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REGULAR PAPER

Improving the management of air traffic congestion during the approach phase

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Abstract

Nowadays most busy international airports and their corresponding terminal areas are suffering from huge congestion issues due to the simultaneity of their arrival aircraft. The aim of this paper is to establish a new separation method using time- based-separation, speed modification during approach phases and Point Merge System (PMS) so as to ensure efficiently the traffic flow. This work took as a case study the busiest airport of Morocco, The Mohammed V International airport of Casablanca. The proposed management model offers very good results when compared with other models such as the first-come first-served (FCFS) model.

Nomenclature

Abbreviations

AMAN	Arrival Manager
ANSP	Air Navigation Service Provider
APD	Aircraft Performance Database
ASP	aircraft sequencing problem
ATCo	Air Traffic Controllers
ATFM	air traffic flow management
ATM	air traffic management
BADA	base of aircraft data
CARATS	Collaborative Actions for Renovation of Air Traffic Systems
CDO	continuous descent operations
DBS	distance-based separation
Eurocontrol	European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
FCFS	first-come first-served
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
NextGen	Next Generation Air Transportation System
P-RNAV	precision-area navigation
PMS	Point Merge System
PSO	particle swarm optimisation
RPKs	revenue passenger kilometers
SAA	Speed Adjustment algorithm
SESAR	Single European Sky ATM Research

SRA	Speed Restriction algorithm
TBO	trajectory-based operation
TBS	time-based separation
TMA	terminal manoeuvering area

Symbols

A_i	Aircraft number i
D	The flown distance by an aircraft
$d_{i,Sk}$	The flown distance by aircraft i in the arc k
EP_i	Entrance point number i
H_i	Holding area number i
K_i	Initial approach point number i
p	Landing order number following the Sequencing algorithm
PM17	Point Merge of runway 17
q	The landing order number following the FCFS algorithm
Rfi	The estimate time of aircraft number i to penetrate into zone 2
Ri	Radius of zone number i
Sk	PMS arc number k
SLK	The point merge of the runway 35
$test_{fi}$	The estimate landing time of aircraft number i according to FCFS
$test_i$	The estimate landing time of aircraft number i after separation
$testv_i$	The estimate landing time of aircraft number i after speed adjustment
t_{fi}	The estimate time of aircraft number i to penetrate into zone 2
t_k	The time left for aircraft nubmer k to land
V_{app}	Approach speed
V_{ar}	Touchdown speed
V_e	Entrance speed
V_f	Final speed
V_i	Initial speed

Greek symbol

α	the arc opening angle of the merge point configuration
θ	the incoming angle

1.0 Introduction

On 6 February 2020 in Geneva, The International Air Transport Association (IATA) has released its statistics on world passenger traffic for the year 2019, showing that the demand revenue passenger kilometers (RPKs) increased by 4.2% over 2018 [1]. Which corresponds to the increasing numbers of aircraft movements' all over the world especially in Europe and the USA. To face this continuous growth and in order to build a flight operation system by 2030, when air traffic volume is predicted to double from its current level, the International Civil Aviation Organization (ICAO) has produced the global air traffic management operational concept. Based on this concept, The European Organization for the Safety of Air Navigation (Eurocontrol) produced the Single European Sky ATM Research (SESAR). In the USA, the Federal Aviation Authority (FAA) elaborates an infrastructure program to modernise the national airspace system called the Next Generation Air Transportation System (NextGen). Other organisations concentrate on developing newer tools and technologies to upgrade the air traffic management system. For example, Japan has implemented a Collaborative Actions for Renovation of Air Traffic Systems (CARATS). This tool requires cooperation with diverse aviation stakeholders in order to change Japan's air traffic system in a decisive and long-term manner [2]. In view of the enormous increase in air traffic flows, managing the airspace in a terminal manoeuvering area (TMA) is the most challenging task in the

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entire Air Traffic Management (ATM) system, and it is believed to be the root cause of all limitations and delays imposed on scheduled flights. The factor pushing Air Navigation Service Providers (ANSPs) to expedite the establishment of multiple supports in order to handle the complexity and volume of future aviation traffic.

The integration of such tools is necessary and can help Air Traffic Controllers (ATCos) maintain the safety of the current level of air traffic despite the growth in its flows. These tools make it simpler to plan efficient arrival sequences and to optimise aircraft trajectories and arrival times in order to maintain a steady stream of arrival traffic. They also help apply the Continuous Descent Operations (CDO) procedures assisted by arrival merging techniques, (such as the Point Merge System [PMS]) and reduce the total flight's duration, flown distances and fuel use.

2.0 State of art

The volume of air traffic has dramatically risen over the past few decades, and predictions indicate that this trend will continue growing. In fact, the scenario, referred to as "controlled growth" by Eurocontrol's prediction specialists, stated that the number of flight movements in Europe is expected to reach 14.4 million in 2035, which is 1.5 times the volume in 2012 [3]. The ongoing expansion of civil aviation has far-reaching impacts. On one hand, during peak hours, the air navigation system has practically hit its capacity limit (i.e. the physical capacity is less than operational capacity). On the other hand, it will be more difficult to control air traffic bottlenecks and there will be more delays. The TMA surrounding the airport has typically been the first region to have congestion issues and delays. The TMA is that crucial transition dynamic space between the landing surfaces and the upper airspace. Moreover, it has also been identified as a vital sector and continues to be the greatest barrier for the world's ATM. Given that the TMA has been regarded as one of an airport's limitations and that its capacity is viewed as crucial to the point where it cannot be simply raised; operations with modern aircraft on the available runways became complicated and difficult. Which made aircraft operations management a vital part of air transportation systems. Therefore, and since optimising takeoff and touchdown times is a cost-effective approach to increase the aircraft numbers, depending on the available runways capacity, our particular instance concerns finding a solution for the Aircraft Sequencing Problem (ASP). These are the summaries of the most relevant works and contributions that consider some aspects of our work: In order to reduce emissions into the environment and energy usage, the research [4] describes a system for automatically creating effective curved and continuous descent approach trajectories in a common TMA. In [5] the authors, according to statistics, establish dynamic models to describe potential behaviours of traffic (divided in three flow phases) including following, holding and manoeuvering. The paper [6] proposes a medium-term conflict detection and resolution approach to detect time-based separation infringements between aircraft and then allocate dynamic arrival routes taking into consideration the execution of continuous descent approaches. By comparing the theoretical organisation of the queue with the actual distribution seen in the TMA, the contribution [7] proposes a model that gives a remarkably accurate representation of the traffic. The publication [8] proposes an optimised model which integrates 4D trajectory-based operations and employs sector-less airspace configurations Along with handling the flight-by-flight difficulties of rerouting, ground-holding delays, fuel use and flight cancellation. To minimise the effort of the ATCos, the authors of paper [9] conduct an experiment including the task of merging aircraft onto a single route. Depending on the various traffic levels that were evaluated, significant effects of the aolution space diagram were discovered, and respondents submitted subjective effort ratings at predetermined intervals of time. A novel method for automatically integrating several aircraft flows in a busy TMA is presented in the study [10]. The writers of this paper [11] address the issue of air ATCos' workload stress by determining the primary stressors and arriving at a ranking of likely remedies that may be used as soon as such a problem is detected in order to be lessened. The paper [12] critically reviews Air Traffic Flow Management (ATFM) research and development efforts (conducted by the official organisations like ICAO, IATA, the FAA and Eurocontrol) hold the most potential for realistic technological adoptions, delivering clear advantages in the sense of increased effectiveness and safety at an era when aviation traffic is growing. In [13] a data-splitting approach is suggested to resolve the ASP on one runway under both separate and combined modes of operation with the goal of optimising total throughput. Safety separation requirements, expansive time frames, and restricted position changing are some examples of these realistic limits. The authors of the paper [14] examine and simulate a few effects of potential solutions for aligning the airport runway system's landing capacity to associated demand. A new Arrival Manager (AMAN) algorithm relies on the merging optimisation technique is proposed in [15] and it also optimises aircraft itineraries to support Trajectory-Based Operations (TBO). The suggested AMAN algorithm illustrates the compromise between reducing flight time and energy consumption. Concentrating on an integrated system, the contribution [16] provides a systematic analysis of the airplane over the airport's organisational system. It gives information on the interdependencies between components affecting performance and presents a fresh methodological approach to assess and forecast the systems status at the rotation stage. A multi-level PMS approach is used in the paper [17] to provide an effective trajectory planning method to address the problem of integrating of arrival and departure traffic on parallel runways. It can provide a fairly close continuous descent approach for arriving aircraft, a cost-effective climb for departing aircraft, simpler runway allocation and trajectory control solutions. It also demonstrates effective and dynamic sequencing efficiency in the TMA. The authors of the paper [18] attempt to improve ASP research by more effectively utilising the structural information that is unique to the issue. Their suggested techniques perform better than current cutting-edge aircraft sequencing algorithms. The contribution [19] outlines an approach for optimising flight operations that will help ATCos choose and manage landing and departure schedules at airports that are practical from an operational standpoint. The paper [20] concentrates on regulating the time of arrivals once the descent has already begun, evaluating the achievable time frame (and related fuel consumption) of CDOs that don't need using either the thrust or the speed-brake throughout the whole descent. The paper [21] focus on modeling the aircraft landing problem using a program with a formulation that consists on breaking down the problem into sub problems: scheduling, sequencing and landings problems. The contribution [22] takes into account the planning of aircraft landings on one runway. In order to establish some time frame limits for each aircraft's landing time and a minimum separation time between consecutive landings according to their wake turbulence class, it studies the static inputs and the dynamic changes of the arrival flights. In their study [23], the authors propose an updated requirement and capacity alignment approach for managing air traffic flow capacity. That can be used to reduce potential conflicts between aircraft trajectories prior to takeoff. Their goal is accomplished by making small changes to aircraft's timeframes of arrival at complex en-route crossroads, which are easily converted into pre-tactical measurements and lessen the ATCos' effort associated with Separation Management interventions.

