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# Innovative Airport and ATM Concept (Operating an Endless Runway)

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## Abstract

*This paper presents an innovative and radical new concept for future airport operations, consisting of an airport with one circular circumventing runway, called The Endless Runway. This runway is used for take-off and landing in any direction from any point on the circle and offers through this the unique characteristic a sustainable capacity in all wind conditions through the possibility for an aircraft to operate with headwind during the take-off and landing phase. By placing airport facilities inside the circle, the airport will be more compact, runway crossings can be avoided and taxiing aircraft will be able to shorten their global trajectory through optimised arrival and departure routes. The project, the Endless Runway, is partly funded under EC FP7 [1].*

## 1 Introduction

Where SESAR expects a three-fold increase in air traffic for the year 2020, vision statements beyond that date [1][3][4] expect an even further increase to a five-fold increase of aircraft use by 2050, based on the growth of the world population and a progressed mobility. The global fleet of aircraft is expected to grow fivefold from 19,800 in 2011 to a 100,000 aircraft in 2050! As was identified by ACARE, the Advisory Council for Aeronautics Research in Europe, the lack of capacity at airports is a major constraint to growth in air transport today and in the following decades. These numbers demonstrate that without a radical new airport concept providing fast and efficient aircraft handling with capacities beyond state-of-the art, the expected growth in air traffic cannot be realised.

A number of physical constraints on runways and runway operations, such as wake vortex separation minima and cross- and tailwind limits, and of societal and environmental constraints limiting airport and traffic expansion (new runway, night traffic, etc.), make it hard to improve the performance of conventional airport configurations significantly.

Directionality of runways results in a dependency to the wind direction and speed and using the same approach path results in trailing aircraft having to avoid wake vortices from leading aircraft.

This paper presents a fundamentally new and innovative approach to runway operations, where the major motivation of the study is to provide a sustainable airport capacity under all wind conditions whilst maintaining a high level of safety, reducing operating costs, and keeping environmental considerations in mind: *the Endless Runway*. The aim of the project is to investigate, through simulations, the feasibility of the concept.

## 2 The concept

A novel and radical concept is proposed here: *the Endless Runway*, a concept which consists of an airport with one circular circumventing runway, that fits for both seasonal and hub airports [5] [6]. This runway is used for take-off in any direction and landing from any direction and will allow aircraft to shorten their global trajectory through optimized departure and arrival routes and will offer the unique characteristic that the runway can be used under any wind condition through the possibility for an aircraft to operate always with headwind during take-off and landing. Moreover, runway crossings are avoided and runway overruns cannot occur since the runway has no end.

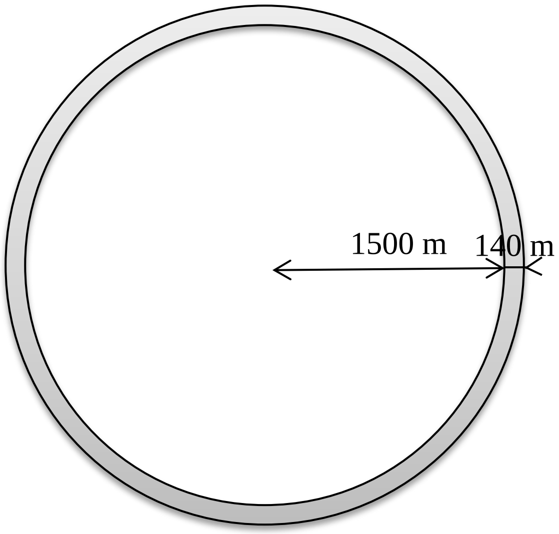


**Figure 1 - Top view of the Endless Runway**

The design of *The Endless Runway* consists of a banked circular track with all facilities for aircraft, passengers, baggage and freight handling located inside the circular runway. The circle of the runway has an inner radius of 1.5 kilometres, see Figure 1: it is large enough to provide room for airport infrastructure inside the circle and this magnitude should allow current-day aircraft to use the circular runway without significant structural modifications due to the turn. This compact airport design will allow aircraft to efficiently move from the runway to the gate and vice versa, reducing the taxiing phase and thus optimising global aircraft trajectories. In addition, passenger fast transfer times can be achieved. Moreover, it makes the airport footprint smaller than a conventional one: around 850 hectares compared to 3,257 hectares for a comparable hub airport in terms of traffic like Roissy CdG airport [7].

