EVALUATION OF OPERATIONS ON AN AIRPORT WITH A CIRCULAR RUNWAY

Dupeyrat M**, Aubry S****, Hesselink H***, Loth S*, Remiro A**, Schmollgruber P****, Verbeek R***, Welman C*****
***DLR, **ISDEFE, ***NLR, ****ONERA**

Keywords: *circular runway, airport concept, air traffic simulation*

Abstract

This paper presents an innovative concept for airport operations in the long-term future, based on a radically new airport design encompassing a circular circumventing runway. The Endless Runway project, mostly funded by the European Commission during the Framework Programme 7 (FP7), aims at evaluating the benefits and identifying the constraints associated to this kind of airport. The possibility to operate the airport whatever the wind direction and for every aircraft type, the optimization of air and ground aircraft trajectories through the use of the best runway section, as well as the compact airport footprint are part of the observed gains. Those must be balanced with the high runway construction cost, additional safety issues in gusty winds and the impossibility to extend the runway system if additional capacity is desired. A foreseen application could be a small airport dedicated to unmanned aircraft operations or a large hub airport with limited traffic mix and high reliability of operations.

1 General Introduction

One of the scenarios of the European Research Establishments in Aeronautics (EREA) Air Transport System (ATS) 2050 study [1], the Unlimited Skies scenario, imagines an explosive growth of air traffic. If this happened, the lack of capacity at airports would be a major constraint to growth, as recognized by ACARE, the Advisory Council for Aeronautics Research in Europe. Airports form already a major bottleneck in the air transport system. If nothing is done, part of the demand may not be accommodated.
Extending existing airports or building new ones might be a solution. However it usually faces the opposition of inhabitants and takes many years between the first identification of the need and the completion of the construction. For instance, making a runway longer to accommodate larger aircraft or departures if the runway was specialized for arrivals, adding a tangent runway to an existing runway system in order not to close the airport in high crosswind, extending the airport outside of its current limits, are all measures that may encounter the refusal of the local residents.

While airport capacity needs to be increased, authorities ask for optimised trajectories in order to reduce fuel consumption, emissions and possibly noise. Current aircraft routes based on standard procedures in the departure and approach phases are far from being direct: an aircraft flying from Toulouse-Blagnac to Paris-Orly, on a day of Autan wind (coming from the south east), will take off facing the wind from runway 14L or 14R almost in the opposite direction of its destination.

In order to tackle the airport network capacity limitation and the efficiency requirement, an alternative design to current airports is proposed: a circular runway concept. The main underlying idea is to operate the runway in any direction safely whatever the wind direction, with any aircraft category, including those with long take-off and landing rolls.

Circular runways were actually considered since the very beginning of aviation. Clément Ader in

France started with a first circular take-off at the end of the 19th century. All along the 20th century, engineers submitted articles, reports and patents related to circular runway concepts. In the middle of the 1960s, flight trials with takeoffs and landings were even undertaken by U.S. army pilots on a circular car track in Arizona. Despite the foreseen benefits, the concept was abandoned after the 1960s due to the need for new navigation and guidance techniques and to the high building cost. In the light of new technologies and considering additional constraints on airports, it appeared relevant to give a new look at this concept at the dawn of the 21th century. This is the objective of *The Endless Runway* project, a European FP7 project led by research organizations (NLR, DLR, ILOT, INTA and ONERA) from 2012 to 2014.

2 Flying to and from a circular runway

The project objective is to define two concepts of airports with circular runways: one for a hub and one for a seasonal airport. In both cases, the geometrical properties of the runway are identical.

The runway inner radius is set to 1500 meters. Thus the total runway length, of about 10 000 meters, is long enough to operate several aircraft simultaneously on the runway and to build airport infrastructures inside, while keeping the airport compact.

The runway width that can be used by aircraft is set to 140 meters as a compromise between discomfort due to higher centripetal acceleration for a narrower runway and the cost of a wider runway.

In order to limit the effects of the centripetal force, the circular runway lateral profile is banked with increasing angles from inwards to outwards, as shown on Fig. 1. In this manner, it is possible not to have lateral friction between the aircraft tires and the runway surface at all. As the aircraft accelerates to take off, it moves from the flat inner part of the runway towards the outer banked part until it reaches the lateral position on the runway whose bank angle fits its lift-off speed. The same applies the other way around during landing.

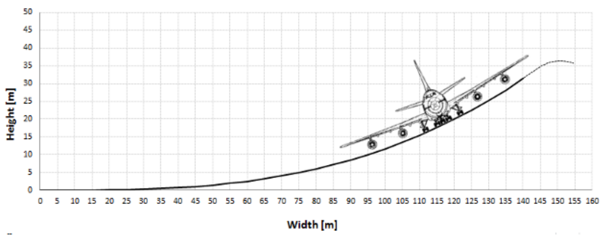

Fig. 1. Runway profile

It is possible to make takeoffs and landings on a runway with this geometry, even with old and heavy aircraft like a B747. However simulations indicate that take-off and landing distances are increased by 8 % and 12 % respectively compared to a straight flat runway. The roll angle after take-off will reach 30°, and 25° before touchdown for aircraft with high take-off and landing speeds. The distance between aircraft elements like the engines or the wingtips and the ground is reduced compared to a flat runway, and finally passengers experience a lateral acceleration up to 1 $m.s^{-2}$, which is acceptable compared to the limit commonly accepted in rail transportation in bend set to 1.2 $m.s^{-2}$ [2].