3.0 Problematic

3.1 Inbound convergence point

Most TMAs are not centred on the inbound traffic convergence point. Moreover, many factors change frequently such as: wind, weather, noise reduction procedures and other operational procedures which lead to many runway configuration scenarios and therefore the change of the final approach phase and the respective inbound convergence point. This paper took as case study the Mohammed V airport, which has two parallel runways 35/17. Figure 1 shows a simplified version of the airport's TMA with the corresponding convergence points.

Furthermore, the convergence point is variable while the shape of the terminal area remains the same, which is impossible for the last one to be centred on the convergence point.

3.2 The FCFS concept

There are several issues in the current radar vectoring method: Significant workloads for ATCos, multiple radio communications, difficult positions for pilots to determine their location, troubles in the

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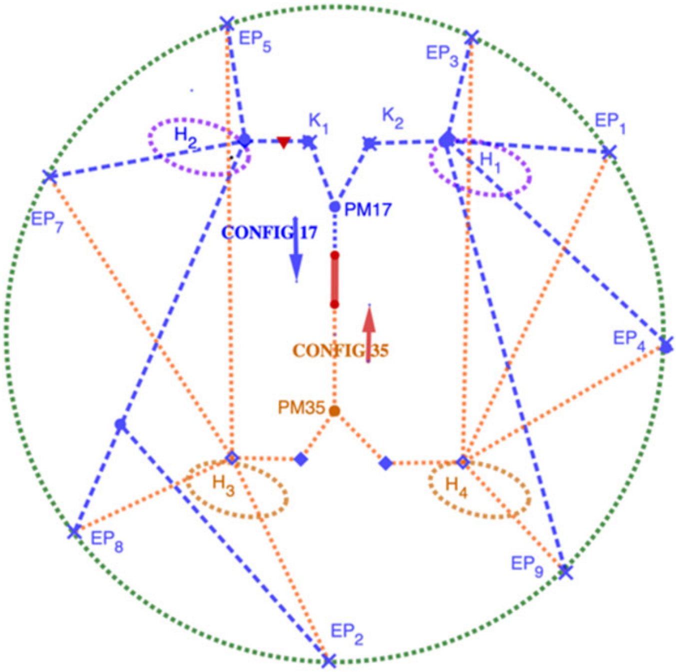

Figure 1. *Different runways configurations.*

prediction and improvement of vertical profiles. Before that, the ATCos have to establish a sequence for the inbound traffic using FCFS concept. Let SLK be the convergence point, we assume that we have two aircrafts on arrival: A_1 and A_2.

3.2.1 Same speed and different distance

With the same performance in term of speed V as mentioned in Fig. 2. The aircraft A_2 will cross the lateral TMA boundary before the aircraft A_1 but the last one is a 30NM away from the point SLK with a touchdown estimate in 14 min while A_2 is 50NM away from SLK with a touchdown estimate in 18 min. According to the FCFS A_2 will land in 18 min, and taking into account the 2 min of spacing at landing, it will add a minimum delay of 6 min for A_1 to land and an additional flown distance of $D \geq 6min \times V$ to its path. While if A_1 lands before A_2, no delay will be generated for both aircraft. So, it is clear that the first aircraft that crossed the lateral boundaries of the TMA is not necessarily the first one to land.

3.2.2 Same distance with different speeds

Now we suppose that we have two aircraft on arrival: A_1 and A_2 (A_2 with less performance in speed V than A_1) with speeds $V_1 > V_2$ and A_1 will cross the TMA boundaries first. We define t_k (the time left for aircraft k to land), with $t_1 = 15min$, $t_2 = 18min$. Aircraft A_2 at the same distance to SLK as A_1 as illustrated in Fig. 3. So according to the FCFS concept, if A_2 will land in 18 min, and taking into account the 2 min minimum spacing between 2 aircraft at landing, It will add a minimum delay of 5 min for A_1, and a crossed distance $D \geq 5 \times V_1$ in addition to A_1's path, while if A_1 lands before A_2 no delay will be generated for both aircraft. Following this example, the new touchdown estimates of A_1 and A_2 are: $t_1 \geq 21min$ and $t_2 = 18min$. The closest aircraft to the convergence point is not necessarily the first one to land.