Wind direction, wind speed, and visibility conditions are the major factors in the decision of air traffic control to use a certain runway configuration. Limits on tailwind and crosswind components determine whether runways can be used or not, and low visibility limits the use of dependent runways. The fixed direction of the runways results in a dependency to the wind direction, and to the fact that following aircraft must use the same approach path, resulting in the need for wake turbulence separation. *The Endless Runway* operates a concept consisting of a circular runway that allows take-off in any direction and landing from any direction, avoiding the constraints mentioned before.

## 3 Airport layout

The proposed airport design is more compact than a conventional airport as most of the airport facilities are located inside the circle to avoid runway crossings. Access to the airport is provided through tunnels passing under the runway. *The Endless Runway* studies large airports where the circle size should allow a sufficient number of operations for the following categories of airports:

- *Large hub airports* with a mix of traffic, including mid-size and large aircraft. Roissy Charles de Gaulle is considered as our reference.
- *Seasonal non-hub airports*, with a mix of traffic, but where mid-size aircraft are predominant. Palma de Mallorca is considered as our reference.

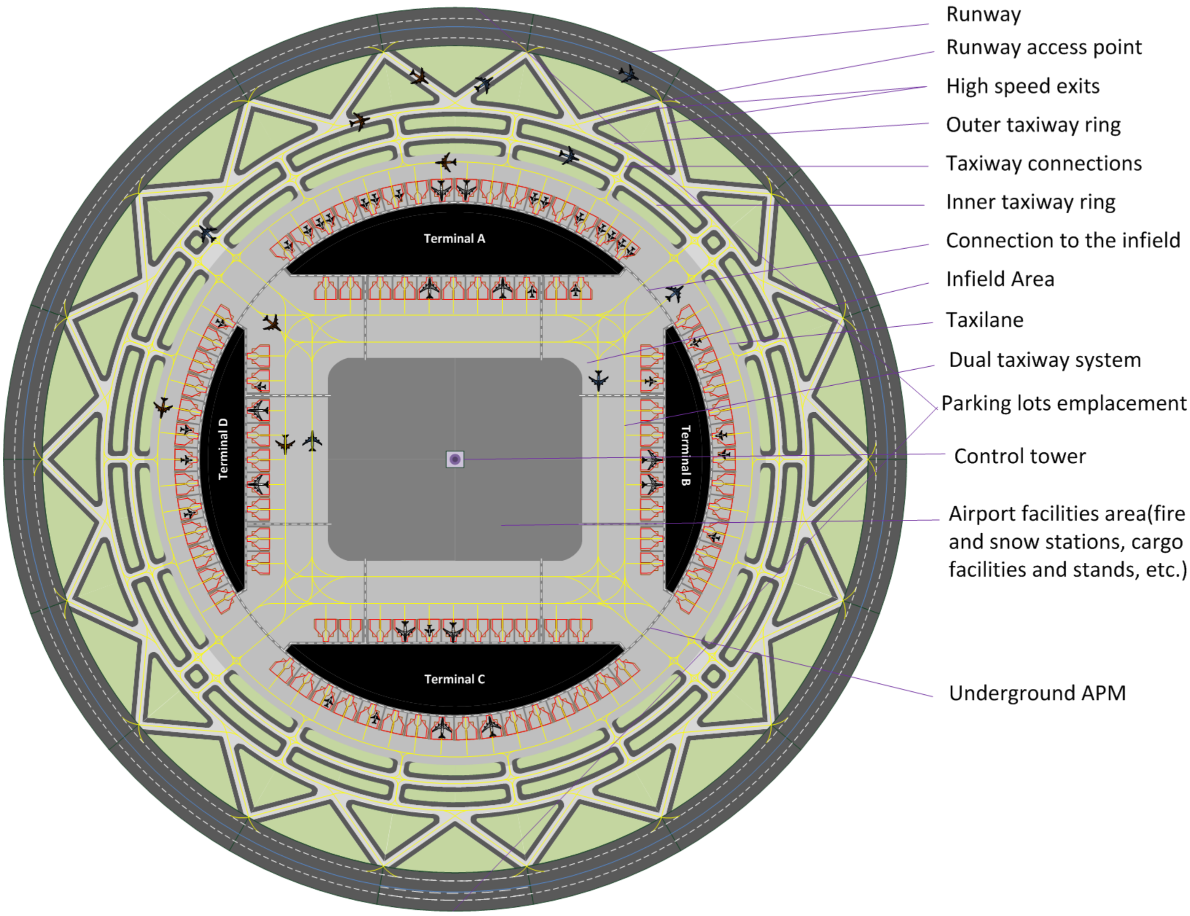


**Figure 2 - Endless Runway airport airside elements**

The following design principles are applicable to both airport types, see Figure 2.

The runway is a banked circle with a radius of 1,500 meters at the inside of the track. This size affords to operate several aircraft at the same time on the runway. It is small enough to keep the airport compact in terms of surface and to minimize taxiways and runway construction and maintenance costs.

The width of the banked track is set to 140 meters and its transversal profile is defined considering aircraft constraints (speed and ground clearance). Eighteen runway access points are provided. Thus, runway exists are located every 524 meters, which is optimal for runway occupancy time. In fact, airport design rules state that a long runway (3,500 m) at a busy airport should have exit taxiways located every 450 to 600 meters ([8])

To deal with peak periods, the number of stands for the reference airport is 133. Four terminal buildings are located in such a way that aircraft taxiing distances are limited and passengers experience an easy flight transfer (hub-airport) through a dedicated Automated People Mover (APM).

The airport's taxiway system consists of two taxiway rings just inside the runway: an outer and an inner taxiway ring. The taxiways connecting the runway with the outer circular taxiway are high-speed exit taxiways. They are 318 meters long and make a 45° angle with the tangent to the runway. The high speed exits will preferably be used as high speed entries for departing aircraft as well and aircraft can already start their take-off roll early. The length of the entry provides sufficient space for one aircraft waiting for take-off without interfering with aircraft on the runway