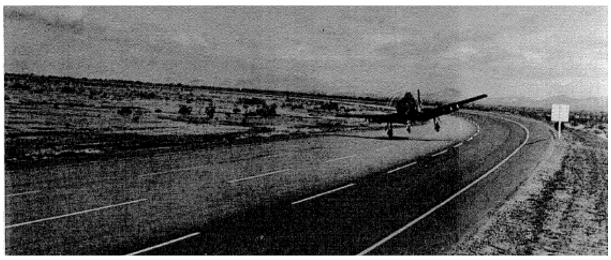

Fig. 2. Flight trial on General Motors track, Arizona, 1964-1965

Former pilots' experience in 1964 and 1965 states that at first it was difficult to land with the correct roll angle and on the speed circle corresponding to the landing speed. However, pilots reported that the bank of the runway tended to correct piloting errors. Aids such as a marking on the runway helped them for positioning (see Fig. 2). Of course, current satellite navigation and guidance means take these obstacles away. In order to remove manual piloting uncertainties and to allow the operations in low visibility conditions, automated operations for aircraft willing to operate on the circular runway is mandatory for a broad application.

3 A new aircraft adapted to operations on a circular runway

As the Endless Runway project proposes a radical new layout for the airport, additional studies defined an Endless Runway Aircraft Concept (ERAC) that is optimized for operations on such circular runway.

As for any aircraft design study, the first step consists in defining the mission to be performed by ERAC. To evaluate its take-off and landing performance against the ones of the B747-100, the respective reference missions should be relatively similar. Nevertheless, because of economic changes over decades, the requirements of the mission evolve. Thus, the classification of the B747-100 as "large aircraft" in the 1960's wouldn't be valid in 2050 for the ERAC entry into service. For this reason, it is decided to specify the ERAC mission based on the one of the B777-300.

The seating capacity is fixed to 450 passengers divided into 2 classes while the design range is set to 8000 NM (similar to the B777-300 Extended Range) to be consistent with the "large aircraft" category specified in [2]. From the operations point of view, the cruise speed is established to Mach 0.8 (reduced speed for improved environmental impact) and the initial cruise altitude to 33 000 ft.

Initial studies regarding operations of a conventional aircraft on the banked runway provided some guidelines [3] for the ERAC configuration. First, the aircraft wingspan and the engine position must be carefully selected to avoid ground clearance issues. Secondly, to facilitate operations on this kind of runway, the main landing gear track must be as wide as possible to increase the aircraft ground stability. Finally, handling qualities at low speed must be increased to smooth the take-off and landing phases.

Following these main requirements, the design team qualitatively assessed several architectures, starting from conventional ones to bi-fuselage options and blended wing bodies. After several iterations, the designers converged to the configuration illustrated in Fig. 3.

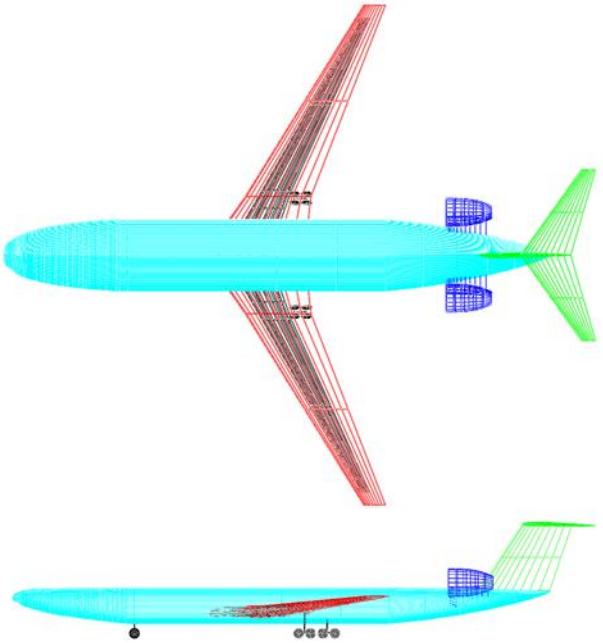

Fig. 3. Plan views of ERAC

The key features of this concept are:

- A double bubble fuselage (concept introduced in [4]) allowing a larger landing gear track;
- A low wing with a span no greater than 65 meters;
- A localization of the engines in the rear zone of the fuselage to avoid ground clearance issues and a large lever arm in case of an engine failure;
- A classical T-Tail empennage related to the engine position;
- Larger control surfaces with respect to current civil transport aircraft.

Once the configuration was frozen, the next step consisted in sizing the complete aircraft. To this end, a conventional statistical analysis [5] has been combined with the method presented by Jenkinson in [6]. In parallel, a constraints' analysis has been carried out in order to find out the most suitable thrust-to-weight ratio for ERAC knowing that the banked runway degrades take-off performances. In the end, the overall sizing process converged to an aircraft concept with a take-off weight of 266 tons equipped with two engines providing each a maximum thrust of 416.5 kN (at sea level). Subsequently, the design team performed a refined aerodynamic analysis with various tools ([7][8]) to both confirm the hypothesis made during the sizing and determine all necessary coefficients to perform the ERAC simulations in FlightGear ([9]). As a complement, inertia assessments of ERAC have been done with OpenVSP ([10]).

Based on the same approach as for the B747 [11], ERAC simulations have been performed manually, following as closely as possible the ideal ground trajectory (Fig. 4).

Fig. 4. ERAC flight simulations with FlightGear

The evaluation of various takeoffs and landings with FlighGear confirmed that ERAC allows safer operations on the runway because of its better controllability and higher ground clearance. From a performance point of view, the take-off distance in the nominal case (all engines operative) is reduced by about 21 % when compared to the one of the B747-100 on the same circular runway. This gain is clearly the result of the high thrust-to-weight ratio (0.32) of ERAC. For the landing distance, the measured value does not change significantly as expected (ERAC and the B747-100 have a similar wing loading).

