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Publication date
2015

Document Version
Final published version

Published in
Proceedings of the18th Euro Working Group on Transportation (EWGT) Conference

Citation (APA)
Janic, M. (2015). Matching the airport runway capacity to demand: Analysis, modelling, and applying some innovative solutions to Dubai International Airport (DXB). In *Proceedings of the18th Euro Working Group on Transportation (EWGT) Conference*

MATCHING THE AIRPORT RUNWAY CAPACITY TO DEMAND: ANALYSIS, MODELLING, AND APPLYING SOME INNOVATIVE SOLUTIONS TO DUBAI INTERNATIONAL AIRPORT (DXB)

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ABSTRACT

The paper deals with analysis and modelling of a given short- to medium-term solution(s) for matching usually the constrained airport runway capacity to usually growing airside demand. This solution(s) consists of deploying the new technologies supporting the innovative operational procedures developing in the European SESAR (Single European Sky ATM Research) and U.S. NextGen (Next Generation) development programs. They are expected to mainly contribute to increasing of the airport runway landing capacity. In such context, the analysis implies elaboration of the characteristics of the given technologies and procedures and conditions where they could be applied – the congested capacity-constrained airport runway system. Modelling implies development of the analytical models for estimating the effects/impacts of particular new technologies and operational procedures on the given runway system "ultimate" and "practical" capacity. The models are applied to the system of two closely spaced parallel runways of Dubai International airport (DXB) (UAE - United Arab Emirates). The results have indicated that the innovative operational procedures supported by new technologies could have some potential for increasing both the "ultimate" and "practical" capacity of two closely-spaced parallel runways at the given airport (DXB) under given conditions, and consequently contribute to postponing their full saturation.

Keywords: airport, demand, capacity, matching, new technologies, innovative procedures analysis, modelling

1 INTRODUCTION

The runway system capacity of many airports worldwide have come to saturation due to continuously growing demand on the one hand and different constraints in providing adequate capacity to handle such demand on the others. Some illustrative examples of airports operating at saturation of the runway system capacity during almost whole day are London Heathrow airport (UK - United Kingdom) and Dubai International airport (DXB) (UAE – United Arab Emirates). London Heathrow (LHR) has operated two widely-spaced parallel runways in the segregated mode (one exclusively for arrivals and the other for departures with changing pattern) during limited time of the day mainly due to the noise constraints. Dubai International airport (DXB) has operated two closely-spaced parallel runways mostly as a single runway without any specific constraints. The former airport has been the world's largest in handling the international passengers. The latter airport has been one of the fastest growing in the world by developing into the Middle East's strategic hub. Both airports have handled significant proportion of the long-distance/intercontinental flights carried out by the large/heavy including the largest/super heavy A380 aircraft. Under current and prospective conditions characterized by the further growth of air transport demand in terms of the number of passengers, cargo volumes, and aircraft operations, both airports have been considering solutions for increasing the runway system capacity as the crucial element for improving the overall operating performances. At Heathrow airport, the most recent stage of the longer than twenty-years debate about building the third (parallel) runway resulted in the just published report, which has indicated that this third runway would be a solution for the long term increasing of the runway system capacity of the London airport system (Heathrow, Gatwick, and Stansted) (AC, 2015). At Dubai airport, the new airport (DXC) has been built mainly due to the lack of space at the existing DXB airport for building the additional (third) runway. The DXB airport is located almost in the city center with two runways surrounded by passenger and cargo terminals, and these latter by other city buildings. Such development seems to lead to constituting the airport system for Dubai including the existing (DXB) and new (DXC) airport. But in the given context, DXB airport has not been an exception. Currently, the U.S. airports operate 28 pairs of closely-spaced parallel runways. Some of them are San Francisco International (SFO), Atlanta Hartsfield International (ATL), Boston Logan International (BOS), Los Angeles International (LAX), etc. In Europe, the typical example has been Frankfurt International airport (FRA). Despite growing demand, most of these airports have not had options to build the additional runway(s) in order to cope with the prospectively growing demand. The main barriers have been different social (noise) and environmental (land use) constraints, similar to those at the above-mentioned two characteristic airports.