The outer taxiway ring (centerline radius: 1,275 m) is connected with the inner taxiway ring (centerline radius: 1,177.5 m) with single connection taxiways except at the entries/exits to the inner airport area, where a double connection taxiway forms a roundabout to avoid congestion between departing and arriving aircraft.

The connection between the inner and outer ring is located differently from the connections of the runway to the outer ring to avoid mistakes. Indeed, all connections are 10 degrees shifted with respect to the point joining the high speed exit and the outer ring taxiways. Moreover, it avoids complex taxiway junctions and facilitates aircraft crossings through better separation of inbound and outbound flows.

Between the terminals a dual taxiway system is available (yellow lines on Figure 2). The taxiways in between the airport's buildings link the inner circular ring to this inner airfield area. An additional circular taxi lane is available on the outside of the terminal stands to allow pushback operations independent from the outer taxiway rings.

The inner area thus measures around one million $m^2$ providing sufficient room for the major different facilities and for aircraft manoeuvring towards the inner gates.

## 4 Aircraft and passengers

The proposed radical change in the airport layout is directly affecting the aircraft and its passengers. Just as well, the aircraft characteristics during ground runs, end of take-offs and final approaches generate a number of requirements on the circular runway design. This section summarizes the outcomes of the concept studies that have been performed in order to assess the feasibility of aircraft operations on a circular runway, to identify the most promising runway cross section and to define the main characteristics of a specific aircraft tailored to this innovative layout.

As a first point, it must be noted that aircraft operating on a circular runway will, with increasing speed during take-off, move to the outside because of the centrifugal force. In order to limit the forces on the aircraft structure and passengers, the runway is banked. The used part of the runway depends on aircraft speeds: aircraft ground roll takes place between the inner flat part of the runway where its speed is null until part of the runway circle where the angle corresponds to its lift-off speed (and vice versa during landing roll). In other words, the aircraft will touchdown/lift-off on the outer part of the runway and will then move to the inside/outside. Given this unconventional aspect, the classical longitudinal performance models cannot be used. All analyses must then be based on six-degrees-of-freedom simulations in order to assess asymmetric conditions.