As a conclusion for aircraft aspects, conceptual level simulations with FlightGear indicated the possibility to take off and land on a circular runway with a conventional aircraft [3]. Through the design of ERAC, the consortium showed that a tailored aircraft concept could significantly reduce the risk and increase performance for operations on *the Endless Runway* concept. However, the peculiar shape of the runway is a stringent constraint for the aircraft configuration and it is notably opposed to current trends regarding future aircraft concepts that have been proposed in recent studies, like the blended wing body [2].

4 A compact and well-connected airport

Based on former (expired) circular runway patents and on a broad knowledge of airport design, a selection took place to choose the best layout for a hub and a seasonal airport ([12] and [13]). Most facilities for aircraft, passengers, baggage, freight, airport operator and ATC are located inside the circular runway.

The dimensioning of the Endless Runway hub airport was done considering 61 million of annual passengers, which is the current Paris Charles de Gaulle figure. Its top view is presented on Fig. 5.

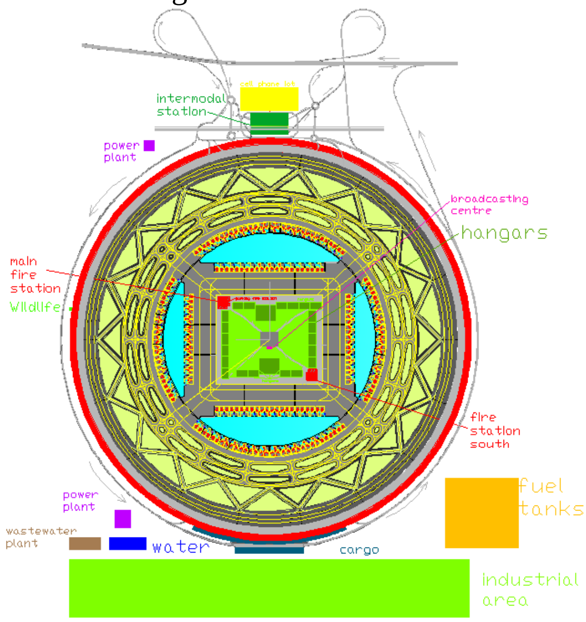

Fig. 5. The Endless Runway hub airport layout

The 1500 meters radius runway offers 18 runway exits and 18 runway entries, as justified in the ATM section. One multi-story car park can be located under the hump of the runway (Fig. 6) to optimize the use of the runway volume.

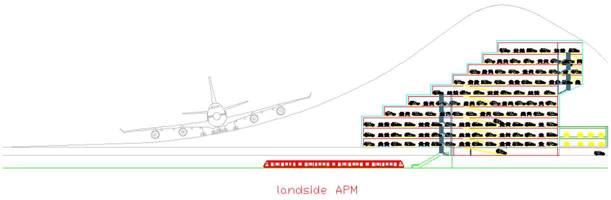

Fig. 6. Parking lots located under the hump of the runway

As depicted on Fig. 7, the taxiway system consists of an outer and an inner taxiway ring between the runway and the terminals area. The outer taxiway, operated in the same direction(s) as the runway, is connected to 18 runway access points through 36 high-speed exit taxiways, where one aircraft can hold if needed. The inner taxiway is operated in the opposite direction to the outer one. Taxiways between the airport's buildings link the inner circular ring to the inner airfield area. Finally, a dual taxiway system is available on the inner part of the terminals. This taxiway design aims at avoiding bottlenecks and at providing a short routing between the aircraft stands and the runway entry or exit point.

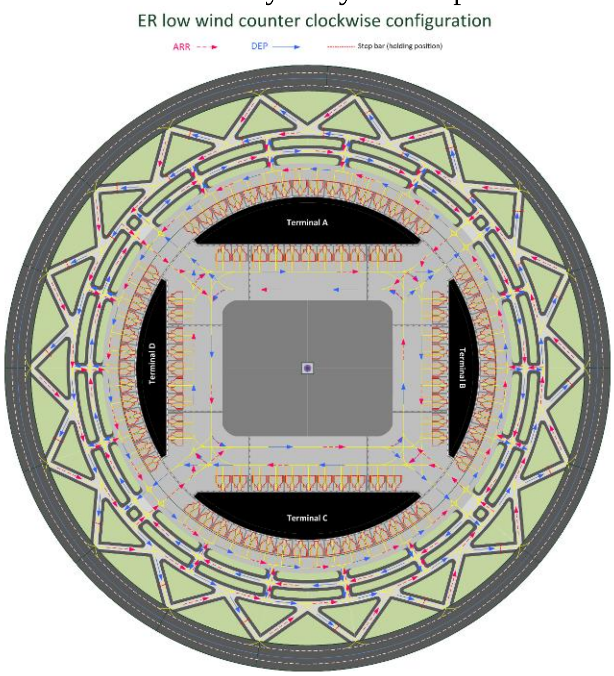

Fig. 7. Endless Runway runway and taxiways

One to four terminals with connected generic gates called Multi-Aircraft Ramp Systems (MARS) can be built depending on the airport category (hub or seasonal), with additional remote stands in the latter case. The number of stands depends on the aircraft categories operating on the airport: 99 positions are available for wide-body aircraft or 198 for narrow-body aircraft, or a certain number in between if both are mixed. Additional remote stands should be added in the central area to accommodate all wide-body aircraft in peak hours. This can be compared with Paris Charles de Gaulle 450 available stands.

Access from the outside to the inside facilities is provided to employees and suppliers through tunnels passing under the runway, and to passengers through an APM (Automated People Mover) connecting the main terminal to the intermodal station located outside and to the under-runway parking lots.

Terminals are interconnected through an APM tube for the transfer of the passengers between the terminals (see Fig. 8).

