis should not be compared with the current declared capacity of the airport in question. As such, the numbers should only be used for relative comparison in the cases presented here. A crucial difference between using CCO and other optimised-path landing concepts is that while arrivals coincide on the runway, which can act as a bottle-neck, departures are disseminated through the entire airspace. An optimal aircraft-routing distribution process does not necessarily limit the CCO Rate that we can use.

4. Methodology

This section describes the methodology used to assess the impact of CCO on airport capacity. The methodology is based on the following modules:

1. Trajectory Generator: this module simulates CCO and standard landing trajectories but standard departures are not.
2. Scheduling algorithm: this module produces departure and arrival schedules taking different features of the airport (route density, aircraft type distribution and CCO percentage) into consideration.
3. Conflict-Detection & Resolution (CD&R) algorithm: this module analyses CCO and landing trajectories to detect and resolve conflicts between air traffic flows.
4. Indicators: this module defines the indicators required to evaluate the number of conflicts detected, the number of ATC interventions, the total delay and the capacity.

4.1. Trajectory generator

The trajectory generator models arrival and CCO trajectories using different methods. The goal of the trajectory generator is to produce a realistic set of trajectories, which operate in the chosen scenario. Later on, the simulated trajectories are used to assess the existence of conflicts between air traffic flows.

4.1.1. Arrival trajectory model

The arrival trajectory model is different to the CCO trajectory model (discussed below) because while the behaviour of CCO trajectories is unknown we do have real landing data to analyse. The arrival flows are based on a set of real arrival trajectories for every STAR, considering different aircraft types (6). It is recommendable to have a large data sample to ensure the accuracy of the statistical distribution.

The model characterises the time elapsed between the STAR entry point and the conflict point, and the time elapsed between the STAR entry point and the runway. A conflict point is the locus where two routes intersect. Aircraft decelerate during descent, however, the information required by the model is the time elapsed. The model calculates two different constant ground speeds: one is the constant ground speed between the STAR entry point and the conflict point, the second is the constant ground speed between the STAR entry point and the runway. Future work will revise the assumption of constant ground speed. It will also look at cross-track deviations from the STAR.
Therefore, the key parameters for simulating arrivals are the statistical distribution of the horizontal speed up to the conflict point \( r \) for the STAR \( q \left( v^q(\mu; \sigma) \right) \), for the whole procedure \( q(\mu; \sigma) \), and the altitude distribution at each conflict point \( h^r(\mu; \sigma) \). The statistical distribution of the speed is calculated using the variables at the STAR Entry Point \( v^\text{SEP} \), \( h^\text{SEP} \) and the conflict point \( v^r, q, h^r \).

\[
\begin{align*}
\dot{v}^q &= \frac{v^\text{SEP} - v^q}{\text{SEP} - r} \\
\dot{v}^r &= \frac{v^\text{SEP} - v^r}{\text{SEP} - r} \\
\end{align*}
\]  

(1)

To validate the model we compared the differences between real altitude \( h_{\text{arrival}} \) and speed \( v_{\text{arrival}} \), for each trajectory, with statistical values. It is vital to relate the altitude with the speed of the trajectory even if the statistical values that we have calculated are not related to one another. The error equations are:

\[
\begin{align*}
\varepsilon_{\text{altitude}} &= h_{\text{arrival}} - h^r(\mu; \sigma) \\
\varepsilon_{\text{speed}} &= v_{\text{arrival}} - v^r(\mu; \sigma) \\
\end{align*}
\]  

(2)

Using data on 3000 arrivals at Palma airport, obtained from DDR2, we saw that the average differences in altitude were less than 5%. Also, the average differences in speed errors were less than 8%. However, the differences in speed errors were reduced to less than 6% when we considered speeds up to the conflict point. In this study, the arrival flows of Heavy, Medium and Light aircraft were analysed separately, as their behaviours are completely different.

4.1.2. CCO trajectory model

This section describes the CCO model and the uncertainty factors used in simulating CCO trajectories.

4.1.2.1. CCO modelling. Airlines, typically, define a flight strategy using the Cost Index \( CI = \frac{\text{Time} \times \text{Fuel}}{\text{Cost}} \). The \( CI \) establishes a trade-off between fuel consumption and the duration of the flight. The authors assume that aircraft fly using a \( CI \) that minimises fuel consumption. The model used for simulating trajectories is (BADA) Base of Aircraft Data (EUROCONTROL, 2014a, 2014b). For this study, we used BADA 4 (B737, A320 y A332) or BADA 3 (PRM1) depending on the aircraft model. We used a third-order Runge-Kutta method (Goeken and Johnson, 2000). Table 1 shows a possible flight structure of a CCO (Airbus, 2002; ICAO, 2014):

Where \( h_p \) is the crossover altitude (altitude at which the CAS Airspeed and Mach represent the same trust airspeed), \( V_{T0} \) and \( V_{IC} \) are the fixed speeds of the take-off and initial climb stage, \( CAS = \text{constant} \) (est) and the mass. The thrust setting is fixed for the different flight phases as well as the speed-profile up to 3,000 feet (ft.). The Take-Off Length (TOL), which is provided by BADA for each aircraft model, is the distance that an aircraft requires to reach an altitude of 35 ft. TOL is relevant in this study since the aircraft will reach 35 ft. at a different location depending on the TOL. Finally, the CCO design assumes that the aircraft fly following the horizontal path of a SID. No lateral deviations from SID are considered in this work. Therefore, in the horizontal a CCO flies a SID but in the vertical it flies an optimised vertical profile.

4.1.2.2. CCO uncertainty. This subsection details the uncertainty of several variables used in this study to obtain a large CCO data sample. The CD&R algorithm acts on the CCO data collected which consists of simulated trajectories. The variables described in Table 2 are those that have the greatest influence on aircraft performance (Pradines and Pablione, 2007; Thipphavong, 2008; Vilardaga and Prats, 2017). There are, however, other factors that could add greater uncertainty such as flap setting, power setting and number of engines. Those factors will be considered in future works.

4.2. Scheduling algorithm

The scheduling algorithm calculates two schedules, one for departures and another for arrivals. The trajectory generator and scheduling algorithm comprise the trajectory-information source used to assess capacity and the existence of conflicts. Scheduling algorithms are useful and widely used to generate schedules in the air transport field (Jacquillat et al., 2017; Lehouillier et al., 2017; Maria et al., 2017; Simaiakis and Balakrishnan, 2016).