It has been decided to use the free and open-source simulator Flight Gear coupled with JSBSim to solve the equations of motion. Advantage of the choice is that models of aircraft are already available and the tool offers good visualisation means. Disadvantage is that models would have to be heavily modified to perform automatic landing manoeuvres, hence landings need to be performed "by hand".

With the objective of validating the simulation environment and assessing the possibility for an existing aircraft to operate a circular runway, a Boeing 747-100 has been modelled based on NASA data [9] and a semi-empirical engine model. The choice of this reference aircraft has been driven by the necessity to have an extensive and reliable database of the aircraft characteristics and to be conservative during this exploratory phase (its specific configuration results in a reduced ground clearance for the outboard engines). Simulations performed on a classical straight runway provided extremely good results when compared with the real data, thus validating the virtual models. The subsequent parametric studies enabled to evaluate the take-off performance of the B747-100 on banked runways with different cross sections. The first conclusions from these tests are:

- It seems feasible to take-off and land on a circular runway with a Boeing 747-100. However, there is a non-negligible risk to have a contact between an outer engine and the track given the small ground clearance.
- The lateral accelerations observed during the ground runs are below 0.47 m/s² and thus acceptable for passengers ([11]).
- The landing gear characteristics recorded during Flight Gear simulations did not show critical behaviour.
- The take-off field length on a circular runway is about 15% higher than the one on a straight and flat track (duration of take-off is about 59 seconds).
- The landing distance on a circular runway is about 23% higher than the one on a straight and flat track (duration of landing phase is about 58 seconds).

Figure 3 gives an impression of using Flight Gear for operating *the Endless Runway*.

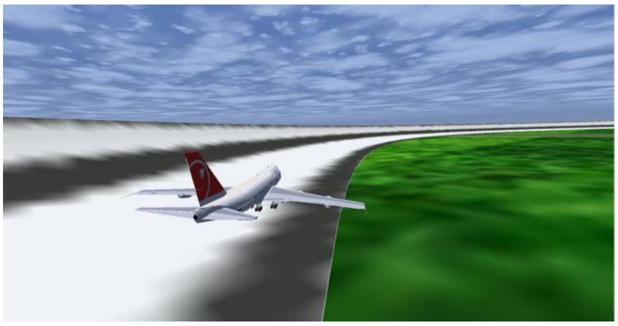

**Figure 3 - Simulation with Flight Gear of the Boeing 747-100 at take-off on a circular runway**

In addition, these simulations provided key inputs to the design and development of *the Endless Runway* concept:

- The runway cross section should provide a linear relationship between the aircraft position on the runway and its speed. This selection is a compromise between the overall size of the runway and the aircraft dynamic behaviour.
- The runway width is fixed to 140 m (see Figure 1), considering that the cross section allows speeds up to 20% more that the lift-off speed of the B747-100 for safety;

With this selected geometry, see Figure 4, in the case of the reference aircraft, the take-off rotation is made at a speed of 160 kts that is reached on the circle with a radius of 1616 m. At this point, the runway bank angle is 20°. During landing, touchdown is performed with a speed of 150 kts on the circle with a radius of 1,605 m where the bank angle is about 24°.

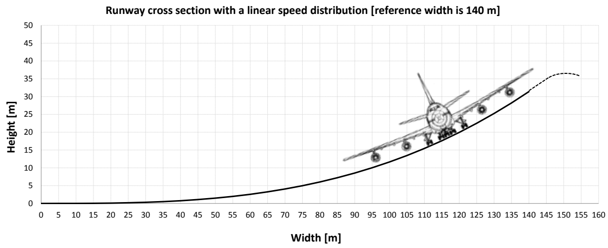


**Figure 4 - The Boeing 747-100 on the banked runway at lift-off point**

Following these initial studies on the shape of the runway and its impact on the aircraft performance, a few key requirements have been identified when preparing the design of an aircraft tailored to *the Endless Runway* concept. In order to reduce the risk of contact between the aircraft and the runway, the span is limited and the engines are located at the rear of the fuselage instead of under the wing. In addition, to increase the ground handling of the aircraft on the circular runway, the track of the landing gear must be increased. Thus, a larger fuselage may be selected. From a performance point of view, the higher take-off distance can be compensated by the selection of powerful engines to achieve a thrust-to-weight ratio higher than the one observed in today's classical configurations. These requirements lead to the following conceptual view of the aircraft tailored to *the Endless Runway* concept, see Figure 5.