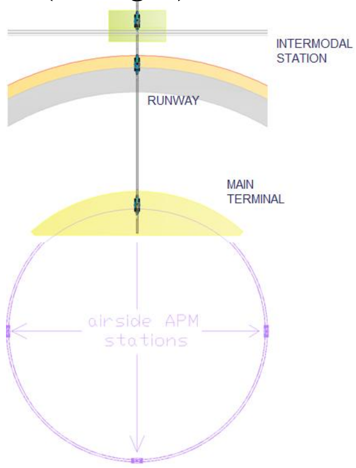

Fig. 8. Endless Runway APM lines and stations

The design of *the Endless Runway* hub airport appears to be compact when compared to a hub airport like Paris Charles de Gaulle (Fig. 9). It represents about 36 % of its surface. On the other hand, the surface of an *Endless Runway* seasonal airport is 26 % higher than the Palma de Mallorca airport used as reference. This can be explained by the unused space in the inner area of *the Endless Runway* seasonal airport, as only one terminal would be necessary to accommodate the passengers, and by the length of the runway itself, which is equivalent to three runways where Palma de Mallorca only has two.

Fig. 9. Impression of an Endless Runway airport footprint overlaid at Paris CdG

As a conclusion regarding the airport design, *the Endless Runway* hub airport's main advantage for both passengers and aircraft is its compactness, which also has its drawbacks: the impossibility to extend the runway to cope with increasing traffic demand and to add new facilities in the inner area (such as additional stands). Moreover, as will be discussed later in the cost-benefit assessment, the cost of construction of such a wide and high circular runway is prohibitive since about 30 million m^3 of raw material should be brought in.

5 Flexible and optimized operations

From the Air Traffic Management (ATM) perspective, the circular runway is seen split in contiguous segments [14]: an aircraft will use a set of contiguous runway segments for take-off and landing, and several aircraft will be authorized to use distinct runway strips simultaneously. With a lower number of segments, unnecessary parts of the runway might be blocked. With a higher number of segments, flexibility is increased as the required runway strip can be optimized based on the required landing and take-off distances. On the other hand a high number of segments leads to more infrastructural, coordination and calculation needs. Analyses have shown that 18 segments is a good tradeoff between flexibility, coordination effort and infrastructure[1]. With an inner runway radius of 1500 meters and 18 segments, the length of one segment is about 550 meters (see Fig. 10). The positioning of entry and exit taxiways at each segment start and end correlates very well with the recommendations given by runway design manuals[2].

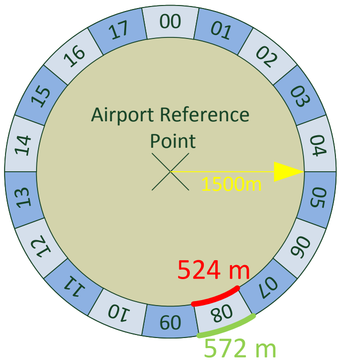

Fig. 10. Runway segments

In correlation with the 18 runway segments, arrival and departure routes have been defined. Departure routes start at the end of the respective runway segment climbing straight out to a height of 5000 feet with an angle of 5°. Arrival routes end at the beginning of a runway segment with a straight path coming from a height of 3000 feet and a glide path angle of 3°. The starting point of the arrival routes and the end point of the departure routes are indicated by TMA (Terminal Manoeuvring Area) entry and exit points. Fig. 11 shows a plan view of the TMA routes network with the circular runway in the middle, and Fig. 12 shows their vertical profile.

---

[1] In the analyses, flight delays have been compared in scenarios with different numbers of segments. It was observed that more than 18 segments did not reduce delays significantly.

[2] Runway exits should be located every 450 to 600 m for a busy 3500 m runway.[13]

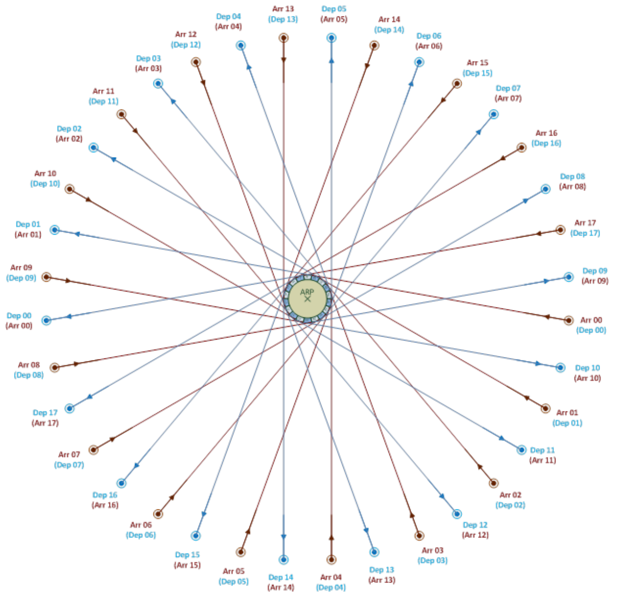

Fig. 11. TMA layout (top view)

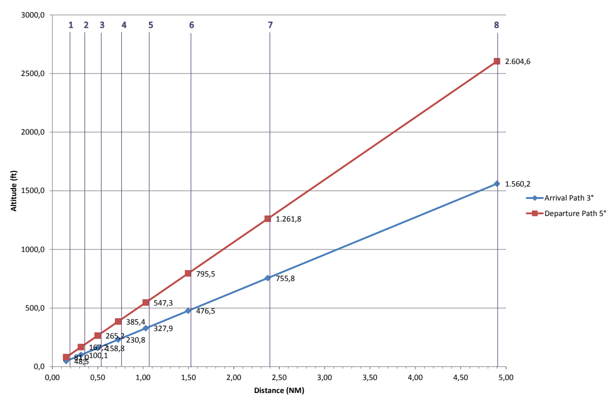

Fig. 12. TMA routes (vertical view)

As the runway can be operated in both directions (clockwise and counterclockwise), the vertical route structure is dynamic. When the direction of operations changes, the departure route of a segment becomes an arrival route and the height of the entry/exit points changes accordingly.