Under the above-mentioned conditions, one among the short- to medium-term solutions for eventual (marginal) increase in the runway system capacity could be deploying the innovative operational procedures supported by the new technologies, which have been developing in the scope of European SESAR (Single European Sky ATM Research) and U.S. NextGen (Next Generation) development program (Erzberger, 2004; http://www.sesarju.eu/; http://www.faa.gov/nextgen/).

This paper aims at elaborating the effects of some of these new technologies and related operational procedures on the capacity of two closely-spaced parallel runways at the given congested airport.

In addition to this introductory section, the paper consists of four other sections. Section 2 describes the main new technologies and related innovative operational procedures expected to eventually increase the airport's runway system capacity. Section 3 describes the analytical models for estimating the landing, taking-off, and total capacity of two closely-spaced parallel runways respecting innovative operational procedures supported by new technologies and different ATC/ATM (Air Traffic Control/Air Traffic Management) separation rules. Section 4 presents an application of the proposed models to the runway system of the above-mentioned Dubai International Airport (DXB). The last section summarizes some conclusions.

2 MEASURES FOR MATCHING THE AIRPORT RUNWAY CAPACITY TO DEMAND

2.1 Background

Different short-, medium and long-term solutions for matching the airport runway system capacity to usually growing demand have been applied exclusively or in different combinations. For example, the short- and medium-term solutions embrace i) optimization of utilization of the existing runway system capacity, ii) deployment of the above-mentioned innovative operational procedures supported by new technologies iii) tactical and strategic air traffic demand management including GDP (Ground Holding Program), and iv) charging congestion. The long-term solutions have included building the additional runway(s) to the existing runway(s) at a given airport and/or the airport system, and as in the case of DXB building completely new airport (DXC).

2.2 Innovative operational procedures supported by new technologies

In particular, the short- to medium-term solution of deployment of the innovative operational procedures supported by the new technologies, has seemed to be, in addition to a single runway, particularly promising in increasing of the capacity of two closely-spaced parallel runways (separated laterally for less than 760m), which currently commonly operate as a single runway with associated capacity. This can be achieved by carrying out safe dependent, i.e., paired ILS/MLS landings and take-offs on these runways (Janic, 2008; FAA, 2013). Such operations would be primarily supported by WTMA (Wake Turbulence Mitigation for Arrivals) and WTMD (Wake Turbulence Mitigation for Departures) integrated automated system recently deployed at several U.S. airports.

The additional new technologies supporting individual and paired landings could be: ADS-B (Automatic Dependent Surveillance Broadcast) in combination with CDTI (Cockpit Display Traffic Information), SWIM (System Wide Information Management), TFDM (Terminal Flight Data Manager), and TFMS (Traffic Flow Management System), ASDE X (Airport Surface Detection Equipment – Model X) and IDACS (Integrated Departure and Arrival Coordination System), all with the ATC/ATM (Air Traffic Control/Management) ground components and avionics. The same as above-mentioned excluding the last two could support take-offs (FAA, 2013; http://www.faa.gov/nextgen/; http://www.sesarju.eu/).

Specifically, as applied to the closely-spaced parallel runways, the WTMA and WTMD system, providing continuous monitoring and forecasting of the crosswind conditions, enable on-line modification of the existing (no crosswind) ATC/ATM longitudinal wake vortex separation rules. In case of landings, this could include applying, exclusively or in combination with the existing longitudinal, also diagonal (authorized as FAA Order 7110.308) and/or still not fully authorized vertical separation rules between paired dependent operations. The diagonal separation rules could be applied under conditions when the persistent crosswind is blowing up wakes by leading aircraft away from the path of trailing aircraft in the given landing sequences. The vertical separation rules could be applied to the given landing sequences in combination with the constant or a steeper GS (Glide Slope) angle and usually staggered landing thresholds under all weather (crosswind) conditions. They enable that trailing aircraft stays all the time longitudinally closer to but above the (sinking) wakes of leading aircraft in given landing sequence. In addition, the above-mentioned procedures applied to the closely-spaced parallel runways appear to be particularly convenient mainly due to avoiding deficiencies of the limited runway length and increased traffic complexity, both as compared to their single-runway counterpart (Janic, 2008; 2012; Kolos-Lakatos and Hansman, 2013; Tittsworth et al., 2012).