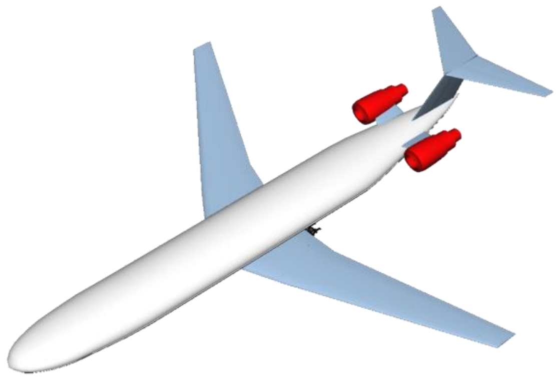

**Figure 5 - 3D model of an aircraft tailored to the Endless Runway Concept**

## 5 Runway operations

Today's operation follows the rule that the runway can only be used by one aircraft at any given time. To achieve the required capacity of the airport, simultaneous use of different parts of the runway should be allowed at *the Endless Runway*.

To allow the most flexible use of the system the runway can be operated in any direction if wind conditions allow so.

For ATM scheduling, we have subdivided the runway into 18 segments, see Figure 6, which correspond to the 18 access points on the runway defined in the Airport layout chapter.

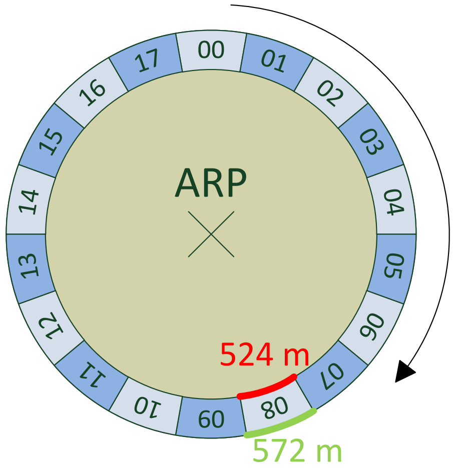


**Figure 6 - The Endless Runway segments**

These segments can be claimed in continuous strips by aircraft that want to use the runway. A booking system coordinates the available runway segments for operation and schedules the aircraft on the runway. For each flight, depending on the airspace user preferred trajectory, the aircraft performances (take-off and landing length and duration, wake-vortex category) and of other traffic constraints, a temporary runway strip is booked during a certain time period. The booking system accounts for avoiding possible wake turbulence encounters through adding additional time reservation when needed.

The taxiway system consists of two parallel rings that are used to coordinate the traffic to and from the runway. While the outer ring is operated in the same direction as the runway, the inner taxiway ring is operated in the opposite direction. The connection to the apron is provided by a number of taxiways, whereas four main entries to the inner part of the apron are available, see Figure 2.

For the operation a distinction has been made between two wind scenarios.

a) If the wind exceeds 20 kts, aircraft aiming at landing or taking-off at some points of the circular runway would experience a crosswind that is not acceptable. Therefore, in strong wind conditions, the aircraft will fly in two streams towards *the Endless Runway* to allow for landing at the touchdown point where dependency from the wind is at a minimum, that is to say as close as possible to headwind, see
b) Figure 7.