Table 1

<table>
<thead>
<tr>
<th>Height limits (ft.)</th>
<th>Aircraft configuration</th>
<th>Speed profile</th>
<th>Thrust setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1,500</td>
<td>(TO) Take-off (flaps extended)</td>
<td>( V_{T0} )</td>
<td>( T_{\text{thrustTO}} )</td>
</tr>
<tr>
<td>1,500-3,000</td>
<td>(IC) Initial climb</td>
<td>( V_{IC} )</td>
<td>( T_{\text{thrustIC}} )</td>
</tr>
<tr>
<td>3,000- ( h_p )</td>
<td>Cruise</td>
<td>( CAS = \text{constant} ) (est)</td>
<td>( T_{\text{thrustCruise}} )</td>
</tr>
<tr>
<td>( h_p )-Cruise level</td>
<td>Cruise</td>
<td>( M = \text{est} )</td>
<td>( T_{\text{thrustCruise}} )</td>
</tr>
</tbody>
</table>
Table 2
Uncertainty model for each influence factor

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>UNCERTAINTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft type</td>
<td>The most common aircraft used at the scenario airport for each aircraft type</td>
</tr>
<tr>
<td>Mass</td>
<td>There are different models available to estimate aircraft mass. The one used in this study is that proposed by Vempati as it is the model which best estimates the mass at departure (Vempati, 2015): uniform distribution $U(0; 1)$ between 99% and 100% of maximum take-off weight (MTOW)</td>
</tr>
<tr>
<td>Speed-profile</td>
<td>The main issue is that the speed-profile varies because not every airline will fly with the same CI. Therefore we introduced a uniform distribution $U(0; 1)$ between 95% and 100% of the optimal speed-profile (CAS/M = ci) as utilised in (FAA, 2009). This means that a B738 will operate with CAS (304-336 knots) and M (0.74-0.82), which exceed typical speed profile values (Airbus, 2002; Boeing, 2005). Cockpit speed errors were taken into consideration by adding a variation of ± 5 knots as per (EASA, 2008)</td>
</tr>
<tr>
<td>Temperature</td>
<td>We analysed the variation in temperature at Palma airport (Spain). Based on empirical data for 2016, the temperature was modelled as normal distribution $N(17.56; 5.94)$. We have not considered temperature deviation with respect to ISA conditions</td>
</tr>
<tr>
<td>Wind</td>
<td>The wind $W(t, h)$ is a grossly complex factor to model since wind behaves as a dynamic variable composed of a vertical ($W_z(t, h)$) and a horizontal ($W_x(t, h)$) component and both components depend on time, altitude and geographical location. The assumptions were as follows: Over a relatively small area there is no dependence on geographical location. The vertical component ($W_z$) of the wind is negligible with respect to the horizontal component ($W_x$). $W_z &lt; W_x \rightarrow W(t, h)$ as $W_z(t, h)$, if we compare orders of magnitude between the time required by the wind to vary and the time required by aircraft to depart, the wind vector is considered to be dependent solely on altitude $W_x(t, h) = W_x(h)$</td>
</tr>
</tbody>
</table>

4.2.1. Operational concept

An airport schedule is a structured sequence of time frames, with one frame from each consecutive aircraft. These time frames are conditioned by several factors: runway separation minima, safety requirements and ATC workload. In this study, the schedule only takes runway separation minima into account. Safety requirements and ATC workload are not considered. Therefore, the output from the scheduling algorithm is a schedule with as many aircraft as the runway separation minima allow.

Runway separation minima are distance/time frames that separate consecutive aircraft (arrivals or departures) to ensure that following aircraft are not affected by wake turbulence. The main factors that determine separation minima are the radar coverage and aircraft wake turbulence. Typically, the minimum separation in a radar-controlled TMA is 3 Nautical Miles (NM) (ENAIRE, 2016) and, in some scenarios, it can be reduced to 2.5 NM. However, the minimum wake turbulence, which depends on the aircraft type, is larger than or equal to the radar separation minimum. For each aircraft pair, the authors selected the largest separation minimum to avoid potential compatibility problems with ATC. In this study, runway separation minima are expressed as time-based separation minima.

Finally, runway separation minima are characterised depending on the type of operation. Standard operations (arrivals and departures) must follow ATC requirements governing segregation between air traffic flows – published or unpublished in the air navigation charts. Table 3 gives the runway separation minima for standard arrivals ($m_d^S$) and departures ($m_d^D$) for each aircraft type pair.

In this study, the assumption is that ATC will not interact with CCO. CCO separation minima are estimated so that once the leading aircraft departs, the pursuing aircraft ensures compliance with the different separation minima (radar and wake turbulence) until both of them are transferred to the en-route controller. Table 4 presents the CCO separation minima ($m_C$) in seconds based on

| Table 3 |
| Runway separation minima (seconds) per aircraft type: Standard arrivals (above) (Erzberger et al., 2016) – Standard departures (bottom) (Perez-Castan et al., 2016). |

<table>
<thead>
<tr>
<th>Standard Arrivals</th>
<th>Pursuing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading</td>
<td>Light</td>
</tr>
<tr>
<td>Light</td>
<td>60</td>
</tr>
<tr>
<td>Medium</td>
<td>64</td>
</tr>
<tr>
<td>Heavy</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard Departures</th>
<th>Pursuing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading</td>
<td>Light</td>
</tr>
<tr>
<td>Light</td>
<td>61</td>
</tr>
<tr>
<td>Medium</td>
<td>61</td>
</tr>
<tr>
<td>Heavy</td>
<td>61</td>
</tr>
</tbody>
</table>
previous works (Pérez-Castán et al., 2016).

Current separation minima ensure separation on the runway and the assumption is that this will be maintained by ATC throughout the rest of the departure or arrival. Therefore, the initial schedule based on standard operations assumes that ATC can handle all aircraft that can take off or land. This assumption is important because it means that we are not estimating the impact on the declared capacity but on the theoretical capacity. Therefore, the theoretical capacity is the maximum number of standard departures that can depart in a period of one hour. It only depends on the standard runway separation minima and aircraft distribution.

The initial schedule is also characterised by the following:

- Air routes density ($\rho$): number of aircraft operating SIDs and STARs.
- Aircraft type distribution ($\Theta$): Light, Medium or Heavy.
- Percentage of departures operating CCO, i.e., CCO Rate ($\alpha$).

These factors are required to produce a consistent initial schedule. The density of SIDs and STARs and the aircraft type distribution are characterised by the airport fleet. However, CCO Rate is one of the variables that will be determined using Monte Carlo simulations, explained in Section 4.

4.2.2. Scheduling algorithm

The scheduling algorithm used has been specially designed for this study to enable implementation of CCO. As previously mentioned, the scheduling algorithm calculates two independent schedules, one for departures and another for arrivals. Fig. 2 gives the flow chart of the scheduling algorithm.

The algorithm is formulated as follows: Let $a$ be a set of arrivals and $b$ a set of departures. Each arrival $a$ is characterised by the associated STAR ($q$), aircraft type ($\Theta$), and landing time ($t_a$). Each departure $b$ is characterised by the associated SID ($p$), aircraft type, whether it operates a CCO or not ($\Theta=1$ CCO otherwise 0) and departure time ($t_b$). The times ($t_a, t_b$) are calculated based on the standard separation minima found in Table 3:

<table>
<thead>
<tr>
<th>CCO</th>
<th>Pursuer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading</td>
<td>Light</td>
</tr>
<tr>
<td>Light</td>
<td>152</td>
</tr>
<tr>
<td>Medium</td>
<td>201</td>
</tr>
<tr>
<td>Heavy</td>
<td>376</td>
</tr>
</tbody>
</table>
where \( m_{\text{arr}} \) and \( m_{\text{dep}} \) are the standard separation minima for an arrival pair and a departure pair respectively. Once the standard schedule has been generated, the algorithm recalculates the departure times where CCO separation minima apply. The algorithm selects aircraft \( c \) flying a CCO and calculates its departure time \( t_b(c) \). CCO separation minima only apply for consecutive CCO. Then, for each CCO the algorithm looks for the preceding CCO (one or more) operating the same SID. In the event of the difference between departure times being less than the CCO separation minimum \( m^{c} \), the pursuing CCO and subsequent departures are delayed to comply with the CCO separation minima, see Algorithm 1.