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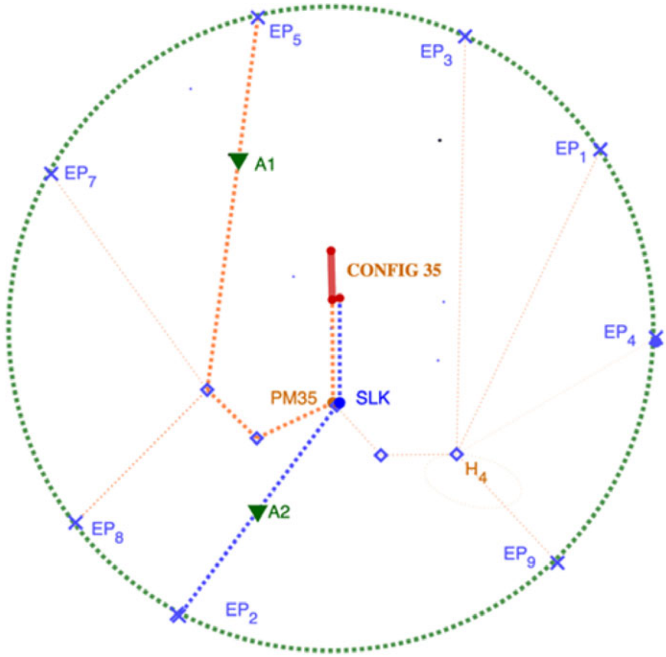

Figure 2. Same speed with different distances.

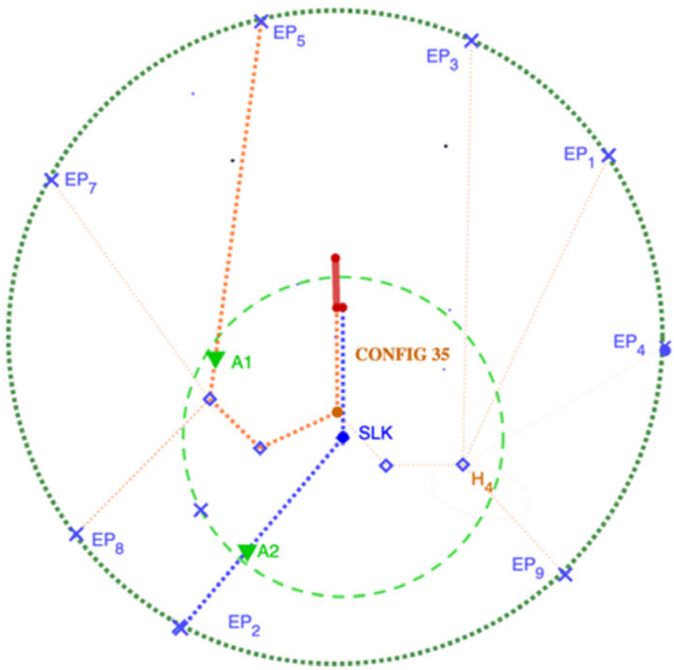

Figure 3. Same distance with different speeds.

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3.2.3 Different distances with different speeds

Now we suppose that we have two aircraft on arrival A_1 and A_2 (A_2 with less performance in speed than A_1) with speeds $V_1 > V_2$ and A_1 will cross the TMA boundaries first as demonstrated in Fig. 3. We definet_k (the time left for aircraft k to land), with: $t_1 = 14min$, $t_2 = 19min$. Aircraft A_2 is closer in term of distance to SLK. So according to the FCFS concept, A_2 will land in 19 min, and considering the minimum 2 min spacing at landing, it will add a minimum of 7 min delay for, and an additional distance of $D \geq 7 \times V_1$ to A_1's path, while if A_1 lands before A_2 no delay will be generated for both aircraft. Following this example, the new estimated landing times of A_1 and A_2 are: $t_1 \geq 21min$ and $t_2 = 19min$. According to the three examples above the closest aircraft to the convergence point is not necessarily the first one to land, so we have to use other criteria more efficient then distance or position to make the best decision.

4.0 The main used concepts

Following the previous section, it is clear that the ATCos are in need of a decision support tool using real time algorithms to help them establish aircraft sequence with the minimum possible delay. Our proposed tool is based on these concepts:

4.1 Time based separation

Time Based Separation (TBS) is an optimal concept for the use of the airspace. It is a system that separates aircraft based on time rather than distance and takes into account aircraft's performance, runway capacity and other factors. In order to use this concept at a specific time, we are going to adopt another concept that allows us to apply our method while respecting the prescribed regulatory separation, the Merge Point concept [24].

4.2 The point merge system

The PMS method is among the most efficient proposed solutions for ATM during the approach phase in a TMA, it is a systematised arrival flow sequencing method developed by the Eurocontrol Experimental Centre in 2006. It is also one of the upgrades of the ICAO Aeronautical System Blocks and considered as a technique to support continuous descent operations (CDO - ICAO doc 9,931) [25].

The PMS concept is meant to provide safety, environmental and capacity benefits under different density situations. Taking into consideration the operational and environmental restrictions and the selected conception, the envisaged gains are:

- Simplify ATCos' tasks.
- Reduce communications and workload.
- Improve pilots' awareness of the situations.
- Efficient traffic flows with a prediction of arrival sequences.
- Enhanced traffic sequences after the PMS.
- Efficient flight trajectory prediction.
- Operations' unification and better ATM.

The PMS is built to function with dense traffic flows without radar vectoring. It is founded on a particular route structure (Precision-Area Navigation). It is made up of a convergence point and predetermined, evenly spaced segments equidistant from this point. An instruction to proceed directly the convergence point is given at the proper time to complete the sequence. When necessary, the segments

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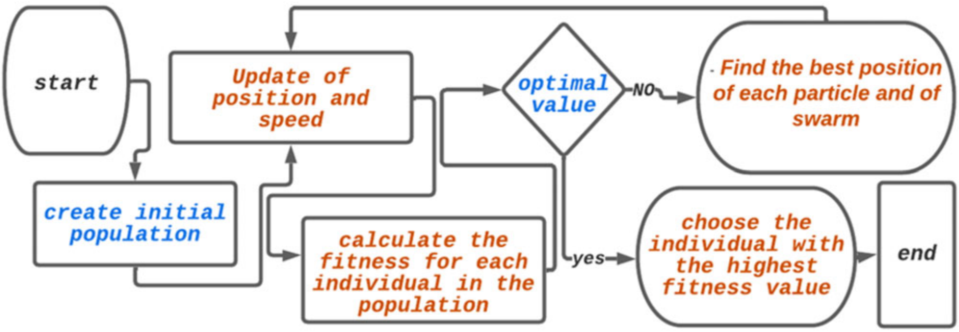

Figure 4. *Particle Swarm Optimization diagram PSO.*

are utilised to delay traffic as trajectory extension, the segments' length is determined based on the corresponding capacity and the needed delay. In the case of our case study space, SLK is the convergence point (Merge Point), the point that all aircraft must pass through to begin the final approach. The ANSP has proposed a model based on the PMS concept to manage traffic in Mohammed V airport TMA. The proposed model is composed of holding circuits feeding an arc of 50NM, which has a capacity of five aircraft (given the prescribed horizontal separation) in order to finally join the SLK point. Once the arc is saturated, the aircraft wait in the holding circuits, and the capacity of each circuit does not exceed nine waiting aircraft, the aircraft goes through the holding circuit in 4 min. The downsides of this proposed model are:

- The arc cannot be supplied with another aircraft until the first one has left it completely.
- The holding time is a multiple of 4 min due to the holding procedure.
- The distance between the holding circuits and the arc is long and generates a significant delay.
- The proposed management ignored the position of the entry points and aircraft's performance.
- Fixed speed in the vicinity of SLK between 220kts and 230kts while there are aircraft that perform it difficultly by consuming more fuel.