In case of taking-offs, the existing and/or slightly modified ATC/ATM time-based separation rules could be applied under convenient crosswind conditions, In particular, the latter implies carrying out successive takes-offs sequentially always from different runway while using the lift-off time as a component of the time-based separation rules in combination with diverging trajectories assigned to the successive departure aircraft immediately after taking-off.

For mixed operations, an innovative procedure applicable under convenient crosswind conditions can be to allow take-off(s) on the runway different than that of the preceding landing(s), i.e., without a need for waiting for the previously landing aircraft to clear its runway as in the case of single runway. At the same time, this take-off should be safely longitudinally separated from the succeeding landing at either runway.

3 MODELLING CAPACITY OF THE CLOSELY-SPACED PARALLEL RUNWAYS

3.1 Some related research

Modelling of the “ultimate”[1] and ‘practical”[2] capacity of the airport runway systems has occupied for a long time researchers, planners, and aviation industry. As a result, many analytical and simulation models have been developed. In particular, the analytical models have usually provided two value parameters for a single runway – one for landing and the other for take-off capacity (Blumstein, 1959; Donohue, 1999; Gilbo, 1993, 1997; Harris, 1972; Hockaday and Kanafani, 1974; Janic and Tosic,

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[1] This is defined as the maximum number of aircraft handled at the given runway system per unit of time (usually 1 hour) under conditions of constant demand for service (Blumstein, 1959).

[2] This is defined as the as the maximum number of aircraft handled at the given runway system per unit of time (usually 1 hour) under conditions of imposing maximum average delay on each of them (Blumstein, 1959).

1982; Janic, 2006; Newell, 1979; Swedish, 1981). Some other models including the FAA Airport Capacity Model, the LMI Runway Capacity Model, and DELAYS as 'Quasi-Analytical Models of Airport Capacity and Delay', based on the analytical single-runway "ultimate" and 'practical" capacity models, have calculated the "ultimate capacity coverage curves and associated aircraft delays, both enabling deriving the 'practical" capacity under given conditions (Gilbo, 1993; Newell, 1979). Recently, the analytical models for estimating the "ultimate" landing capacity of the closely spaced parallel runways and investigating the effects of innovative operational procedures supported by the new technologies developing within the European SESAR and U.S. NextGen research programs were developed (Janic, 2008, 2012; http://www.faa.gov/nextgen/; http://www.sesarju.eu/).

3.2 Objectives and assumptions

The objectives of the paper are to investigate the effects of above-mentioned innovative operational procedures supported by the new technologies to eventual increasing of the current "ultimate" and "practical" capacity of two closely-spaced parallel runways at given airport. For such a purpose, the latest above-mentioned analytical models for calculating the the "ultimate" capacity and existing models for calculating the 'practical" capacity (based on the steady-state quieting model) of two closely-spaced parallel runways are appropriately modified respecting the most recent proved and prospective developments. Such modified models are based on the following assumptions:

- The demand for landings and take-offs on the given two closely-spaced parallel runways is constant during the specified period of time (usually 1 hour);
- The two closely-spaced parallel runways are used in the mixed mode, depending on the prevailing demand, simultaneously for paired landings, paired taking-offs, and paired mixed landings/taking-offs;
- The aircraft are categorized according to their wake-vortex characteristics mainly depending on the aircraft MTOW (Maximum Take-Off Weight), wing span, while respecting prevailing weather (wind) conditions, all influencing the approach and landing speed, and the runway landing/take-off occupancy time;
- The aircraft landing speeds are constant along the final approach trajectories connecting FAGs and runway landing threshold(s);
- The aircraft strictly follow their prescribed four-dimensional approach/departure trajectories appearing exactly as being expected at particular locations;
- The ATC/ATM minimum longitudinal, diagonal, and innovative vertical distance-based separation rules between landings exclusively or in different combinations are applied; the existing and/or modified time-based separation rules between take-offs are applied;
- The maximum average delay per ACM (Aircraft Movement) is specified enabling to derive the "practical" capacity from the calculated "ultimate" capacity using the delay-capacity relationship under steady-state conditions. .