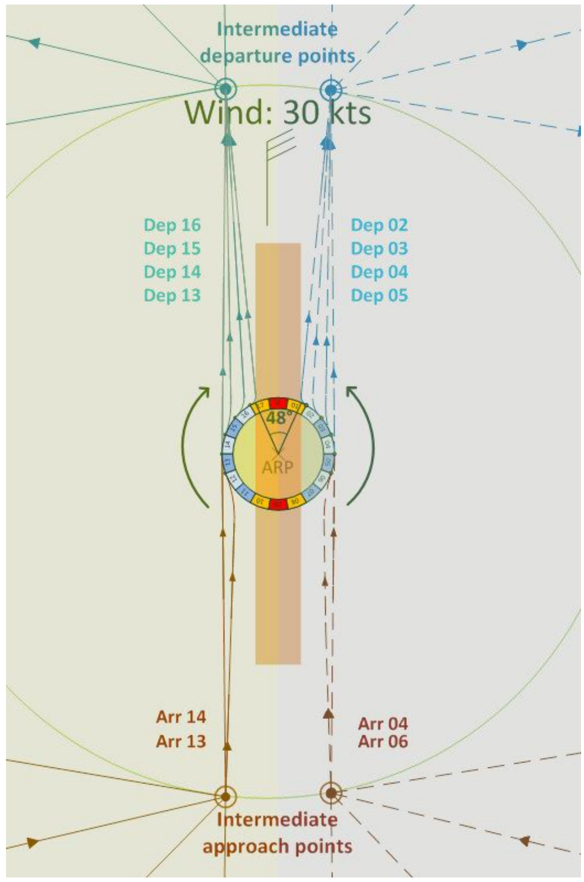


**Figure 7 Operations in strong wind conditions (example 30 kts; the numbers in the arrival and departure routes indicate the touchdown and lift-off segments)**

Aircraft will have to avoid segments with high crosswind during take-off and landing, so that only a limited number of segments of the runway can be use; segments with crosswind above 20 kts will be closed for lift-off and touchdown. 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.

c) In low wind conditions (speed below 20 kts), aircraft can be operated in a flexible manner as all segments are available for take-off and landing, as presented in Figure 8).

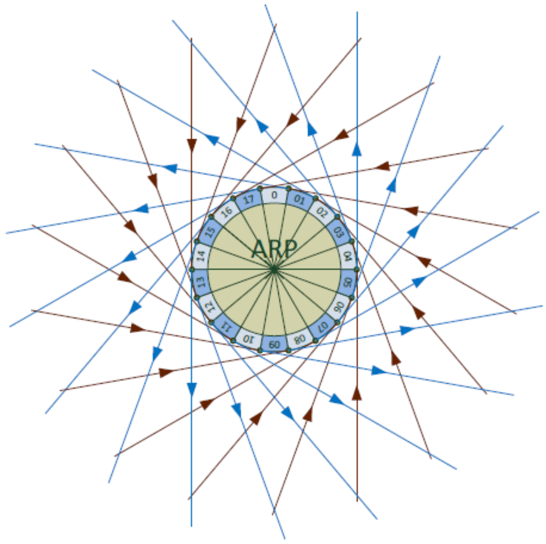


**Figure 8 - Flexible sequencing of aircraft on the Endless Runway**

With changing wind direction where speed remains below 20 kts, the runway continues operating uninterrupted at the full circle. In case of a direction change in strong wind conditions, the open TMA routes gradually “move” with the wind direction. No break in the sequence occurs as is the case with conventional runway configurations, where runways need to be opened or operational directions need to change with changing wind direction. No costly operation for tactical runway changes or runway directions change during operation will be necessary at *the Endless Runway*.

In combination with multiple runway operations and 4D operations, a controller decision support system will need to be available that allows negotiations between aircraft, airport, ATC and the ATM network.

## 6 TMA design

The TMA (Terminal Manoeuvring Area) is a controlled area around busy airports that is intended to coordinate the traffic that is climbing out from and descending towards the airport. The limits of a TMA are not standardized and differ from country to country.

The typical 3,000ft height of arriving aircraft performing an Instrument Landing System (ILS) approach was taken as a requirement to calculate the dimensions of *the Endless Runway* TMA [10]. With a standard 3° glide path angle the distance can be calculated where the final approach (descending from 3,000 ft) starts:

$$final\_dist = \frac{3000ft}{\tan(3°)}$$

For the calculations the touchdown and lift-off points for all segments are defined to be 100 m from the inner runway edge[1]. This corresponds to a distance of 1,600 m (*rwy_radius*) from the airport reference point (ARP) at the centre of the airport. With the final distance and the offset, the radius for the TMA can then be calculated:

$$TMA_{radius} = \sqrt{final\_dist^2 + rwy\_radius^2}$$

Based on these calculations, the TMA around the Endless Runway will cover a circular area around the centre of the airport with a radius of 17,521 m (9.46 NM).