4.3 Particle swarm optimisation (PSO)

The PSO is a metaheuristic technique used to solve an optimisation problem in a particle-based research environment. The PSO algorithm's objective is to relocate these particles to their ideal place. These labels are given to each one of these particles:

- A position
- A speed
- A neighbourhood

Every particle, as seen in Fig. 4, is aware at each iteration of:

- Its prominent location.
- The location of the swarm's ideal neighbour.
- The provided value to the objective function since a comparison between the value of the given criterion by the current particle and the ideal value is necessary after each iteration [26].

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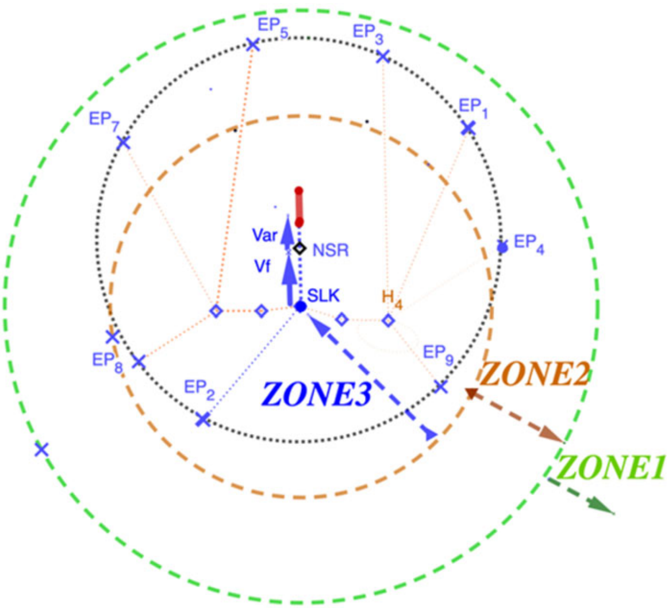

Figure 5. *Zones according to speed.*

5.0 The geometric proposed model

We arrange the aircraft so that the most performant ones are the first to be sequenced and continue so, the aircraft A_k might touchdown from $t_{k-1} + 2min$, which means that the problem to be minimised is t_k with the condition:

$$t_k \geq t_{k-1} + 2min \tag{1}$$

The minimisation of t_k implicates the minimisation of the flown distances.

The associated constraints using this sequencing model are in finding the optimal order. Which means the order that minimise the delays and following it, will make sure the aircraft land in a continuous manner while minimising the additional flown distances and separations between all the aircraft in approach phase.

5.1 Zones according to speed profile

In the TMA during the approach phase, aircraft execute an airspeed profile composed of five main speeds: entry, initial, approach, final approach and touchdown speeds referred to in the same order as $V_e, V_i, V_{app}, V_f, V_{ar}$(1,4 × stall speed). As shown in the simplified graphics in Fig. 5, the TMA of Casablanca Mohamed V airport is sliced up into five zones according to speed variation as detailed before.

- Zone 1 is the entry speed zone V_e starts 60NM away from SLK.
- Zone 2 is the initial speed zone V_i starts 30NM away from SLK.
- Zone 3 is the approach speed zone V_{app} starts 15NM away from SLK.
- The 8NM segment after SLK is the final speed V_f zone just after SLK.
- The 4NM segment before touchdown is the touchdown speed zone V_{ar}.

The mentioned speeds vary depending on aircraft category and each aircraft that exceeds the radius $R3 = 60NM$ can influence the management and sequencing of air traffic.

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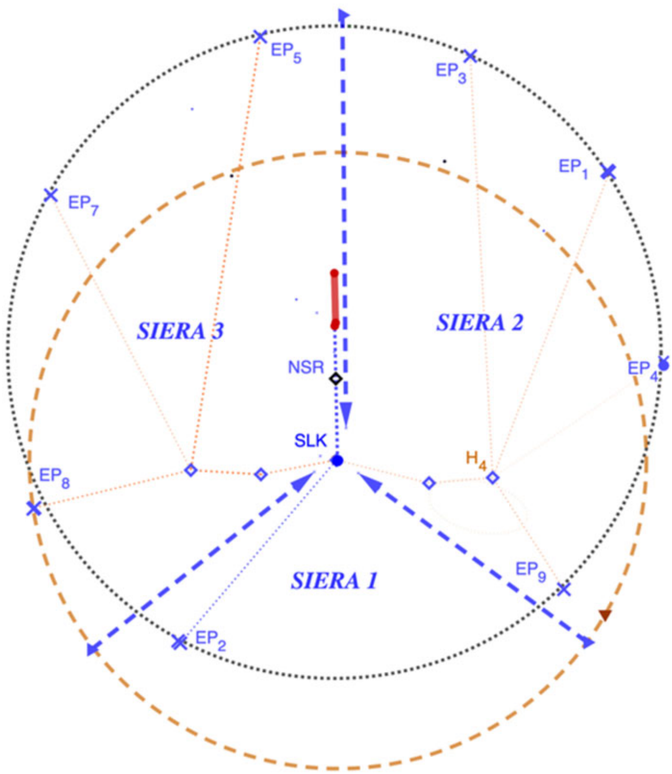

Figure 6. *Incoming zones.*

Considering a flow of aircraft on arrival, Air Traffic Controllers, following the FCFS concept, assign to each aircraft a landing number. Most times, this number changed several times due to the possibility of conflicts between aircraft (e.g. two aircraft reach the SLK point at the same time) or the delay of the second aircraft becomes not acceptable according to precedent one, and its need more vectoring which lead to more delay for booth of aircraft.

The sequencing model proposed by [25] aims to separate the aircraft and sequence them so to join the convergence points. Based on this model and the issues encountered by ATCos such as the mentioned conflict above, our model proposes to separate the aircraft according to the runway. The employed methods in this work take into account the current navigation circumstances, speed restrictions, flight levels, . . . etc.

5.2 Zones according to incoming area

Aircraft can join the terminal area (approach area) from three different main zones as shown in Fig. 6:

- SIERA1: Aircraft coming from the south (approach direction)
- SIERA2: Aircraft coming from the north-east (northeast approach direction)
- SIERA3: Aircraft coming from the north-west (opposite approach direction)

SIERA2 arrival aircraft have 3 min delay more than SIERA1 and SIERA3 arrival aircraft have 6 min delay more than SIERA1 due to restrictions, special procedures and departures conflicts. In this work, we aim to construct a real time algorithm that assigns to each aircraft an optimal landing order number, in which, aircraft with the highest performance will be served first, and so on.

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5.3 The delay based on the FCFS concept

In order to know the benefit of our method we have to calculate the delay generated by the FCFS concept. Once the "x" aircraft are in zone 1, the algorithm calculates "tfi" the estimate time to penetrate into zone 2 of each aircraft Ai. Based on their penetrating estimates time, and in accordance with the FCFS concept, the algorithm arranges the aircraft in descending order based on their performance to determine the landing order number. $q : j \to q(j)$, with $j \in \{1, 2, 3, \ldots, n\}$ is the landing number of aircraft $Aq(j)$. Thus, the succession of the aircraft is: $\{Aq(1), Aq(2), \ldots, Aq(n)\}$. Consequently $Aq(1)$ lands at: $t_{f_1} = tq(1)$, and $Aq(2)$ can land at $t_{f2} = max(t_{f1} + 2min, tq(2))$. The runway is ready to receive $Ap(2)$ after $t_{f1} + 2min$, this separation takes into account the liberation of the runway and the longitudinal separation on final approach and so on for the rest of $Aq(j)$.

We define $Rfi = t_{fi} - tq(i)$ the aircraft's $Aq(i)$ delay and i is the landing sequence number following the FCFS method.