3.3 Structure of the models

3.3.1 "Ultimate" capacity

3.3.1.1 The landing and taking-off capacity

Similarly as at other analytical models of 'ultimate" runway system capacity, the average inter-event time for different combinations of landing and/or taking-off sequences at corresponding runway thresholds of two closely-spaced parallel runways can be calculated as follows:

$$\bar{t} = \sum_{i/k,j/l} p_{i/k} \cdot \tau_{ik/jl} \cdot p_{j/l} \tag{1a}$$

and the landing and/or taking-off capacity (ACM/h):

$$\lambda = T/\bar{t} \tag{1b}$$

where

i, j	is the leading and trailing aircraft category, respectively, in the landing sequence *(ij) (ij* $(ij) \in N$;
N	Is the number of the aircraft categories in the landing or departing fleet mix;
k, l	is the landing runway of the aircraft *(i)* and *(j)*, respectively ($k, l = 1, 2$);
$p_{i/k}, p_{j/l}$	is the proportion of the aircraft category *(i)* and category *(j)* in the aircraft fleet mix, which land at or depart from the runway *(k)* and *(l)*, respectively
$\tau_{ik/jl}$	is the minimum time between landing or departing of the aircraft of category *(i)* and *(j)* at and from the runway *(k)* and (l), respectively (s); and
T	is the time interval for which the capacity is calculated (h).

3.3.3.2 The total capacity

The total runway system capacity for mixed operations (ACM/h) can be calculated as follows:

$$\lambda = (1 + p_d)\lambda_a \tag{2a}$$

$$\lambda = (1 + p_a)\lambda_d \tag{2b}$$

where

p_d, p_a	is the probability of time gaps enabling safe take-offs and landings between successive landings and/or taking/offs, respectively; and
λ_a, λ_d	is the landing and taking-off runway system capacity, respectively (ACM//h)

3.3.3.3 The inter-event time between landings

The inter-event time $\tau_{ik/jl}$ in Eq. 1a for landings is determined for different sequences respecting the aircraft final approach speeds and the ATC/ATM separation rules applied. For example, Figure 1(a, b) shows scenarios when the ATC/ATM minimum vertical separation rules are applied to different landing sequences. The following notation is used:

$t_{ai/k}$	is the landing occupancy time by the leading aircraft *(i)* landing at the runway *(k)* (min);
$\delta^l_{ij}; \delta^d_{ij}$	are the ATC/ATM minimum longitudinal and diagonal separation rules, respectively, applied to the aircraft landing sequence *(ij)* (nm);
d	is the lateral (right angle) separation of two closely-spaced parallel runways (nm);
H_{ij}^0	are the ATC/ATM minimum vertical separation rules applied to the aircraft landing sequence *(ij)* (ft (feet));
$\alpha_{i/k}, \alpha_{j/l}$	is the GS (Glide Slope) (final approach) angle of the leading and trailing aircraft *(i)* and *(j)* landing at the runways *(k)* and *(l)*, respectively (^{0});
$\gamma_{i/k}, \gamma_{j/l}$	is the length of final approach path of the leading aircraft *(i)* landing at the runway *(k)* and of the trailing aircraft *(j)* landing at the runway *(l)*, respectively (nm);
ε_{kl}	is the staggered distance between two closely spaced parallel runways *(k)* and *(l)* (nm); and
$v_{i/k}, v_{j/l}$	is the final approach speed of the landing aircraft *(i)* to the runway (k) and the aircraft *(j)* to the runway *(l)*, respectively (kts -knots).

a) Sequence: $v_{i/k} \le v_{j/l}$

Figure 1a(i) shows the case when the leading aircraft *(i)* lands on the closer runway *(k)* and the trailing aircraft *(j)* on the staggered runway *(l)*. Figure 1a(ii) shows the opposite runway use.