Algorithm 1 (Scheduling for applying CCO separation minima).

1. Input: \( t_a, c, m^{c}, p \)
2. For \( c = 1 : T_{\text{max}} \) do
3. Select the set of departures \( \text{DEP} \) that operates the same SID \( p(c) \) as \( c \).
4. Select from \( \text{DEP} \) the set of aircraft that departs before \( \text{DEP} = \text{DEP}(t_b(\text{DEP}) < t_b(c)) \).
5. Calculate the time differences \( \Delta t \) between \( \Delta t = t_b(c) - t_b(\text{DEP}) \).
6. If \( \Delta t(i) < m^{c}_{\text{DEP}(i)c} \) then
7. \( \text{del} = m^{c}_{\text{DEP}(i)c} - \Delta t(i) \)
8. Delay \( \text{del} \) every aircraft from \( c \)
9. End if
10. End for
11. Output: \( t_b \).

This algorithm also considers restrictions imposed by the intrinsic characteristics of the CCO separation minima between Light and Heavy pairs. These separation minima are so large that a Heavy aircraft can influence a Light aircraft even if the Heavy aircraft is not the last CCO flying the same route.

To illustrate the scheduling algorithm, we propose the application to a schedule of six aircraft (Light, Medium1, Medium2, Medium3, Medium4 and Heavy) where aircraft Medium2 and Medium3 perform a CCO. The operational characteristics for each aircraft (SID, aircraft type and CCO) are showed in the first columns of Table 5. The scheduling algorithm calculates the departing time for each aircraft considering the standard separation minima (column 5). Then, it detects if there is consecutive CCO that follow the same SID (aircraft 2 and 3). In this case, the algorithm calculates the required delay in fulfilling CCO separation minima and recalculates the new departure times \( t_b \).

### 4.3. Conflict-detection & resolution algorithm

The horizontal separation minimum \( L_{\text{min}} \) is, typically, 3 NM, and the vertical separation minimum \( H_{\text{min}} \) is 1000 (ft) feet in a TMA. A conflict is an infringement of the horizontal and vertical separation minima in the airspace. Therefore, the goal of the CD&R is to detect and resolve conflicts between CCO and arrivals, but not between standard departures and arrivals. The authors have assumed that ATC can manage standard operations and have not considered the impact on ATC workload. Therefore, the introduction of CCO implies no ATC intervention to resolve conflicts when the aircraft are airborne. The following subsections briefly explain the operational concept of the CD&R. They explain in detail each of the algorithms used to build the different CD&R modules: conflict point location, blocking-areas, conflict-detection and resolution. The diagram in Fig. 3 shows the iterative process of the CD&R.

For each CCO, the CD&R analyses whether or not it is in conflict with arrivals. To do this, the CD&R needs information from the trajectory generator and the scheduling algorithm. It also needs the location of the conflict points so that it can characterise the vertical profiles of the arrival trajectories. Therefore, when a CCO is going to take-off, the CD&R analyses the trajectories of both the CCO and the arrival with which it may be in conflict. Two conditions must be satisfied for there to be a conflict: (1) both aircraft must

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>SID (p)</th>
<th>Aircraft type (( t ))</th>
<th>CCO (S)</th>
<th>Standard Separation (( m^{c} ))</th>
<th>Departure time (( t_b ))</th>
<th>CCO Separation (( m^{c} ))</th>
<th>( \text{del} )</th>
<th>Departure time (( t_b ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>71</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>60</td>
<td>71</td>
<td>110</td>
<td>39</td>
<td>119</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>60</td>
<td>131</td>
<td>-</td>
<td>-</td>
<td>170</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>66</td>
<td>191</td>
<td>-</td>
<td>-</td>
<td>230</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>77</td>
<td>251</td>
<td>-</td>
<td>-</td>
<td>230</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>-</td>
<td>328</td>
<td>-</td>
<td>-</td>
<td>367</td>
</tr>
</tbody>
</table>
cross the conflict point with a vertical separation minimum of less than $H_{\text{min}}$; and (2) the arrival must be inside the blocking-area at the same time that the CCO is taking off. If both conditions are satisfied, there is a high probability of separation infringement. The CD &R algorithm resolves the conflict in advance by delaying the CCO by as much time as is required for the arrival to leave the blocking-area. Fig. 4 illustrates this situation. From now on in this paper, these future separation infringements shall be called conflicts because ATC resolves them when CCO is about to take-off even though the conflict would occur several minutes later. The look-ahead time of the CD&R algorithm is up to a maximum of 20 min which is the largest time that an aircraft requires to leave every conflict point.

4.3.1. Conflict-point location

The first task of the CD&R is to locate the conflict points between the departure and arrival routes. The conflict points are located at the intersections of the SIDs and STARs of the airport in question. A geographical analysis of SIDs and STARs enables us to identify:

1. The SID $(p)$ and STAR $(q)$ involved at each conflict point $(r)$, and
2. The distances between the conflict points and the starting points of the SIDs and STARs.

### Table 6
Sample data from the conflict-point database.

<table>
<thead>
<tr>
<th>Conflict point</th>
<th>SID $(p)$</th>
<th>STAR $(q)$</th>
<th>$x_{\text{conf}}-x_f$ (NM)</th>
<th>$x_{\text{conf}}-y^f$ (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SID1</td>
<td>STAR2</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>SID1</td>
<td>STAR5</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$r$</td>
<td>SID4</td>
<td>STAR4</td>
<td>75</td>
<td>42</td>
</tr>
</tbody>
</table>
The location of each conflict point is given by the horizontal distance between the runway ($x_{\text{runway}}$) and the conflict point ($x_r^p$) for the SID and the horizontal distance between the STAR entry point ($x_{\text{star}}^a$) and the conflict point for the STAR ($x_r^a$). Table 6 gives the information for each conflict point.

4.3.2. Blocking-area

A blocking-area is a geographical window that fulfils the following condition: if an aircraft is inside the blocking-area, another aircraft will suffer a block to its normal operation. Each blocking-area is associated with a conflict point which in turn is related to a set of SIDs and STARS. In this case, if the arrival is inside the blocking-area when the CCO is ready to take-off, there is a high probability of a separation minima infringement.

Based on the position of the arriving aircraft, there are two critical situations regarding the initial or final points of the conflict-area. The conflict-area is a circle whose centre is a conflict point and whose radius is the horizontal separation minimum. The first critical situation occurs when the arrival is at the beginning of the conflict-area, and the CCO is leaving. The second critical-situation occurs when the arrival is leaving the conflict-area and the CCO is entering.

Therefore, the blocking-area algorithm divides the equations into two groups:

- Initial critical-situation: the time spent by a CCO of set $c$ to leave conflict point ($d_f^c$) is equal to the time required by an arrival of set $a$ to fly distance $d_f^a$.
- Final critical-situation: the time spent by a CCO to reach initial point $d_f^c$ is equal to the time required by an arrival of set $a$ to fly the distance $d_f^a$.