For departures an average climb angle of 5° is defined. Taking this, the departure_height at the TMA exit can be calculated again using the final_dist as departure distance.

$$dep\_height = final\_dist \times \tan(5°) = 5000ft$$

[1] The touch-down and lift off points are related to the approach/lift-of speed of the aircraft. As a simplification of the calculations a common value of 100m was chosen.

Summarizing the calculations, the TMA has a minimum lateral dimension of 9.46 NM around the Airport Reference Point (ARP) and vertical limits from the airport height to 5,000ft. Figure 9 presents these dimensions. The departure and arrival routes start/end tangential at the start/end of a runway segment.

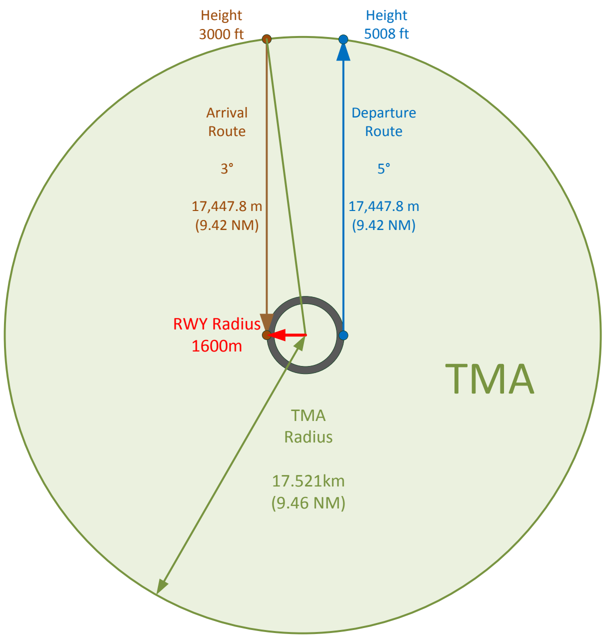


**Figure 9 - TMA dimensions**

With a number of 18 segments on the runway, there are also 18 different arrival and 18 different departure routes. Every route starts at the border of a segment. Figure 10 shows the 18 segments (00-17) of the runway, the routes and the start/end points at the borders of the segments. The picture displays the definition of the routes in a counter-clockwise operation mode. In a clockwise operation the lateral profile of the routes are mirrored. The departure routes become arrival routes and vice versa[2].

[2] The vertical profile changes as well. While all arrival routes start at 3000ft the departure routes end at around 5000ft. Therefore the vertical position of the start/end point is also dependent on the direction of operation

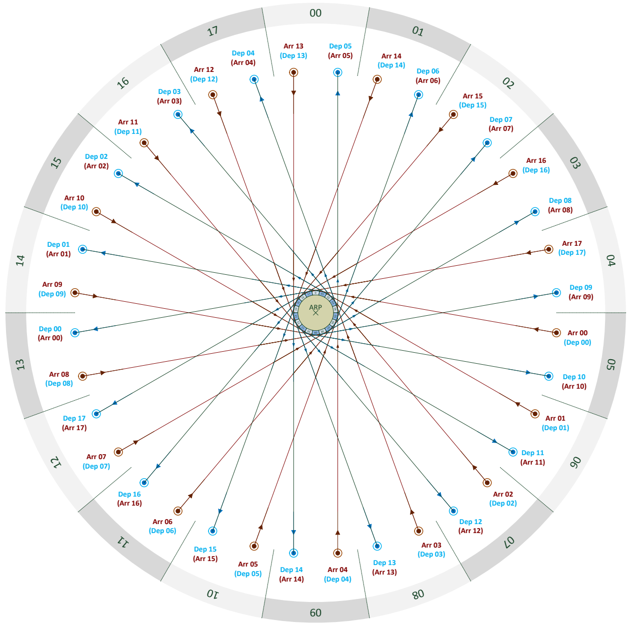

**Figure 10 – TMA Arrival / departure route structure**

Aircraft in the TMA are separated either vertically (from 4.9 to 10 NM, where no intersections between the routes exist) or laterally (within 4.9 NM, where several crossings in the routes occur). For vertical separation 1000ft was used and for lateral separation 1.5 NM

## 7 Results

Simulations have been performed to evaluate the proposed TMA and runway operations. The objectives of the simulations concerned calculation of capacity and delay and the use of the runway booking system.