The lateral separation in the TMA is set to 1.5 NM for aircraft using different routes, half the current value. When using the same route the separation is kept at today's radar separation rules. As a consequence, aircraft are laterally separated when entering/leaving the TMA. Up to about 5 NM from the runway, aircraft are vertically separated by 1000 feet thanks to the TMA routes geometry. Closer to the runway, separation is done by the planning and controlling tools. On the runway itself, both a time separation and a distance separation are applied to the aircraft, depending on their wake category and their roll length.

In operation, a distinction has been made between two wind scenarios. If the wind exceeds 20 kt, aircraft must avoid segments with high crosswind during take-off and landing, therefore the number of possible segments is limited. In these conditions, aircraft will fly in two streams towards *the Endless Runway* to allow landing at the touchdown point where crosswind is minimum (close as possible to headwind, see Fig. 13).

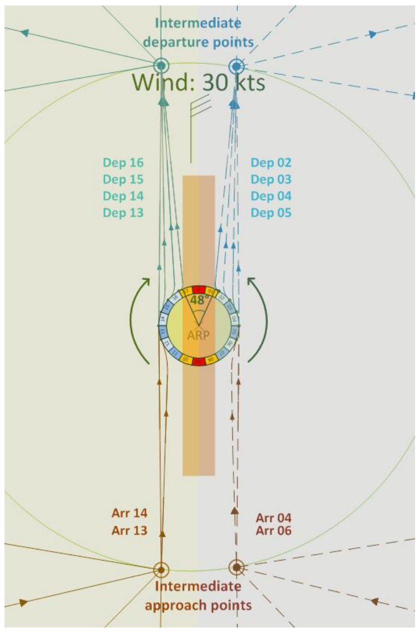

Fig. 13. Operations in strong wind conditions

Traffic flows must be directed towards the operational lift-off and touchdown points. The high wind scenario is similar to operating two parallel independent runways, with a capacity estimated to 80 movements per hour.

In low wind conditions (speed below 20 kt), aircraft can be operated in a flexible manner as all segments are available for take-off and landing, as presented in Fig. 14.

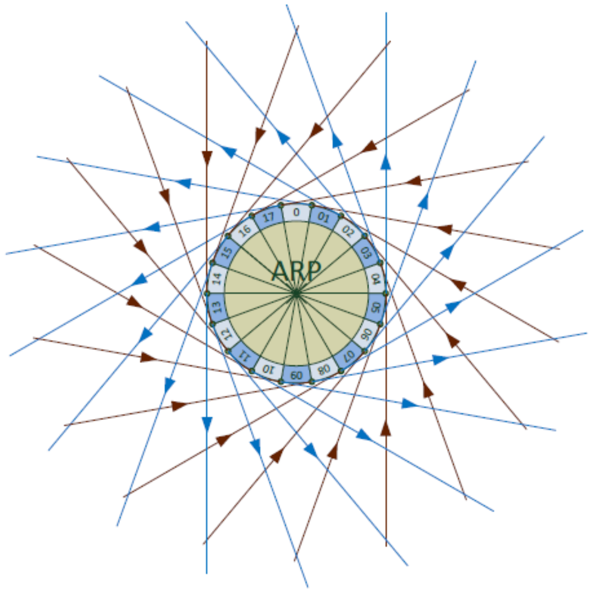

Fig. 14. Flexible sequencing of aircraft on the Endless Runway

Simulations have focused on the low wind scenario as it is expected to be the more demanding and challenging one. A simulation framework has been set up looking for the runway itself, the TMA and the ground [15]. The following paragraphs detail each part of it.

Runway simulation

A runway scheduling algorithm was developed and used in order to generate a conflict-free traffic scenario. Based on real traffic data of a busy day at Charles de Gaulle airport, contiguous *Endless Runway* segments are booked for an aircraft during a given time. The requested segments are deduced from the origin and destination airports of the respective flights by looking for the segment providing the shortest flight distance.

Then, the Runway Scheduler performs a "first-come, first-served" sequencing: each departure and arrival is used to generate a demand, sorted using the desired take-off or landing time on the runway. Depending on the aircraft type, the roll length is computed using the Eurocontrol Base of Aircraft Data (BADA) [16] modelling. A safety margin is added to this length, which gives the total number of segments to be booked by each aircraft.

If the requested segments are available at the requested time, they are booked. Otherwise, the scheduler looks for another part of the runway where the same number of segments is available. In the worst case, it waits for the earliest time slot when such a number of segments are freed up.

When booking the segments, the Runway Scheduler takes into account the constraints related to the aircraft wake categories, based on the ICAO wake turbulence separation minima. For instance, it prevents a light aircraft from immediately following a heavy one by waiting 3 minutes.

The generated traffic file shows the requested timeslots for a given section of the runway and the attributed one, and computes the delay. The following table (**Erreur ! Source du renvoi introuvable.**) is an extraction of the output of the Runway Scheduler.

It is possible to have a graphical view of the runway segments reservation over time [17]. Fig. 16 is a radial view, which shows the segments booking from the simulation start (center) to the end (edges). The blue boxes represent the departures, the orange ones the arrivals, with a green line as the boundary of the first booked segment and a red line as the end of the last booked segment.