Therefore, the algorithm ensures that both aircraft maintain the separation minima throughout the conflict-area. The relative movement (average speed) of both aircraft ($v_f, v_a$) determines the length of the blocking area. To simplify the calculation, the authors approximated the motion of both aircraft to continuous movement at constant speed between the conflict point and the initial point, as explained in Section 3. Fig. 5 gives a diagram showing the operational features of both situations:

The algorithm determines the length and position of the blocking-area based on the location of the initial and final points of the conflict-area:

$$L_i = x_f^c - L_{\text{min}} - d_f^c$$

$$L_f = x_f^a + L_{\text{min}} - d_f^a$$

$$d_f^c = d_f^a \frac{v_f^a}{v_f^c} = \left(x_f^c - x_{\text{runway}} + L_{\text{min}}\right) \frac{v_f^a}{v_f^c}$$

$$d_f^a = d_f^c \frac{v_f^a}{v_f^c} = \left(x_f^a - x_{\text{runway}} - L_{\text{min}}\right) \frac{v_f^a}{v_f^c}$$

4.3.3. Conflict-detection and resolution algorithm

The conflict-detection algorithm detects conflicts between CCO and arrivals. The algorithm performs the following calculations for each CCO. Firstly, the algorithm selects the CCO ($c_r$) that pass through conflict point $r$ (following SID $p(r)$). It also selects arrivals ($a_r$) that pass through conflict point $r$ (following STAR $q(r)$). Then, the algorithm calculates the position of each arrival ($x_g^a (t_b (c_r))$) at the departure time of each $c_r$. Finally, it checks to see if the aircraft cross with vertical separation minimum of less than $H_{\text{min}}$ (Eq. (8))

$$\text{Fig. 5. Initial critical-situation: location of the initial point of the blocking-area (Left); Final critical-situation: location of the final point of the blocking-area (Right).}$$

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and if the arrival is located inside the blocking area (Eq. (9)).

\[ h_i^p(t_r) - h_{c}^p(t_r) < H_{\text{min}} \quad \text{(8)} \]

\[ x_g^a(t_r(c_r)) \in [L_l, L_r] \quad \text{(9)} \]

where \( h_i^p(t_r) \) and \( h_{c}^p(t_r) \) are the altitudes of an arrival and a CCO at the conflict point \( r \). If this condition is satisfied, then a CCO and an arrival will cross infringing the vertical and horizontal separation minima.

The conflict resolution algorithm then communicates to ATC the intervention required to resolve the conflicts between CCO and arrivals. see Liang et al. (2017) for a parallel-runway case study. The options available to ATC are to level-off one of the aircraft, to block off one of the aircraft, to prevent the CCO from taking off until the arrival had left the blocking area. As previously explained, a blocking area is an interval of an arrival route which, if it contains an arrival, blocks the departure of a CCO until the arrival leaves the blocking area. In this paper, we delay CCO for two reasons: firstly, it is the worst case scenario in terms of capacity and secondly, it minimises ATC intervention in the air. Another solution would be to allow the CCO to take off and for ATC to resolve the conflict in the air using clearances. However, this would significantly increase ATC workload and would also increase the complexity of the tactical airspace, which is outside the scope of this work.

Therefore, the conflict-resolution algorithm calculates the final departure time of the CCO \( (t_b(c_r)) \). Eq. (10) gives the time delay required to ensure that the arrival leaves the blocking area \( t_d \).

\[ t_d = \frac{L_r - x_g^a(t_b(c_r))}{v_g^a(t_r)} \quad \text{(10)} \]

Algorithm 2 presents a summary of the pseudo-code developed for the conflict-detection and resolution algorithm.

Algorithm 2 (CD&R algorithm to detect and resolve conflicts between CCO and arrivals).

1. **Input**: \( t_b, a, c, r, m^c, p, q, h^c, h^p \)
2. For \( r = 1: r_{\text{max}} \) do
3. Select the SID \( (p(r)) \) and the STAR routes \( (q(r)) \) that pass through the conflict point \( r \).
4. Select the set of CCO \( (c_r) \) that operates the route \( p(r) \) and the set of arrivals \( (a_r) \) that operates the route \( q(r) \).
5. For \( c_r = 1: c_{\text{max}} \) do % for each CCO
6. For \( a_r = 1: a_{\text{max}} \) do % for each arrival
7. Calculate the position of the arrival \( a_r \) at the departing time of \( c_r \) \( (x_g^a(t_r(c_r))) \).
8. Calculate the location of the blocking area \( [L_l, L_r] \) associated to the arrival \( a_r \) and CCO \( c_r \).
9. If \( h_i^p(c_r) - h_{c}^p(a_r) < H_{\text{min}} \) & \( x_g^a(t_b(c_r)) \in [L_l, L_r] \) then
10. \[ t_d = \frac{L_r - x_g^a(t_b(c_r))}{v_g^a(t_r)} \]
11. Delay \( t_d \) every aircraft from CC.
12. End if
13. End for
14. End for
15. Output: \( t_b \).

Lastly, ATC intervention refers to the number of actions that ATC must perform to produce a departure schedule without conflicts. Each ATC intervention delays CCO take-off and avoids a conflict with an arrival. When ATC delays a CCO, subsequent departures are delayed by the same time delay. For this reason, the number of ATC interventions does not match the number of conflicts. This process goes through as many iterations as necessary until the departure schedule is completely free of conflicts. This conflict-free schedule is the final departure schedule and is by a CCO Rate.

To illustrate the CD&R algorithm, we explain an example of a conflict between a CCO and an arrival. Let's assume that a CCO is operating the SID \( p = 2 \) (which concur in the crossing-point \( r = 3 \), with \( v_{\text{min}}^{m_c} = 180 \) kts, \( h_{\text{min}}^{m_c} = 11,000 \) ft and departing time \( t_b = 0 \); and an arrival operating the STAR \( q = 4 \) (which concur in the crossing-point \( r = 3 \), with \( v_{\text{min}}^{m_c} = 200 \) kts, \( h_{\text{min}}^{m_c} = 11,500 \) ft and located at \( t_b = 0 \) at \( x_g^a(t_b) = 35 \) NM from the STAR entry point. The crossing-point \( r = 3 \) is located at \( x_{\text{min}}^{m_c} - x_{\text{min}}^{m_c} = 22 \) NM and \( x_{\text{min}}^{m_c} - x_{\text{min}}^{m_c} = 61 \) NM. Firstly, the CD&R corroborates that there is a vertical infringement \( h_i^p(r) - h_{c}^p(a_r) \) = 500 < 1000 ft. Secondly, the CD&R calculates the location of the blocking area \( [L_l, L_r] = [26, 47.1] \) NM. There is a horizontal conflict in the case the arrival is located inside the blocking area, in this case, \( x_g^a(t_b) = 35 \) \( \in [L_l, L_r] \). As vertical and horizontal separation are infringed, the CD&R calculates the delay required to avoid a conflict based on \( (10) \), \( t_d = 217.8 \) seconds. In this example, the ATC delays 217.8 s the CCO to avoid a conflict with the arrival. When this situation occurs in a one-hour sequence, the scheduling must be rescheduled by delaying the subsequent aircraft from the CCO involved.
4.4. Indicators

The indicators considered when evaluating the schedules are:

- Conflict indicator: number of conflicts detected by the CD&R over a one-hour period.
- ATC indicator: number of ATC interventions required to provide a one-hour schedule that is conflict-free.
- Capacity indicator: maximum number of aircraft that can operate in an airport over a one-hour period without experiencing conflicts.
- Total Delay: sum of the different delays experienced by each aircraft in the conflict-free schedule compared to the initial schedule.