Algorithm 1

Compute t_i, for $i = 1, \ldots, n$
Find q
Compute testfi for $i = 1, \ldots, n$
Compute the delay Rfi for $i = 1, \ldots, n$

- We found p and q, respectively, the landing order number (Sequencing algorithm) and the landing order number (FCFS concept).
- We calculated t_i and t_{fi}, respectively the touchdown estimates of aircraft $Ap(i)$ (Sequencing algorithm) and the touchdown estimates of the aircraft $Aq(j)$ (FCFS concept).
- We calculated Ri and Rfi, the delays of aircraft $Ap(i)$ (Sequencing algorithm) and $Aq(j)$ (FCFS concept).

Now the question is: How should $Ap(i)$ fly along and consume the delay Ri while landing continuously at t_i, without any delay according to $Ap(i-1)$?

5.4 Our proposed geometric model

The solution to the issue is in the anterior section of the PMS concept by adding another arc, the two arcs will permit to re-order the aircraft that follow each other while remaining equidistant from SLK point as shown in Fig. 7. The idea behind this proposition is simple, after finding the permutation p, we must permute the aircraft with the following landing order: $\{Ap(1), Ap(2), \ldots, Ap(n)\}$, with the aircraft $Ap(i)$ for $i = 2, \ldots, n$ flies the delay Ri in the two arcs:

$$S1 = R22\pi/3 = 302/3 = 62.8NM$$

$$S2 = R12\pi/3 = 152/3 = 31.4NM$$

The choice of the $2\pi/3$ angle is made due to the constraints of actual navigation and also to ensure strategic separations with aircraft on departure. The three angles of incidence to joined $S1$ are:

- $\Theta 1 = \pi/6$ assigned to aircraft coming from the zone SIERA1 since the traffic flow and the network of air traffic services routes feeding the TMA from the southern sector.
- $\Theta 2 = 0$, $\Theta 3 = 0$ respectively assigned to aircraft coming from the zones SIERA2 and SIERA3.

$d_{i,S1}$ is the flown path of Ai is arc $S1$ and $d_{i,S2}$ is the flown one in arc $S2$ by the same aircraft. *Constraints for each aircraft* A_i:

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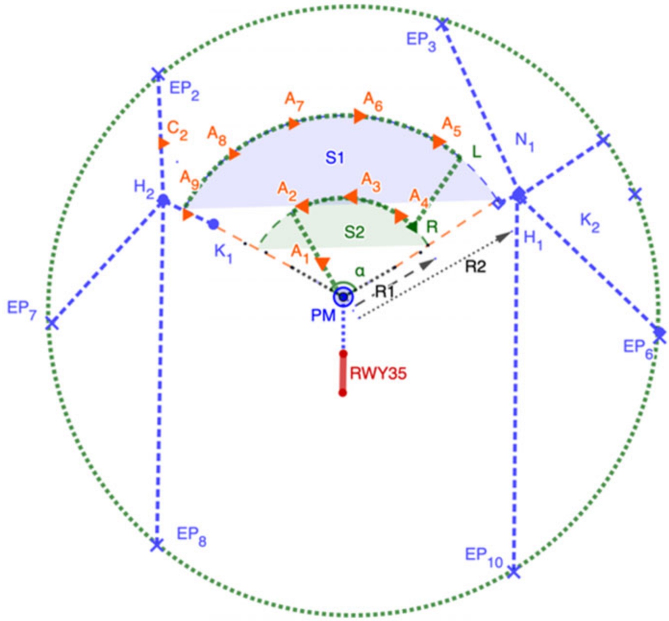

Figure 7. *Merge point concept with two arcs.*

$$0 < d_{i,S2} < S1 - R2 \times \Theta j, \text{for } j = 1, 2, 3. \quad (2)$$

$$0 < d_{i,S2} < max(S2 - R1\Theta j - (d_{i,S1})/2, R1\Theta j + (d_{i,S1})/2), \text{ for } j = 1, 2, 3. \quad (3)$$

$$d_{i,S1} < d_{i,S2} \quad (4)$$

It is clear that the flown distance over the arc S_1 by an aircraft A_i coming from the zone SIERA1 is: $d_{i,S1} \in [0, S1 - 5\pi]$, as well as the flown distance over the arc $S1$ by an aircraft Ai coming from the zones SIERA2 or SIERA3 is $d_{i,S1} \in [0, S1]$. For the flown distance over the arc $S2$ by an aircraft coming from the zone SIERA1, it is better to instruct it to fly in the longest direction so as to better utilise the arc $S2$. Therefore, $d_{i,S2} \in [0, max(S2 - (d_{i,S1})/2, (d_{i,S1})/2)]$, as well as for the aircraft coming from the zones SIERA2 or SIERA3, with $d_{i,S2} \in [0, max(S2 - (d_{i,S1})/2, (d_{i,S1})/2)]$. As for the third constraint, it comes from the fact that we want to minimise the flown distance over both arcs because the speed V_i, in the arc $S1$ is higher than the speed V_{app}, in the arc $S2$.

5.5 Modelisation

In the previous sections, we calculated the delay Ri of each aircraft $Ap(i)$ and suggested that aircraft should consume these delays over the arcs while remaining equidistant from the SLK point. We assume: $d_{i,S1} = d_{i,1}$ and $d_{i,S2} = d_{i,2}$.

$V_{p(i),2}$ is the initial speed V_i for the aircraft $Ap(i)$ and $V_{p(i),3}$ is the approach speed V_{app} for the aircraft $Ap(i)$ with:

$$fi(d_{i,1}, d_{i,2}) = \frac{d_{i,1}}{V_{p(i),2}} + \frac{d_{i,2}}{V_{p(i),3}} \quad (5)$$

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Consequently, the multi-objective minimisation function is:

$$min \sum_{i=2}^{n} |fi(d_{i,1}, d_{i,2}) - r_i| \quad (6)$$

u.c:

$$d_{i,1} < S1 - R2 \times \Theta j$$

$$d_{i,2} < max\left(S2 - R_1 \times \Theta_j - \frac{d_{i,1}}{2}, R_1 \times \Theta_j + \frac{d_{i,1}}{2}\right)$$

$$d_{i,1} < d_{i,2}$$

$$d_{i,1} > 0$$

$$d_{i,1} > 0$$

6.0 The optimisation proposed model

6.1 The concept of speed restriction

Once the "n" aircraft are in zone 1, after detection of the aircraft's type and ground speed, the algorithm calculates the estimate landing time t_i of the aircraft A_i by checking an aircraft performance database" (APD), which contains information concerning the performance of many aircraft' types such as base of aircraft data (BADA). Based on their touchdown estimates and performance, and in order to find the best permutation, the algorithm organises aircraft in a decreasing ranking: $p : j \to p(j)$, for $j \in \{1, 2, 3, \ldots, n\}$ the landing sequence number of $Ap(j)$ aircraft. So the order of aircraft goes as: $\{Ap(1), Ap(2), \ldots, Ap(n)\}$. Consequently $Ap(1)$ lands at: $t_1 = tp(1)$ and $Ap(2)$ might land from $t_2 = max(t_1 + 2min, tp(2))$. The runway is ready to receive $Ap(2)$ after $t_1 + 2min$, this separation takes into account the liberation of the runway and the longitudinal separation on final approach and so on for the rest $Ap(j)$.