Type	ICAO Code	Callsign	Departure airport	Arrival airport	Wake category	Aircraft bearing (°)	Number segments (including buffer)	Booking duration (s)	First requested segment	Last requested segment	Requested booking start	First booked segment	Last booked segment	Effective booking start	Delay (s)	Comment
ARRIVAL	A318	AFR1423	EDDM	**LFPG ER**	M	253	4	54	0	15	08:59:07	9	6	08:59:40	33	Follows AFR3539. Wake turbulence (H, M): 3 min
DEPARTURE	A320	AF782UM	**LFPG ER**	LFBO	M	187	5	88	17	13	09:00:50	1	15	09:00:50	0	Shifted from 17 to 1 (2-segment shifting).
ARRIVAL	B744	AFR349	CYUL	**LFPG ER**	H	101	5	59	11	7	09:01:24	11	7	09:01:24	0	Request granted without modification
DEPARTURE	A321	BAW307	**LFPG ER**	EGLL	M	72	6	87	12	7	09:01:50	17	12	09:02:18	28	Follows AF782UM

Fig. 15. Sequencing of traffic demand on the Endless Runway

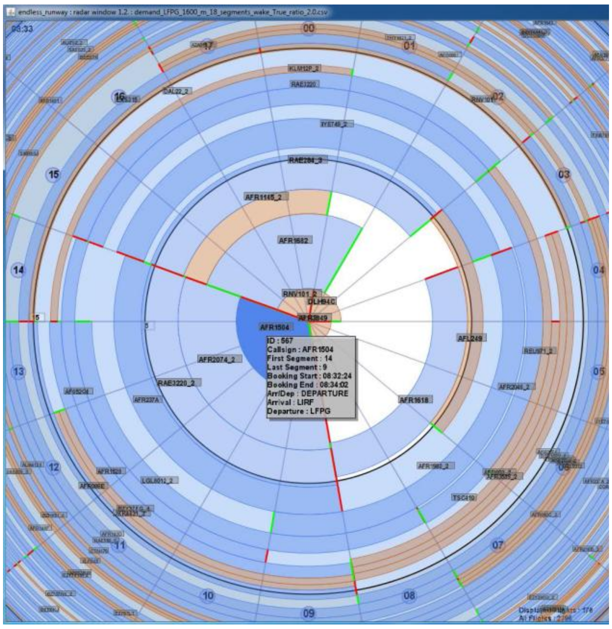

Fig. 16. Runway booked segments along time

In addition to the real traffic file which was defined as the 1.0 scenario, scenarios with traffic increased by 50% and 100%, named respectively scenario 1.5 and scenario 2.0, were built to identify the limit in terms of capacity. Of course, delay comes into consideration, as shown in Fig. 17. From that perspective, the 110 % demand is the maximum that can be tolerated for the sake of the quality of service.

Traffic ratio	Number of flights	Max fligts per hour	Average delay with wake rule (h:min:s)	Max delay with wake rule (h:min:s)
100.0%	1570	110	00:00:21	00:04:16
110.0%	1727	121	00:00:33	00:07:18
120.0%	1887	127	00:01:16	00:09:23
130.0%	2042	131	00:03:41	00:20:11
140.0%	2198	146	00:12:53	00:41:58
150.0%	2365	150	00:27:31	01:04:09
200.0%	3140	179	02:37:43	05:11:33

Fig. 17. Runway delay for various traffic demands

TMA simulation

The TMA simulation used the traffic files provided by the runway scheduler. The 1.0 traffic demand already showed a high number of conflicts especially between arriving and departing flights (see Fig. 18).

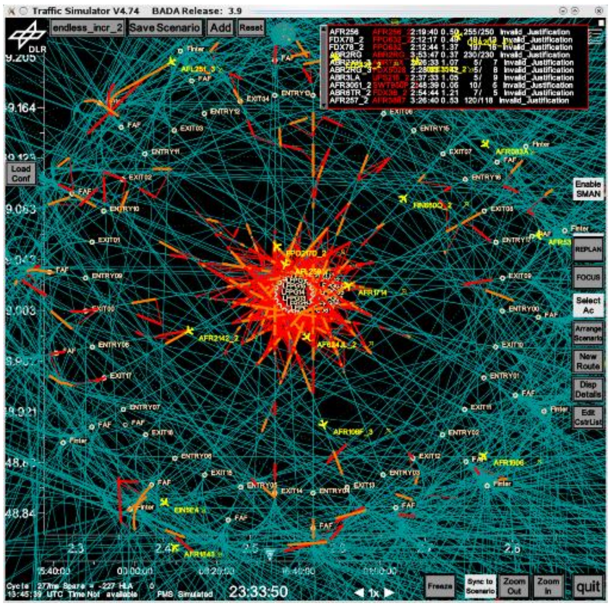

Fig. 18. Conflicting flights in the TMA

This result indicated that the TMA could not handle all the traffic. Each conflict was analyzed and the most disturbing flights deleted[3]. With this pragmatic approach a TMA conflict-free scenario was produced but the number of handled flights decreased, having a direct impact on the capacity of the system. The following results have been obtained from the simulations.

Traffic ratio	Demand	Runway	TMA
Scenario 1.0	110	110	87
Scenario 1.5	177	148	102
Scenario 2.0	222	160	111

Fig. 19. Accommodated number of flights on the runway and in the TMA

The maximum number of flights that can be handled is heavily dependent on the traffic mix and on the requested segments (aircraft direction). Therefore there is no direct correlation between the maximum demand figure and the maximum achievable capacity. In the 1.0 scenario the runway is capable of handling the traffic, not the TMA. A 1.5 or more demand cannot be handled by the runway either.