In both cases, the minimum separation is established at the moment when the leading aircraft *(i)* is at its landing threshold. The inter-arrival time of aircraft *(i)* and *(j)* at the thresholds of their runways when the ATC/ATM horizontal, vertical, or diagonal separation rules are exclusively applied can be calculated as follows:

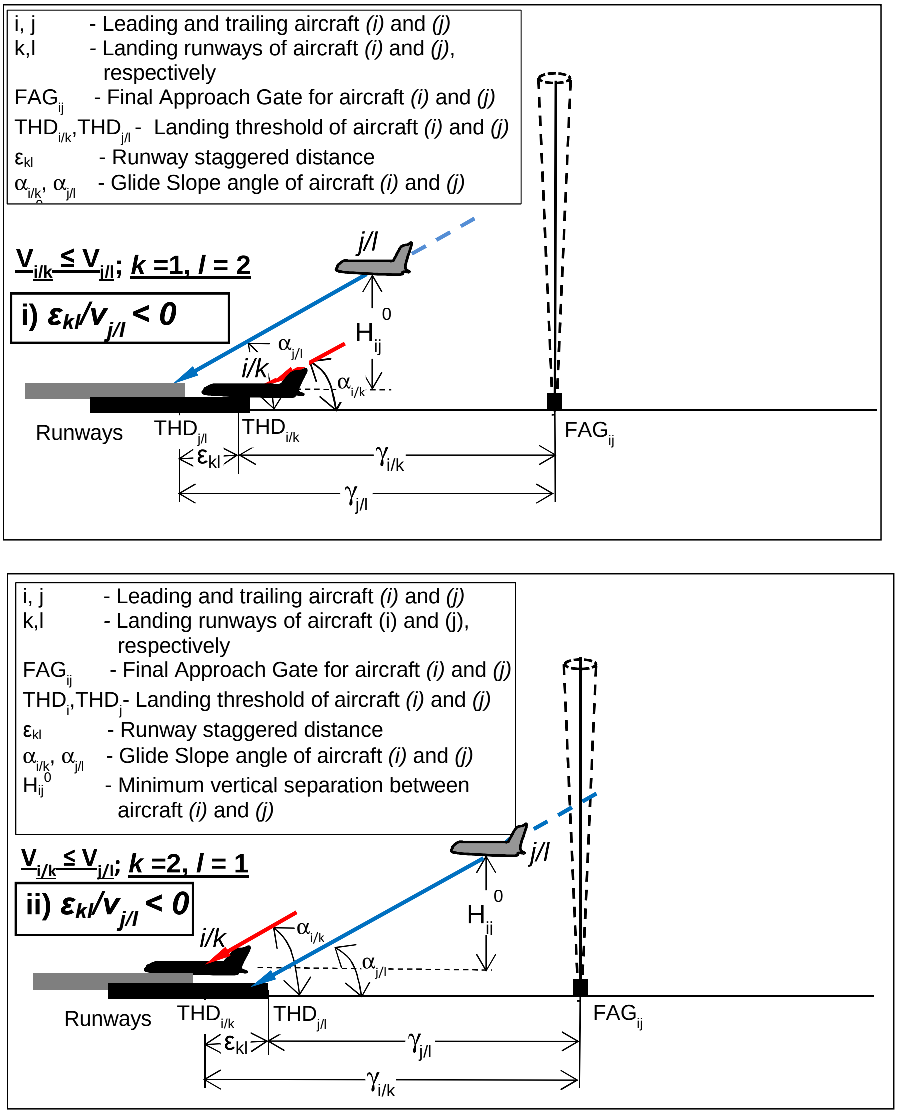
$$\tau_{ik/jl} = \left[\min\left(\frac{\delta_{ij}^{l}}{v_{j/k}}; \frac{\sqrt{\left(\delta_{ij}^{d}\right)^2 - d^2}}{v_{j/l}}; \frac{H_{ij}^{0}}{v_{j/l} tg\alpha_{j/l}} \right) \pm \frac{\varepsilon_{kl}}{v_{j/l}} \right] \qquad (3a)$$