5. Capacity simulation method

This section discusses the design of the capacity simulation method. This model is used to determine the theoretical airport capacity as a function of CCO Rate.

5.1. General description of the method

Airport capacity is ultimately a function of the required separation distance between different air traffic flows. However, standard separation minima between two consecutive departing flights are usually not distance-based but time-based. The objective of this capacity simulation is to identify changes in airport capacity due to changes in aircraft departure procedures. Typically, airport capacity is defined as the total number of aircraft that can operate over a one-hour period.

The capacity method utilized to study the effects of the CCO uses time-based separation between consecutive flights and employs the conflict-detection algorithm to detect conflicts between air traffic flows. Using the runway separation minima set out in Table 3, the scheduling algorithm calculates the theoretical capacity based on the maximum number of departures or arrivals. As a consequence of the previous assumptions, the theoretical landing capacity is fixed because all arrivals are considered to be standard operations. Therefore, the scheduling algorithm provides a random schedule which complies with the runway separation minima, aircraft type distribution and air route densities. ATC is responsible for managing these aircraft to avoid conflicts, however, this activity is not contemplated in this study. The theoretical departure capacity experiences modifications due to variations in the CCO Rate (from 0% to 100%). The new CCO separation minima are calculated so that they do not require ATC intervention. The CD&R ensures separation between arrival flows and CCO flows by delaying CCO on the runway so that no conflicts occur. As such, the implementation of CCO will reduce airport capacity. The main issue is to quantify the reduction in capacity and evaluate how the CCO Rate affects airport capacity.

Prior to carrying out the study, we expected that changes in variables such as aircraft distribution, routing, and CCO Rate would have an impact on airport capacity. Specifically, two of the main variables are the routing distribution and the departure schedule. Two CCO following the same SID are separated by CCO separation minima. However, two CCO following different SIDs are separated by standard separation minima, which supposes that the runway capacity is not reduced. The arrival distribution routing may present a strong influence with the integration of departure flows. The existence of SIDs and STARs which concurs in high density traffic conflict points will imply the reduction of airport capacity as well.

5.2. Monte Carlo simulations

The Monte Carlo simulations are designed to study the theoretical airport capacity subject to variations in different factors. The authors carried out a large number of capacity simulations to identify the main drivers and evaluate the variation in airport capacity. The capacity simulations assess the implementation of CCO based on the CCO Rate selected and other parameters such as aircraft distribution, routing distribution and trajectories. Each experiment performs Monte Carlo simulations for a selected CCO Rate. The Monte Carlo simulations follow the methodology set out in Section 2, in other words, an initial schedule is produced based on the CCO Rate, SID/STAR and aircraft distribution; conflicts are detected; and conflicts are resolved which gives us the final schedule.

In this study, the authors performed ten experiments: varying the CCO Rate from 0% to 100% in increments of 10%. Each Monte Carlo experiment permutes the variables, applies the methodology and obtains the capacity and conflict indicators. Each experiment is repeated 10^4 times to obtain a set of statistically convergent results. As such, each repetition provides a different scenario because the entire set of variables changes as well as CCO and arrival trajectories. These variables are the arrival and departure schedules, the routing distribution of each schedule, and the altitude and speed distribution of the CCO and arrivals at each conflict points. Finally, the Monte Carlo simulations present the results statistically.

The Monte Carlo metrics for each indicator are:

- Minimum value.
- Average value ($\mu$).
- Maximum value.
- Standard deviation ($\sigma$).
- 95% value ($\mu + 2\sigma$).
- Probability of minimum value ($P_{min}$).
6. Description of the scenario: Palma airport

This section explains why Palma airport has been selected for the implementation of CCO, how the vertical profile of arrivals and CCO are calculated, and identifies the conflict points. Palma TMA (Spain) is located in Barcelona FIR, adjacent to Marseilles FIR and comprises three airports – Palma de Mallorca, Menorca and Ibiza. Palma is the primary airport and the scenario of this study. Palma is a high density traffic airport with two parallel runways having a declared capacity of 32 departures and 32 arrivals. The east configuration of Palma airport is considered for this study. The fleet distribution at Palma airport in 2016 was: 2.5% Light, 33% B737 family (Medium), 40% A320 family (Medium), and 2.5% Heavy. 95% of the Palma fleet was Medium. Specifically, B738, and A320 families accounted for more than 73% of the fleet distribution. As such, the influence of Medium aircraft was extremely significant. This data was obtained from the DDR2.

Fig. 6 highlights the conflict points between the SIDs and STARs of Palma airport. Initially, eleven conflict points were detected between SID and STAR routes. Although Fig. 6 represents potential conflicts between departures and arrivals at Palma airport, the authors also studied the impact of CCO on departure and arrival flows at Menorca and Ibiza airports.

The CCO paths were extracted based on previous simulations, as explained in Section 2.2. The simulations were carried out on the most widely-used aircraft at Palma - PRM1 (Light), B738 (Medium) and A332 (Heavy). Arrival flow data was taken from a sample of arrivals at Palma airport over a one-month period spanning July and August 2016. This period was chosen because it is the busiest time of the year. Over 3000 arrival trajectories were selected. We discarded those trajectories that did not follow STAR because they could have been subject to vectoring.

Table 7 gives the main characteristics of the relevant SIDs and STARs for each conflict point. It also shows the information required for the simulations. The following information is given for each conflict point: the SID/STAR procedures involved; the number of aircraft per hour flying each procedure \( p_{SID}, p_{STAR} \); the distance between the conflict point and the runway \( (x_f - x_{run}) \); the distance between the conflict point and STAR entry-point for arrivals \( (x_{EP} - x_f) \); and the altitude distribution of CCO and arrival flows \( (h_f, h^2) \) for Medium aircraft in terms of FL. Table 7 shows the altitude distributions for Medium aircraft only, however, the authors did calculate these for all aircraft types.

![Fig. 6. Diagram showing the SIDs and STARs at Palma airport highlighting points of conflict points.](image)
Table 7
Summary of the operational characteristics of SIDs and STARs for each conflict point.