[3] Some of the flights cause more than one conflict. Therefore deleting one flight may lead to the elimination of more conflicts

Ground simulation

The ground simulation focused on the 1.0 traffic scenario as higher demands were not relevant as shown by the runway and TMA simulations. Running the ground simulation using DDR (Demand Data Repository) data from Eurocontrol[4] to simulate the turnaround (connection of arrival and departure flights), a stand availability problem was recognized. Due to the high number of heavy aircraft during peak hours, the Multi-Aircraft Ramp Systems approach (two mediums or one heavy) was brought to the limits as the number of stands was not sufficient. Besides this the long turnaround durations have another negative effect. With the given traffic scenario the simulation could not be run as aircraft were blocking taxiways waiting for available stands (deadlock situations). To get an indication of whether the taxiway system itself could also limit the ground capacity, an alternate approach was taken. All heavy aircraft were redefined to medium size and the simulation was run again[5]. The success of this new run demonstrated that the taxiway system is not limiting.

In conclusion, Paris Charles de Gaulle has a declared capacity[6] of 115 movements per hour on a configuration of four parallel runways, while simulations have shown that *the Endless Runway*, whose length is equivalent to three long straight runways, can accommodate about 87 aircraft per hour in the low wind case, and 80 movements per hour in the high wind case. This lower performance in terms of capacity must be counterbalanced with the efficiency figures exposed below.

In fact, thanks to the route network exposed above and to more direct routes in the TMA, the average flight distance can be reduced by 1 % to 2 % based on an average 700NM flight. Then, thanks to the taxiway exits, taxiway and apron layout, taxi times are 40 % to 95 % of the taxi times observed on a conventional hub airport [18]. Finally, the runway entry taxiways location permits to avoid holding for runway crossings, which saves another one or two minutes on the taxi time. Flight times and distances are thus reduced, which has a positive impact in terms of fuel consumption and cost and associated emissions.

6 Noise Impact

An assessment has been made concerning the impact that *the Endless Runway* would have on societal aspects as noise. From the proposed arrival and departure routes, it is clear that the airport will generate noise in any possible direction. A calculation has been made using the Integrated Noise Model (INM) software, where traffic on the busiest day Paris Charles de Gaulle has been used to determine the noise impact over the year. The accumulated noise is corrected for the total number of flights in 2013 (472,000 movements) as the busiest day multiplied with 365 would give about 20 % more movements than actually realized in 2013. In this manner, a comparison between the noise contours of *the Endless Runway* (Fig. 20), and the actual noise contours of Paris Charles de Gaulle in 2013 (Fig. 21) can be made. Noise is indicated in L_{den} (Level day-evening-night), the standard European noise metric for measuring noise around airports.

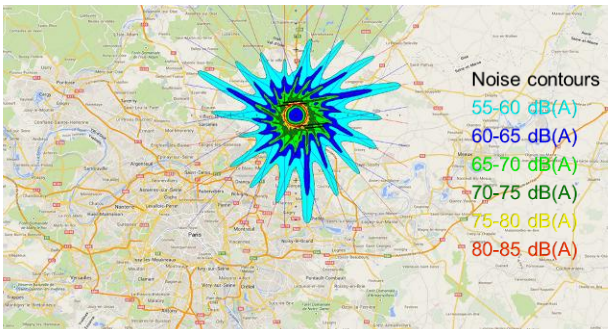

Fig. 20. INM noise contours for the Endless Runway airport

[4] The available data were not always sufficient to identify flight pairs directly. Some logical algorithms were put in place to find as much correlations as possible.

[5] It was considered, that the taxi behavior of heavy and medium aircraft are slightly different only.

[6] Declared capacity concerns the number of movements that is used for planning purposes; the actual number of movements may be slightly higher or lower because of traffic mix (aircraft separation) and operational use of the airspace around the airport.

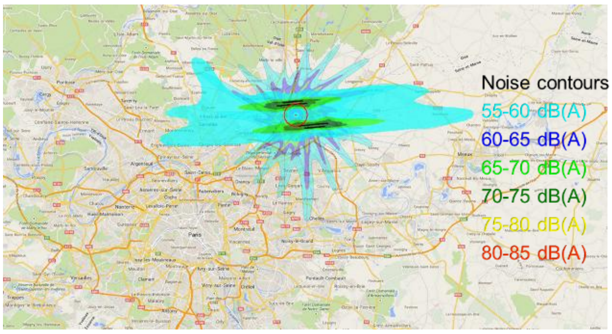

Fig. 21. Noise contours comparison between The Endless Runway and Paris Charles de Gaulle airports

For the comparison of the two airports (*the Endless Runway* vs. the 2013 Paris Charles de Gaulle scenario), precautions must be taken as the location of the current Paris Charles de Gaulle airport and runways was decided in consideration with the environment and surrounding communities. Therefore, highly populated areas appear affected by *the Endless Runway* airport, which would normally be built further from the agglomeration. The question behind those contours maps is whether more people would accept to be impacted by the airport noise nuisances but with less frequency, or whether they prefer to know exactly where the corridors are, with strong nuisances for the population below. Several discussions with local residents lead to the conclusion that the second option is preferable in dense areas, but no hint is given for remote airports.
Finally, regarding ground airport noise, the height of the runway should avoid it to spread outside of its boundary.

7 Cost benefit analysis

A cost analysis was done based on a basic cost model, developed in [18], which distinguishes several cost factors. Estimations had to be made, like the cost of constructing the banked runway. Fig. 22 compares the costs between a standard airport and a minimum and a maximum estimate for the Endless Runway airport.