6.2 The speed restriction algorithm (SRA)

We define $Ri = t_i - tp(i)$ as the aircraft $Ap(i)$ delay and i is the touchdown sequence number. It is clear that $R1 = 0$ as the aircraft $Ap(1)$ has no delay for landing.

Algorithm 2

Compute t_i for $i = 1, \ldots, n$
Find p
Compute $tp(i)$ for $i = 1, \ldots, n$
Compute the delay Ri for $i = 1, \ldots, n$

These delays Ri will be stored to be used later in comparison studies. These flown distances in the two arcs: $d_{i,1}$ and $d_{i,2}$ will be stored to be used later in comparison studies.

Algorithm 3

Compute t_i for $i = 1, \ldots, n$
Find p
Compute testi for $i = 1, \ldots, n$
Compute the delay Ri for $i = 1, \ldots, n$
Compute $d_{i,1}$ and $d_{i,2}$ according to function 1 for all $i = 1, \ldots, n$

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6.3 The concept of speed adjustments

In the previous sections, we used the stored speeds from the APD, but in practice, ATCos can modify aircraft' speeds in the approach area within approximately a range of $[-15\%; +15\%]$. If the aircraft A_i is the first to land and the aircraft A_j is the final one, the crew of A_i will be instructed to keep the highest speed they can do while the A_j crew will be instructed to reduce to the lowest feasible speed. The aircraft's type, weight, altitude and other factors affect its speed. In our proposed model, the stored speeds V_e, V_i and V_{app} will be modified of $[-10\%; +10\%]$ range. Compared with the FCFS model and the speed restriction model, the gain of this procedure is enormous. For an aircraft Ai, it might arrive before its estimate computed touchdown time by the radar (according to the stored speeds in the database APD). This will also decrease the delay; moreover, in some scenarios the aircraft will touchdown before their t_i (computed estimate touchdown time with speed restrictions).

6.4 Simulation

At a predetermined time, we will run our algorithm and generate the locations of randomised aircraft flying in from three areas (SIERA1, SIERA2, SIERA3). Randomly distributed speed profiles were generated.

A defined objective function to optimise and a particle-based study space are required in in order to use the PSO. The algorithm's goal is to relocate these particles to their optimal location. Any particle has:

- A location (i.e. particle coordinates).
- A velocity at which the particle can move: each particle shifts position across iterations. It navigates based on its best neighbour, best position and past position.
- A neighbourhood: a group of particles that directly influence a particle, particularly the one with the best criterion.

Every particle has instantaneously the knowledge of:

- Its best visited location. The determined criterion's value and its coordinates are essentially retained.
- The location of the swarm's ideal neighbour, as determined by the optimum sequencing.
- The provided value to the objective function since after iterations a required comparison between the value of the given criterion by the current particle and the ideal value are made.

6.5 The speed adjustment algorithm SAA

The new speed is calculated utilising this equation:

$$V_{k+1} = c_1 V_k + c_2(bestp - p) + c_3(bestv - p) \tag{7}$$

Where:

- V_{k+1} and V_k are the particle's speeds at iterations $k + 1$ and k.
- $bestp$ is the particle's best position.
- $bestv$ is the particle neighbourhood's best position at iteration k.
- p is the particle's position at iteration k.
- c_1: a constant or dynamic coefficient throughout iterations.
- c_2 and c_3: coefficients that are produced at random for each iteration.

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Using the calculated speed, the particle's future position can be identified as follow:

$$X_{k+1} = X_k + V_{k+1} \tag{8}$$

Where: X_k is the particle's position at iteration k. X_0 and V_0 are generated at the beginning of our algorithm. The computation of the percentages for each aircraft $Ap(i)$ for $i = 2, \ldots, n$ is a minimisation problem described as:

$$min|tvi(ai; bi; ci) - testvi| \tag{9}$$

Under constraints:

$$10\% \leq ai \leq 10\%$$

$$10\% \leq bi \leq 10\%$$

$$10\% \leq ci \leq 10\%$$

with:

$$tvi(ai; bi; ci) = \frac{A(p(i))}{(ai+1)V_{p(i);1}} + \frac{15}{(bi+1)V_{p(i);2}} + \frac{15}{(ci+1)V_{p(i);3}} + \frac{8}{V_{p(i);4}} + \frac{4}{V_{p(i);5}} \tag{10}$$

$$testvi = testv(i-1) + 2min. \tag{11}$$

6.6 Delay computation

In this section, the optimisation will intercede in the delay's calculation. The concept is identical to that of the earlier paragraphs. To obtain the permutation p, we will arrange aircraft in a performance descending sequence based on their estimates of touchdown.

$Ap(1)$ will be instructed to accelerate to the maximum possible speed, therefore 10% will be added to the recorded speeds in the aircraft performance database APD. After that, the touchdown estimates will be modified taking into account the condition: $testv1 < tp(1)$.

Then, to ensure that the aircraft $Ap(2)$ would land at: $testv2 \geq testv1 + 2min$, we will determine the speeds' percentages a, b and c in a 10%.

The same procedure will be repeated for each aircraft $Ap(i)$ respecting:

$$testvi \geq testv(i-1) + 2min$$

Algorithm 4

For each particle.
Initiate position.
Establish its best position p as its optimal position.
If $f(p) < f(g)$, we change the swarm's best position.
Initiate the particle's speed.
Until we reach the maximum iteration or a certain value of the criterion...
For each particle...
Randomly select C_2 and C_3...
Update the particle's speed using to the formula 13.
Update the position x_i.
If $f(x_i) < f(p_i)$,
Update the particle's best position.
If $f(p_i) < f(g)$, update to the swarm's best position.
g is the optimum.

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Algorithm 5

Calculate t_i for $i = 1, \ldots, n$
Find *p*.
Calculate *testi* by computing *ai*, *bi* and *ci* (minimising 154 . . .for $i = 1, \ldots, n$).
Calculate the delay/gain *Rvi* for $i = 1, \ldots, n$.
Calculate $d_{i,1}$ and $d_{i,2}$ in case of $Rvi > 0$ according to the problem 6. . .for $i = 1, \ldots, n$ taking into account the percentages *bi*, *ci*.

After that, we will calculate the aircraft $Ap(i)$ delay *Rvi* after the modifications of speed:

$$Rvi = testvi - tp(i) \quad if \quad Rvi > 0.$$

If not, *Rvi* stands for the aircraft's $Ap(i)$ gain. The associated speeds to the aircraft $Ap(i)$ are:

Algorithm 6

Compute t_i for $i = 1, \ldots, n$.
Find *p*.
Compute *testi* by Computing *ai*, *bi* and *ci* for $i = 1, \ldots, n$.
Compute the delay/gain *Rvi* for $i = 1, \ldots, n$.