<table>
<thead>
<tr>
<th>Conflict point</th>
<th>SID</th>
<th>$\rho_{SD}$</th>
<th>$x_{SD} + x_{SPM}$ (NM)</th>
<th>$h_f (\mu, \sigma)$</th>
<th>STAR</th>
<th>$\rho_{STAR}$</th>
<th>$x_{STAR} + x_{SPM}$ (NM)</th>
<th>$h_f (\mu, \sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GALAT2B/2L</td>
<td>3.2</td>
<td>22</td>
<td>(119.9; 4.4)</td>
<td>LORESS2M</td>
<td>11.6</td>
<td>61</td>
<td>(117.6; 10.4)</td>
</tr>
<tr>
<td></td>
<td>BPS2B/2L</td>
<td>2.2</td>
<td></td>
<td></td>
<td>TOLOSS2M</td>
<td>2.0</td>
<td>46</td>
<td>(140.6; 1.0)</td>
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<td></td>
<td>DRAG02B/2L</td>
<td>5.3</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PIMA1B/1L</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>MERS54B/1L</td>
<td>13.8</td>
<td>38</td>
<td>(171.2; 6.6)</td>
<td>KENAS3M</td>
<td>0.1</td>
<td>37</td>
<td>(95.6; 5.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LUNIK2M</td>
<td>10.9</td>
<td>36</td>
<td>(100.0; 6.5)</td>
</tr>
<tr>
<td>3</td>
<td>ISTER2B/1L</td>
<td>0.6</td>
<td>35</td>
<td>(161.2; 6.6)</td>
<td>KENAS3M</td>
<td>0.1</td>
<td>39</td>
<td>(90.2; 7.8)</td>
</tr>
<tr>
<td></td>
<td>MORS2E/1L</td>
<td>0.4</td>
<td></td>
<td></td>
<td>LUNIK2M</td>
<td>10.9</td>
<td>38</td>
<td>(92.0; 8.5)</td>
</tr>
<tr>
<td>4</td>
<td>ISTER2B/1L</td>
<td>0.6</td>
<td>41</td>
<td>(180.6; 8.5)</td>
<td>RIX072M</td>
<td>1.1</td>
<td>59</td>
<td>(211.3; 5.7)</td>
</tr>
<tr>
<td>5</td>
<td>ISTER2B/1L</td>
<td>0.6</td>
<td>72</td>
<td>(253.1; 8.0)</td>
<td>MORS3M</td>
<td>0.4</td>
<td>22</td>
<td>(168.7; 36.8)</td>
</tr>
<tr>
<td></td>
<td>MORS2E/1L</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>CAS01B/1L</td>
<td>1.7</td>
<td>11</td>
<td>(57.1; 2.3)</td>
<td>KENAS3M</td>
<td>0.1</td>
<td>66</td>
<td>(98.6; 5.4)</td>
</tr>
<tr>
<td></td>
<td>MEBUT1B/1L</td>
<td>0.1</td>
<td></td>
<td></td>
<td>LUNIK2M</td>
<td>10.9</td>
<td>65</td>
<td>(118.1; 12.0)</td>
</tr>
<tr>
<td></td>
<td>OSGAL1B/1L</td>
<td>0.9</td>
<td></td>
<td></td>
<td>RIX072M</td>
<td>1.1</td>
<td>90</td>
<td>(136.5; 8.6)</td>
</tr>
<tr>
<td></td>
<td>BAVER1B/1G</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CAS01B/1L</td>
<td>1.7</td>
<td>23</td>
<td>(115.3; 4.6)</td>
<td>MORS3M</td>
<td>0.4</td>
<td>82</td>
<td>(138.3; 7.5)</td>
</tr>
<tr>
<td></td>
<td>MEBUT1B/1L</td>
<td>0.1</td>
<td></td>
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<td>MAKEB1M</td>
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<td>48</td>
<td>(87.3; 8.7)</td>
</tr>
<tr>
<td></td>
<td>OSGAL1B/1L</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BAVER1B/1G</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>CAS01B/1L</td>
<td>1.7</td>
<td>40</td>
<td>(177.6; 6.5)</td>
<td>OSGAL1M</td>
<td>0.1</td>
<td>15</td>
<td>(111.3; 6.3)</td>
</tr>
<tr>
<td></td>
<td>MEBUT1B/1L</td>
<td>0.1</td>
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</tr>
<tr>
<td></td>
<td>BAVER1B/1G</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>BAVER1B/1G</td>
<td>1.0</td>
<td>62</td>
<td>(238.3; 8.9)</td>
<td>MEBUT1M</td>
<td>0.0</td>
<td>22</td>
<td>(117; 4.2)</td>
</tr>
<tr>
<td>10</td>
<td>BAVER1B/1G</td>
<td>1.0</td>
<td>75</td>
<td>(255.2; 8.6)</td>
<td>LAMP1M</td>
<td>1.6</td>
<td>18</td>
<td>(126; 8.5)</td>
</tr>
<tr>
<td>11</td>
<td>BAVER1B/1G</td>
<td>1.0</td>
<td>80</td>
<td>(266.4; 8.9)</td>
<td>IZ1M</td>
<td>1.1</td>
<td>16</td>
<td>(121.5; 12.1)</td>
</tr>
</tbody>
</table>

7. Results and discussion

This section presents the results of the Monte Carlo experiments into how the integration of CCO at Palma airport affects capacity. In each experiment, the Monte Carlo algorithm carried out $10^4$ simulations. This means that in total 110000 simulations were performed. The results of these are shown in the following tables and figures.

7.1. Conflicts

The conflict indicator gives the number of conflicts, between CCO and arrivals, that appear between a departure and an arrival schedule. A conflict occurs when a CCO is about to take-off, and an arrival is located inside the associated blocking-area. Table 8 gives the results of the conflict indicators for each percentage variation in CCO.

The number of conflicts increases with increasing CCO Rate, but once a CCO percentage of 40% is reached the number of conflicts remains more or less constant at around nine. The maximum number of conflicts is over 21. These results are logical because the probability of a conflict occurring increases with an increasing number of CCO. The minimum number of conflicts is steady at 0 conflicts except for the range 40-70% in which the minimum number of conflicts is one. Experiments with 0 conflicts mean that there are schedule combinations that are free of conflicts between CCO and arrivals. When there is a conflict in the range 40-70% this is due to the high number of aircraft in the initial schedules. CCO separation minima rarely apply between departures. This explains

Table 8
Number of conflicts as a function of CCO Rate.

<table>
<thead>
<tr>
<th>% CCO</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Minimum Conflicts</td>
<td>0.00</td>
<td>3.06</td>
<td>5.42</td>
<td>8.04</td>
<td>9.88</td>
<td>10.15</td>
<td>9.94</td>
<td>9.68</td>
<td>9.26</td>
<td>8.77</td>
<td>8.68</td>
</tr>
<tr>
<td>Average Conflicts</td>
<td>0.00</td>
<td>3.06</td>
<td>5.42</td>
<td>8.04</td>
<td>9.88</td>
<td>10.15</td>
<td>9.94</td>
<td>9.68</td>
<td>9.26</td>
<td>8.77</td>
<td>8.68</td>
</tr>
<tr>
<td>Maximum Conflicts</td>
<td>0.00</td>
<td>3.06</td>
<td>5.42</td>
<td>8.04</td>
<td>9.88</td>
<td>10.15</td>
<td>9.94</td>
<td>9.68</td>
<td>9.26</td>
<td>8.77</td>
<td>8.68</td>
</tr>
<tr>
<td>Probability of minimum Conflicts</td>
<td>0.00</td>
<td>3.06</td>
<td>5.42</td>
<td>8.04</td>
<td>9.88</td>
<td>10.15</td>
<td>9.94</td>
<td>9.68</td>
<td>9.26</td>
<td>8.77</td>
<td>8.68</td>
</tr>
<tr>
<td>Standard deviation ($\sigma$)</td>
<td>0.00</td>
<td>1.55</td>
<td>2.08</td>
<td>2.42</td>
<td>2.70</td>
<td>2.73</td>
<td>2.45</td>
<td>2.72</td>
<td>2.72</td>
<td>2.72</td>
<td>2.69</td>
</tr>
<tr>
<td>95% confidence interval ($\mu + 2\sigma$)</td>
<td>0.00</td>
<td>6.16</td>
<td>9.27</td>
<td>12.50</td>
<td>15.28</td>
<td>15.62</td>
<td>14.84</td>
<td>15.13</td>
<td>14.71</td>
<td>14.23</td>
<td>14.06</td>
</tr>
</tbody>
</table>
why departures in the 40–70% are more likely to experience a conflict than those in the 80–100% range. In other words, correct optimisation of the departure and arrival schedules can mean that CCO can be implemented without the conflicts occurring. However, the probability of having a schedule with 0 conflicts is extremely low; slightly more than $10^{-4}$.