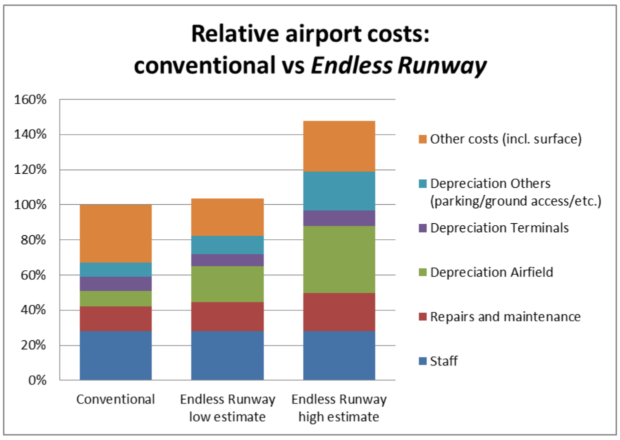

Fig. 22. Relative airport development costs

It appears that an Endless Runway airport would be between 1.1 and 1.6 times more expensive than a conventional one.

On the benefits side, smaller ground acquisition costs due to the compactness of the infrastructure (36 % of Paris Charles de Gaulle), and shorter flying and taxi times leading to more efficient flights and less fuel consumption are in favor of *the Endless Runway* concept.

Conclusion

In this paper, a concept for operating a circular runway has been evaluated from various perspectives: the aircraft, the airport, and the operations. *The Endless Runway* has proven to be a feasible concept at least in the nominal conditions studied in the project timeframe, even though some particular aspects should be further studied (amongst others: flight dynamics near the runway especially in gusty conditions, safety procedures in case of go-around, accurate navigation systems usable for circular landings). The main benefits of circular airports are their compactness and the reduction of ground and air trajectories, but they must be balanced with a moderate capacity, a high construction cost, a lack of flexibility in the inner infrastructure and the impossibility to operate some future aircraft configurations (like the blended wing body). In the course of the project, focus was made on hub airports, however, with these findings, it appears that circular airports could find a better application in the long term for RPAS airports with a small radius (for example 400 meters), little infrastructure in the middle and less constraint on the maximum tolerable lateral acceleration, or for large hub airports where arrival and departure streams are more uniform and separated, making best use of the route network structure through less conflicts ([18]).

Acknowledgements

The authors would like to thank:

- The European Commission for the financial support of the Endless Runway Project, contract N°308292, and the European Commission scientific project officer I. Konaktchiev for his encouragement through the project;
- A. De Giuseppe for his work regarding the conceptual design of ERAC during his internship at ONERA;
- G. de Witt for his work on the landing roll analysis during his internship at NLR.

References

References [2], [11], [12], [13], [14], [15] and [18] are freely accessible under the Endless Runway project website: http://www.endlessrunway-project.eu/documents/index.php.

[1] Lamiscarre B, Hermetz J, Le Tallec C, Brunet M, Joulia A, Chaboud T. *ATS 2050 phase 1: Research paths for a viable air transport system in 2050*. ONERA, 2010.

[2] Dupeyrat M, Aubry S, Schmollgruber P, Remiro A, Loth S, Vega Ramirez M, Hesselink H, Verbeek R, Nibourg J. *D1.2 The Endless Runway State of the Art, runway and airport design, ATM procedures and aircraft*, version 2.0, November 2011.

[3] Hesselink H, Loth S, Dupeyrat M, Aubry S, Schmollgruber P, Vega Ramirez M and Remiro Bellostas A. Innovative Airport and ATM Concept (Operating an Endless Runway), CEAS 4th Air & Space conference, Sweden.

[4] Greitzer E. M., Slater H. N. , *The MIT, Aurora Flight Sciences and Pratt&Whitney Team, Volume 1: N+3 Aircraft Concept Designs and Trade Studies*, 2010.

[5] Roskam J., *Airplane Design: Part I Preliminary Sizing of Airplanes*, Darcorporation, 1985.

[6] Jenkinson L. R., Simpkin P., Rhodes D., *Civil Jet Aircraft Design*, 1999.

[7] AVL website: http://web.mit.edu/drela/Public/web/avl/.

[8] W.H. Mason, Software for Aerodynamics and Aircraft Design website: http://www.dept.aoe.vt.edu/~mason/Mason_f/MRsoft.html#SkinFriction, Virginia Tech.

[9] FlightGear Flight Simulator website: http://www.flightgear.org.

[10] OpenVSP parametric aircraft geometry tool website: http://www.openvsp.org, NASA.

[11] Schmollgruber P, De Giuseppe A, and Dupeyrat M. *D3.2 The Endless Runway Aircraft Aspects*, version 1.0, September 2013.

[12] Hesselink H, Verbeek R, Welman C, Dupeyrat M, Schmollgruber P, Aubry S, Loth S, Remiro A, Vega Ramirez M. *D1.3 The Endless Runway concept description: High-level overview*, version 2.0, December 2012.

[13] Remiro A, Welman C. *D2.2 The Endless Runway Airport Infrastructure*, version 1.0, September 2013

[14] Loth S, Dupeyrat M, Hesselink H and Verbeek R. *D4.2 The Endless Runway ATM Operational Concept*, version 1.0, June 2013.

[15] Loth S, Dupeyrat M, Hesselink H and Verbeek R. *D4.3 Simulation of the Endless Runway: Modeling and Analyses*, version 2.0, September 2013.

[16] Eurocontrol, User manual for the base of aircraft data (BADA) Revision 3.9, EEC Technical/Scientific Report No. 11/03/08-08, 2011, http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html.

[17] Urban, Beate und Rudolph, Florian, Helm, S. Michaela. Development of an HMI to Monitor and Predict Passenger Progress in the Landside Process Chain for a Holistic Airport Management. *Deutscher Luft- und Raumfahrtkongress 2012,* Berlin, Proceedings, pp 62, 2013.

[18] Hesselink H. *D5.2 Assessment of the Endless Runway*, version 1.0, January 2014.

8 Contact Author Email Address

maud.dupeyrat@onera.fr

Copyright Statement