$Vp(i); 1 = V_e$, $Vp(i); 2 = V_i$, $Vp(i); 3 = V_{app}$, $Vp(i); 4 = V_f$ and $Vp(i); 5 = V_{ar}$.
$A(p(i))$ is the position of the aircraft $Ap(i)$ in zone 1.
Distances computation
With the same concept in the past sections, to consume the delay in the arcs' path, while we shall consider the modified calculated speeds in the delay section, with:

$$fi(d_{i,1}; d_{i,2}) = \frac{d_{i,1}}{(bi + 1)Vp(i), 2} + \frac{d_{i,2}}{(ci + 1)Vp(i), 3} \tag{12}$$

bi and *ci* are the speeds' percentages of the aircraft $Ap(i)$ related in sequence with *Vi* and *Vapp*. *Rvi* is the aircraft $Ap(i)$ delay after speed adjustments. The new minimisation problem is:

$$min \sum_{i=2}^{n} |fi(d_{i,1}, d_{i,2}) - Rvi| \tag{13}$$

u.c:

$$d_{i,1} < S1 - R2 \times \Theta j$$

$$d_{i,2} < max\left(S2 - R_1 \times \Theta_j - \frac{d_{i,1}}{2}, R_1 \times \Theta_j + \frac{d_{i,1}}{2}\right)$$

$$d_{i,1} < d_{i,2}$$

$$d_{i,1} > 0$$

$$d_{i,1} > 0$$

7.0 Applications

In a decreasing performance order, we will arrange the aircraft to find the permutation *p*. Then, we will instruct the first aircraft $Ap(1)$ to accelerate to the maximum possible speed, after that we will add a 10% to its recorded speeds in the database APD.

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Table 1. *Four aircraft scenario application*

Aircraft A_i	A_1	A_2	A_3	A_4
Aircraft position	11	19	5	20
Associated zone (entrance side)	0	1	0	2
Touchdown estimates	0.2471	0.3420	0.3374	0.6036
Permutation P	A_1	A_3	A_2	A_4
Permutation Q	A_3	A_1	A_2	A_4
Touchdown estimates speed restriction	0.2471	0.3374	0.3714	0.6036
Touchdown estimates FCFS	0.3374	0.3714	0.4045	0.6036
Touchdown estimates speed adjustment	0.2313	0.3173	0.3513	0.5703
Delay speed restriction	0	0	0.0294	0
Delay speed adjustment	−0.0158	−0.0201	0.0093	−0.0333

Next step is updating the touchdown estimates with speeds' adjustments: $testv1 < tp(1)$.

Then we will proceed to the optimisation of the problem 15 to compute a, b and c the speeds' percentages within $a \pm 10\%$ interval so that the aircraft $Ap(2)$ might land at:

$testv2 > testv1 + 2min$. The same process for the remaining aircraft $Ap(i)$ will be repeated with the condition: $testvi > testv(i-1) + 2min$. Once done, Rvi the aircraft Ap(i) delay after speeds' adjustments will be computed as: $Rvi = testvi - tp(i)$. In the case where $Rvi > 0$, the crossed distances $d_i;_1$ and $d_i;_2$ respectively in the arcs $S1$ and $S2$ are computed for each aircraft $Ap(i)$ by minimising 23 under constraints 24 while incorporating the modified speeds.

7.1 Application for four aircraft ($n = 4$)

Table 1 description

- **A/ Aircraft** A_i: As a reference order, the descending order of speeds was chosen, with A_1 having the highest speed profile and A_4 having the lowest.
- **B/ Aircraft position**: Computing $A(i)$ the position aircraft Ai in a circle of $R3 = 30Nm$ which is the first zone with profile $V(i)$

A number ui has been selected at random within the interval [0;1] (uniform law) for each aircraft Ai

- If $ui < 1/3$, then A_i is inbound from zone SIERA1, we put $O(i) = 0$.
- If $1/3 \leq ui < 2/3$, the aircraft A_i is inbound from zone SIERA2, we put $O(i) = 1$.
- If $2/3 \leq ui \leq 1$, then A_i is inbound from zone SIERA3, we put $O(i) = 2$.
- **C/ Associated zone (entrance side)**: As a result of this draw, A_1 is inbound from zone SIERA1, A_2 from SIERA2, A_3 from SIERA1, and A_4 from SIERA3. In order to remember this data, we must store it in a vector O, where the value of $O(i)$ is either 0,1 or 2.
- **D/ Touchdown estimates**: Compute the touchdown estimates (in hours) for each A_i in the order of reference.
- **E/ Permutation p**: Determine the ideal permutation p to reduce the delay (touchdown number based on the sequencing concept).
- **F/ Permutation q**: Determine the permutation q (FCFS touchdown number).
- **G/ Touchdown estimates speed restriction**: Compute the estimated landing time testi based on the sequencing concept (speed restrictions) with ti associated with $Ap(i)$.

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Table 2. *Four aircraft scenario application percentages*

A_i/percentage	a	b	c
A_3	0.1	0.1	0.1
A_1	0.1	0.1	0.1
A_2	−0.1	−0.0557	0.0575
A_4	0.1	0.1	0.1

- **H/Touchdown estimates FCFS**: Compute the touchdown estimate time tf based on the FCFS concept with tfi associated with $Aq(i)$.
- **I/ Touchdown estimates speed adjustment**: Compute the touchdown estimate $testv$ based on the sequencing concept (speed adjusments) with $testvi$ associated with $Ap(i)$, by computing the percentages of modified speeds associated to $Ap(i)$ are:
- **J & K/ Touchdown estimates speed adjustment**: Delays computation for each $Ap(i)$, compute the delays Ri and Rvi (in hours) according to sequencing with speed restrictions and speed adjustments models.

Speed Modification:

In Tables 1 and 2 we found that the 10% addition to the speeds V_e, V_i and V_{app} (stored in the database) to the aircraft A_1 was applied, the same for A_3 and A_4. While for aircraft A_2, V_e was reduced by 10%, V_i was reduced by 5% and V_{app} was increased by 5%. The delays of the aircraft: A_1, A_3 and A_4 have been reduced to zero; on the other hand the aircraft A_2 has a delay of $R2 = 1min45s$. Sometimes, speed adjustments will allow us to land the aircraft before their estimated landing times, as for A_1, A_3, and A_4.

Cumulative delays:

Compare cumulative delays according to FCFS, sequencing with speed restriction and speed adjustments:

- $Rcf = 0.0469 \times 4 \times 60 = 11min15s$ (cumulative delay for FCFS).
- $Rcs = 0.0073 \times 4 \times 60 = 1min45s$ (delay with speed restrictions).
- $Rcv = -0.0150 \times 4 \times 60 = -3min36s$ (gain with speed adjustments).

The gain using sequencing with speed restriction is:

$$11min15s - 1min45s = 9min20min.$$

The gain using sequencing with speed adjustments is:

$$11min15s + 3min36s = 14min51s.$$

Flown and cumulative distances:

Aircraft are required to fly the maximum distance in the arc $S2(31.5NM)$. For the flown distances:
for the model with speed restrictions;
in the case where: $Ri \times V(p(i); 3) < 31.5$, all the distance $d_{i,1}$ will be run on $S2$.
in the case where: $Ri \times V(p(i); 3) \geq 31.5$, $d_{i,1} = 31.5$ will be run on $S2$ and the remained distance $d_{i,2}$ on $S1$ for the model with speed adjustments;
and the case where $Rvi \times (1 + ci)V(p(i); 3) < 31.5$: all the distance $d_{i,1}$ will be run on $S2$
and the case where $Rvi \times (1 + ci)V(p(i); 3) \geq 31.5$, $d_{i,1} = 31.5$ will be run on $S2$ and the remained distance $d_{i,2}$ on $S1$
where $V(p(i); 3)$ is the V_{app} of the aircraft $Ap(i)$ and (ci) is the percentage of the approaching speed $Ap(i)$ calculated by minimization.
Aircraft A_2 must cross $6.5Nm$ in the arc $S2$.
In the speed adjustments' model A_2 must cross $2Nm$ in the arc $S2$.