Lastly, the standard deviation is more or less constant for every experiment with a value of less than three conflicts. This implies that most of the simulations have numbers of conflicts close to the average value. Fig. 7 confirms this fact. In this figure we see that the 95% conflict base-line is equidistant from the average and maximum base-lines (5 aircraft), double the standard deviation. Fig. 7 depicts the evolution of the conflict indicator metrics and shows that they stabilise around fixed values. The conflict peak occurs, not at a CCO Rate of 100% but at 50%. This finding will be verified when we look at the capacity results below. This is due to the fact that as the CCO percentage increases few aircraft can depart. In short, when looking at number of conflicts, the worst CCO percentage as regards the implementation of CCO is around 50%.

### 7.2. ATC intervention

ATC intervention refers to the number of actions that ATC must perform to provide a conflict-free departure schedule. The number of ATC interventions is not the same as the number of conflicts. Table 9 shows the number of ATC interventions. The number of ATC interventions increases with increasing CCO percentage, but once a CCO percentage of 40% is reached the number remains more or less constant at around 2.8 interventions. In this respect, these results are similar to those of the conflict indicators. However, there is a significant difference between the number of conflicts to be resolves and those that require ATC intervention. This difference is accounted for by the fact that on average five conflicts do not require intervention because they are resolved by delaying the previous CCO. The maximum number of ATC interventions does not remain constant but rather increases with increasing CCO percentage. The maximum number of ATC interventions increases with increasing CCO Rate. However, the figures for minimum number of ATC interventions are similar to those for the conflict indicator. There are schedules with 0 ATC interventions except for experiments in the range 40–70%. Similarly, the probability of having a schedule with 0 ATC interventions is extremely low, slightly more than $10^{-4}$. In short, it is possible for CCO to be implemented without ATC intervention but to do so an excellent conflict-free optimisation technique is required.

Lastly, the standard deviation is constant for every experiment. This low value (slightly more than one intervention) implies that most of the simulations have a number of ATC interventions close to the average value. Fig. 8 depicts the evolution of the ATC intervention indicators. The ATC intervention peak occurs, not at 50%, but at 100%. However, the other metrics behave similarly to the conflict indicators. These ATC intervention results strongly support the implementation of CCO because ATC only has to intervene three times on average to achieve zero conflicts over a one-hour period. In future works, the authors will study how the ATC workload varies as a function of CCO and standard trajectories because the impact on ATC workload is of vital importance.

### 7.3. Total delay

Total delay is the sum of the individual delays required to produce a conflict-free departure schedule. Each delay is calculated as the difference between the initial departure time and the new departure time. Table 10 gives the total delay. As in the case of number of Conflicts and number of ATC interventions, the average Total Delay increases with increasing CCO Rate and peaks at a CCO Rate of about 40%. Thereafter, the Total Delay steadily decreases with increasing CCO Rate. The average Total Delay is around 10 min. The maximum and 95% indicators (seen in the figure below) have a similar shape, however, the gap between them is significant being over 8.3 min. The minimum Total Delay is 0 min. This means that there are cases in which the final schedule coincides with the initial schedule. These results confirm what we saw with the number of Conflicts and the number of ATC interventions.

![Fig. 7. Number of conflicts as a function of CCO Rate.](image)
Table 9
Number of ATC Interventions as a function of % CCO.

<table>
<thead>
<tr>
<th>% CCO</th>
<th>Minimum ATC int.</th>
<th>Average ATC int.</th>
<th>Maximum ATC int.</th>
<th>Probability of min ATC int.</th>
<th>Standard deviation (σ)</th>
<th>95% confidence interval (μ ± 2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>10%</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>20%</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>30%</td>
<td>1</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>40%</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>50%</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>60%</td>
<td>1</td>
<td>8</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>70%</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>80%</td>
<td>1</td>
<td>8</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>90%</td>
<td>1</td>
<td>8</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>100%</td>
<td>1</td>
<td>9</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Fig. 8. Number of ATC Interventions as a function of CCO Rate.

Table 10
Total Delay (minutes) regarding % CCO.

<table>
<thead>
<tr>
<th>% CCO</th>
<th>Minimum Total Delay</th>
<th>Average Total Delay</th>
<th>Maximum Total Delay</th>
<th>Probability of minimum Total Delay</th>
<th>Standard deviation (σ)</th>
<th>95% confidence interval (μ ± 2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>10%</td>
<td>0</td>
<td>3.27</td>
<td>5.92</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>20%</td>
<td>0</td>
<td>5.92</td>
<td>8.65</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>30%</td>
<td>0</td>
<td>8.65</td>
<td>10.75</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>40%</td>
<td>0</td>
<td>10.75</td>
<td>11.02</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>50%</td>
<td>0</td>
<td>11.02</td>
<td>11.07</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>60%</td>
<td>0</td>
<td>11.07</td>
<td>11.02</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>70%</td>
<td>0</td>
<td>11.07</td>
<td>11.02</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>80%</td>
<td>0</td>
<td>11.07</td>
<td>11.02</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>90%</td>
<td>0</td>
<td>11.07</td>
<td>11.02</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>100%</td>
<td>0</td>
<td>11.07</td>
<td>11.07</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Lastly, the standard deviation is pretty much constant for every experiment. Fig. 9 depicts the evolution of the Total Delay indicators. The Total Delay peaks at about 40%, similar to the number of Conflicts. The other metrics behave similarly to the those for number of Conflicts and number of ATC interventions. The average Total Delay is over 10 min that will have a significant impact on network performance and could be an impediment to the implementation of CCO. Further study is required into this area. In short, as Total Delay decreases with increasing CCO Rate complete integration of CCO (100% CCO) is favoured. Furthermore, it is possible to have a schedule with no delay.

7.4. Capacity

Capacity is the maximum number of aircraft that can depart over a one-hour period. As previously mentioned, we are looking at the theoretical capacity of an airport because different operational factors, which reduce the capacity, have not been taken into consideration. The maximum theoretical capacity is 56 standard departures in Palma TMA according to aircraft distribution, standard runway separation minima and air route densities. 56 is also the number of the maximum theoretical capacity for arrivals in Palma TMA. Table 11 shows the results of the different experiments.
Table 11
Theoretical capacity as a function of CCO Rate.