Capacity calculations have been performed through running a typical high density CdG scenario at Paris Roissy Charles de Gaulle – the reference hub airport. The first simulation has been organised such that the first aircraft was able to book a number of segments on the runway (cf. its length necessary for take-off or landing), including one or two additional segments for safety. The following flights were able to book the necessary segments if there was no conflict with other flights on the runway or in the air (TMA). If a conflict occurred, the flight was delayed until no conflict existed anymore.

Several traffic density scenarios have been set up and planned on the available runway segments. Aircraft performance (the number of segments necessary per aircraft type) has been taken into account. All scenarios have then been evaluated with respect to the average delay. With this methodology, for a traffic demand similar to a hub airport in terms of aircraft mix, the following result is observed.

From a capacity point of view, *the Endless Runway* seems to be advantageous compared with a classical runway system: a first evaluation shows that 109 movements per hour are possible in the low wind case, decreasing to 60 movements per hour in the high wind case for a total runway length of about 10,000 m. The average delay in the low wind case was 39 seconds. When allowing a higher average delay, the number of movements could increase, see table below.

| Max flights per hour | Average delay (h:min:s) |
|---|---|
| 109 | 00:00:39 |
| 118 | 00:01:33 |
| 129 | 00:04:27 |
| 137 | 00:19:24 |
| 140 | 00:38:25 |
| 151 | 01:06:27 |
| 261 | 03:09:38 |

As a comparison with the 13,815 m total runway length of Roissy Charles de Gaulle airport and a capacity of 115 movements per hour in 2011, *the Endless Runway* scored similar in number of movements, but on a considerable shorter total runway structure.

## 8 Related work

The idea of a circular runway to avoid cross- and tailwind operations has been considered earlier. The first reference found is an impression from 1919 of a circular structure that would be built on top of skyscrapers in New York [12]. It would allow business travellers to enter the city without delay. In the 1960's flight trials on a circular banked runway were performed by the U.S. Navy, leading to some (expired) patents [13]. The trials proved to be positive as the runway's bank angle kept the aircraft on the right track avoiding them from being swept out of the runway.

Several other patents have been filed e.g. [14][15], based on the idea of a circular track, mostly concerned with new ideas for taking off and landing at some straight segment outside or inside the circle and only using the circular track for the lower speed segments of the take-off and landing roll.

## 9 Conclusions

This paper describes an innovative concept for designing and operating an airport with an *Endless Runway*. An initial operational concept is proposed, based on earlier experiences with a circular banked track; the work performed so far has not demonstrated any show stoppers. ATM simulations are planned in the near future to further assess the impact *the Endless Runway* may have.

It can be concluded that a runway of 1.5 km radius will fit the requirements for the size of the circle. The total runway length is equivalent to about three conventional runways and can accommodate sufficient movements for a large hub airport or a seasonal airport. Also, sufficient space is available inside the circle to cater for gates, terminal buildings, and other necessary infrastructure, such as fire stations. All non-essential facilities will be positioned outside of the circle.

The simulations showed that today's aircraft can take-off and land on a circular runway. However, performances are degraded and the risk of contact between the track and the aircraft is not negligible. Regarding the development of future aircraft, *the Endless Runway* concept implies a limit on the aircraft span associated to the necessary ground clearance. This constraint might be critical since recent studies showed that next generation airplanes would have higher aspect ratios.

ATM procedures will require a high level of automation. Air traffic controllers will need assistance for calculating the optimum take-off and touchdown point for each aircraft, taking other traffic and meteorological conditions into account. Simultaneous aircraft movements for arrivals and departures, both in clockwise and counter-clockwise directions may be possible, where more than one aircraft can occupy the runway at the same time.

## 10 Acknowledgments

The authors would like to thank A. De Giuseppe for his work regarding the assessment of today's aircraft capability to take-off and land on a circular runway and the conceptual design of *the Endless Runway* tailored aircraft.

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