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Table 3. *Nine aircraft scenario application*

A	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
B	10	8	18	2	19	7	8	13	15
C	1	2	1	1	2	2	2	0	1
D	0.2841	0.3307	0.3171	0.2714	0.3793	0.3556	0.403	0.3552	0.5091
E	A_4	A_1	A_3	A_2	A_8	A_6	A_5	A_7	A_9
F	A_8	A_4	A_1	A_3	A_2	A_6	A_9	A_7	A_5
G	0.2714	0.3054	0.3394	0.3734	0.4414	0.4074	0.4754	0.5094	0.5434
H	0.3553	0.3892	0.4232	0.4572	0.4912	0.5252	0.5592	0.5932	0.6272
I	0.2079	0.2691	0.3031	0.3371	0.3711	0.435	0.5361	0.7148	0.9528
J	0	0.0213	0.0223	0.0427	0.0522	0.0857	0.0961	0.1063	0.0343
K	−0.063	−0.015	−0.014	0.0064	0.0158	0.0794	0.1568	0.3118	0.4438

Table 4. *Nine aircraft scenario application percentages*

A_i/percentage	a	b	c
A_8	0.1	0.1	0.1
A_4	0.1	0.1	0.1
A_1	0.1	0.0639	0.0619
A_3	−0.1	−0.0913	0.0748
A_2	−0.0834	−0.0625	0.0417
A_6	−0.1	−0.1	0.0999
A_9	−0.1	−0.1	−0.1
A_7	−0.1	−0.1	−0.0999
A_5	−0.1	−0.1	−0.0999

We will compare the distances accumulated by each principle:

- The cumulative distance in FCFS is 64.5*Nm*.
- The cumulative distance with speed restrictions is 6.4*Nm*.
- The cumulative distance with speed adjustments is 2.17*Nm*.

7.2 Application for nine aircraft (n = 9)

With the same process of the previous section for four aircraft, the sequencing algorithm with speed adjustments SAA provides remarkable results in comparison with the algorithms FCFS and sequencing with speed restrictions SRA for the first nine aircraft.

Tables 3 and 4 resume the obtained results with nine aircraft:

7.3 Application for thirty aircraft (n = 30)

In Mohammed the V airport TMA the instance arrival capacity does not usually exceed nine aircraft. In this section we are going to visualise the gain in the case of 30 aircraft on arrival partitioned in five groups: 4, 5, 6, 7 and 8 aircraft. (Other group partition is also possible.)

Cumulative distances as illustrated in Fig. 8:

- The DCF vector represents the cumulative distances using the (FCFS) concept.
- The DCS vector shows the cumulative distances using the speed restriction model SRA.

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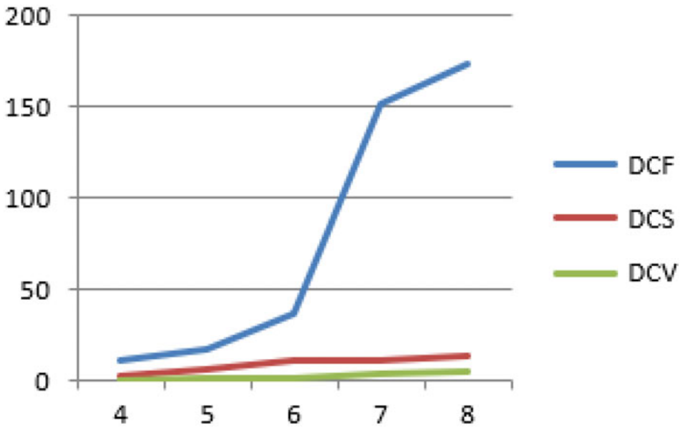

Figure 8. *Evolution of the cumulated distances in Nm.*

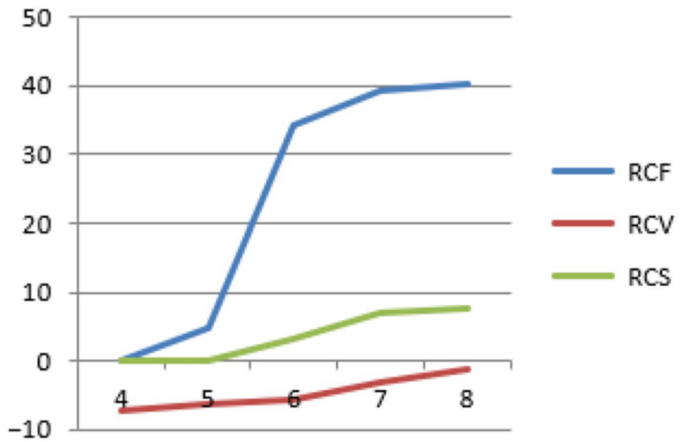

Figure 9. *Evolution of cumulated delays in min of 30 aircrafts.*

- The DCV vector shows the cumulative distances with the speed adjustment model SAA.

Cumulative delays as illustrated in Fig. 9:

- The RCF vector represents the cumulative delays using the (FCFS) concept.
- The RCS vector shows the cumulative delays using the speed restriction model SRA.
- The RCV vector shows the cumulative delays with the speed adjustment model SAA.

7.4 Graph interpretation

As shown in Table 5, the sum of the crossed distances by the 30 aircraft is:

- 388.7*NM* using the FCFS model.
- 43.5*NM* using the speed restriction model SRA.
- 11.1*NM* using the speed adjustment model SAA.

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Table 5. *Aircraft group cumulative distances*

Distance (NM)/aircraft number	4	5	6	7	8
DCF	10.4668	17.0411	36.9504	150.8617	173.4172
DCS	2.3720	6.251	10.5227	10.6193	13.8091
DCV	0	0.9285	1.5492	3.9913	4.6881

Table 6. *Aircraft group cumulative delays*

Distance (NM)/aircraft number	4	5	6	7	8
RCF	0	4.8976	34.3496	39.3388	40.2732
RCV	−7.1991	−6.2753	−5.5763	−2.9835	−1.2777
RCS	0	0	3.1589	6.8815	7.7576

- The cumulative distance using SRA is 2% of the cumulative distance using FCFS.
- The cumulative distance using SAA is 11% of the cumulative distance using FCFS.

As shown in Table 6, the sum of the delays crossed by the 30 aircraft is:

- $1h58min48s$ using the FCFS.
- $17min47s$ using the speed restriction model SRA.
- The sum of the gains is $23min18s$ using the speed adjustment model SAA. The application of SAA allowed us to save $2h22min6s$ compared to FCFS. The application of SRA allowed us to save $1h41min1s$ compared to the FCFS.

For our study case, the SAA algorithm is applicable for nine aircraft maximum at once due to the sum of the lengths of the two arcs, which is $94Nm$. To increase the capacity of the SAA, we suggested adding another arc and passing to $7NM$ longitudinal separation instead of 10NM to handle more aircraft.

8.0 Conclusion

The purpose of this work is to help ATCos establish efficient inbound traffic sequences with a real-time decision tool. This support permit increasing the TMA capacity and enhancing the ATM by lessening the ATCos' workload. Using real-time algorithms operating on the speed performance during the descent and approach phases, this tool proposes the maintain of a high level of safety while cutting down expenses.

The suggested approach offers outstanding outcomes and advantages that reduce costs in terms of flying time, flown distance, energy use and gas emissions.

The most successful method for reducing congestion for inbound traffic in the TMA is to efficiently control the flight profile and speed during the approach phase. However, there could be some other alternative approaches that can be used to better utilise the air resources and manage the air network.

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