<table>
<thead>
<tr>
<th>% CCO</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Capacity</td>
<td>56</td>
<td>54</td>
<td>51</td>
<td>48</td>
<td>46</td>
<td>44</td>
<td>42</td>
<td>41</td>
<td>39</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td>Average Capacity</td>
<td>56.00</td>
<td>55.00</td>
<td>54.45</td>
<td>51.53</td>
<td>50.41</td>
<td>49.28</td>
<td>47.86</td>
<td>45.71</td>
<td>43.60</td>
<td>42.96</td>
<td></td>
</tr>
<tr>
<td>Maximum Capacity</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Probability of minimum Capacity</td>
<td>1</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
<td>2^{-4}</td>
</tr>
<tr>
<td>Standard deviation (σ)</td>
<td>0.00</td>
<td>0.05</td>
<td>0.47</td>
<td>1.58</td>
<td>1.62</td>
<td>1.78</td>
<td>1.87</td>
<td>1.92</td>
<td>1.95</td>
<td>1.99</td>
<td>1.98</td>
</tr>
<tr>
<td>95% confidence interval (μ−2σ)</td>
<td>56.00</td>
<td>55.89</td>
<td>54.45</td>
<td>51.29</td>
<td>48.30</td>
<td>45.54</td>
<td>44.03</td>
<td>41.80</td>
<td>39.61</td>
<td>39.01</td>
<td></td>
</tr>
</tbody>
</table>

As expected, the average and minimum capacities decrease with increasing CCO Rate. At a CCO Rate of 100% the average reduction in capacity is 23%. The maximum reduction in capacity is 37.5%. The decrease in capacity is due to two factors: the introduction of new CCO separation minima, and the delay of departures due to conflicts with arrivals. Therefore, the implementation of CCO has a significant impact on the theoretical capacity. However, the maximum capacity remains constant regardless of the CCO Rate. This means that there are schedule combinations that allow full implementation of CCO (CCO Rate of 100%) with no decrease in capacity. As with the previous metrics, a complex conflict-free optimisation technique may enable CCO to be implemented without using CCO separation minima. However, the probability of occurrence of these combinations is extremely reduced (10^{-4}).

The standard deviation of the capacity remains constant at slightly less than two aircraft. The standard deviation of three indicators (number of conflicts, number of ATC interventions and time delay) is more or less stable from a specific CCO Rate on. However, this is not true in the case of the capacity indicator.
The implementation of CCO affects the four indicators considered. The capacity decreases with increasing CCO Rate, however, the same is not true of the number of conflicts, the number of ATC interventions or Total Delay. In the latter three cases, from a CCO Rate of 40% onwards the values remain constant. In other words, if the impact on capacity was manageable then, as regards number of conflicts and number of ATC interventions, there is no difference between having a CCO Rate of 40% or one of 100%. Furthermore, the values for number of conflicts, number of ATC interventions and Total Delay favour the use of a CCO Rate in the range 80–100% because in the range 40–70% there is always at least one conflict. These results confirm that the implementation of CCO reduces the capacity. However, even with this reduction the resulting capacity is still higher than the current declared capacity (32 departures). This encourages us to continue with our research.

This method is suitable for every airport even if they have different operational and geometric characteristics. The inputs described in Section 3 (air route distribution, air traffic flows, aircraft type and so on) are characteristic of each airport. CCO trajectories can vary depending on the location of the airport, weather and environmental restrictions. Under other conditions, different CCO will be required. Obviously, variations in characteristics of the airport and the inputs will lead to results that are different to those obtained in this study. Airspace design is also a crucial factor because the implementation of CCO depends on the number of conflicts and ATC interventions. In situations where there is a SID and STAR intersection with a high probability of conflict, this intersection should be redesigned to favour the crossing of air traffic flows.

While the results achieved are promising, the primary limitation is that the study focused on a theoretical framework. Further research should assess the impact of CCO on real departures and arrivals and on real CCO trajectories. This will allow us to confirm the results as regards safety, capacity and ATC workload. In-depth analysis is required to assess the impact of CCO trajectories on ATC command and control. Aircraft are capable of flying CCO and airlines are willing to use them. The next step should be to look at the impact of CCO on ATC workload.

8. Conclusions

This paper analyses the impact of CCO on the capacity of a high density traffic airport. The proposed methodology may be used to determine the viability of implementing CCO at an airport by looking at capacity, conflicts, ATC intervention and delay. Therefore, the process for calculating new separation minima and detecting and analysing conflicts gives us conflict-free CCO.

The methodology comprises three sections: a scheduling algorithm, a conflict-detection and resolution algorithm, and Monte Carlo simulations. The scheduling algorithm calculates two schedules, one for departures and another for arrivals, based on the CCO rate. New CCO runway separation minima are considered. These separation minima are larger than current values and, therefore, the most obvious initial impact is that runway capacity decreases with increasing CCO Rate. The CD&R algorithm detects conflicts between CCO and arrivals. In the event of a conflict it delays the relevant CCO until a conflict-free departure can be ensured. These two algorithms enable us to assess the impact of CCO on airport capacity. However, to statistically verify these results, Monte Carlo simulations are carried out in which the CCO Rate is varied.

This paper contributes to the literature on CCO because, to the best of the authors knowledge, it is the first work to quantify the impact of the implementation of CCO on airport capacity. Not only does the methodology ensure conflict-free departures for CCO but it also provides a tool that will facilitate the adaptation of ATC to these new procedures. Furthermore, the statistical assessment carried out on the implementation of CCO provides meaningful results:

1. The average number of conflicts between CCO and arrivals is almost nine conflicts per schedule (or nine conflicts per hour, as each schedule has a duration on one hour). However, there is the possibility of having a departure schedule with 100% CCO which is conflict free.
2. The number of ATC interventions behaves similarly to the number of conflicts. However, the average number of ATC interventions is slightly less than three interventions per schedule. This finding is extremely significant because it means that ATC intervention may not be required in schedules with a CCO Rate of 100%. However, it must be said, that the likelihood of a schedule with 0 ATC is extremely low.
3. Total delay gives the worst results. It increases with increasing CCO Rate until about 40%, similar to the results obtained from number of conflicts and number of ATC interventions. The average total delay is around 10 min although there are schedules that have 0 min delay.
4. The implementation of CCO leads to a decrease in the maximum theoretical capacity. The average reduction is 23%. However, there are schedules with a CCO Rate of 100% in which there was no reduction in capacity.

In summary, optimal distribution of CCO via the different SIDs is necessary to minimise the impact of CCO on capacity. We also require an optimal scheduling process to avoid conflicts between CCO and arrivals. Capacity decreases with increasing CCO Rate. The three other indicators (number of conflicts, number of ATC interventions, and total delay behave differently): above a CCO Rate of 40% all three remain stable. As such, it would be wise to look at full implementation of CCO (CCO Rate of 100%), although factors like ATC workload and complexity may affect the results. Finally, these results encourage us to analyse the impact of CCO in real scenarios. Further work should look at the implementation of real CCO trajectories as well as the other operational factors that affect capacity.
Conflict of interest

The authors declare no conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trc.2018.09.008.

References


ENAIRE, 2016. ERI 1.6-1 ATS surveillance services and procedures.