b) Sequences: $v_{i/k} > v_{j/l}$

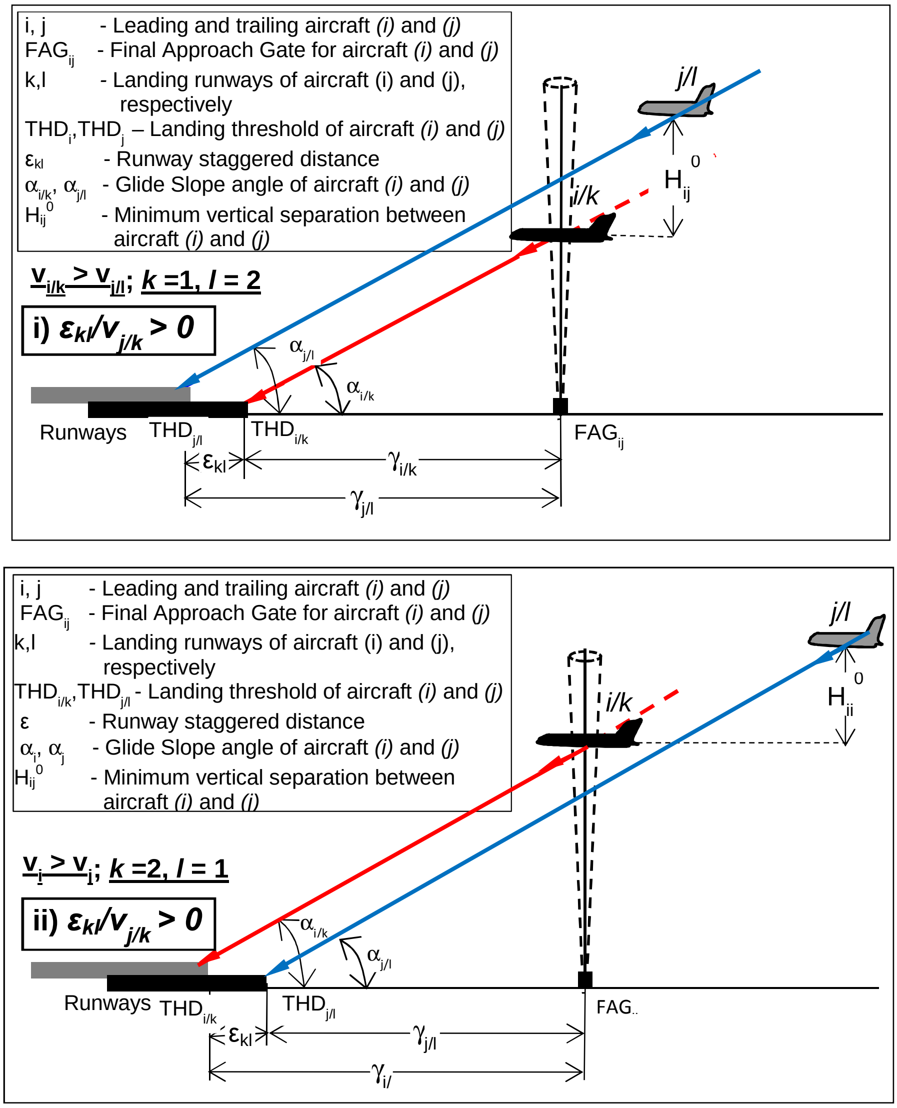
Figure 1b(i) shows the case when the leading aircraft *(i)* lands on the closer runway *(k)* and trailing aircraft *(j)* on the staggered runway *(l)*. Figure 1b(ii) shows the opposite runway use. The ATM/ATC minimum vertical separation rules are applied at the moment when the leading aircraft *(i)* is at its FAG and the trailing aircraft *(j)* is behind it at the safe vertical (and corresponding longitudinal) distance.

The inter-arrival time of the aircraft *(i)* and *(j)* at the landing thresholds of their runways when different ATC/ATM separation rules - horizontal, vertical, diagonal - are exclusively applied can be calculated as follows:

$$\tau_{ik/jl} = \left[\min\left(\frac{\delta_{ij}^{l}}{v_{j/l}}; \frac{\sqrt{\left(\delta_{ij}^{d}\right)^2 - d^2}}{v_{j/l}}; \frac{H_{ij}^{0}}{v_{j/l} tg\alpha_{j/l}} \right) + \gamma_{i/k}\left(\frac{1}{v_{j/l}} - \frac{1}{v_{i/k}} \right) \pm \frac{\varepsilon_{kl}}{v_{j/l}} \right] \qquad (3b)$$



a) Sequence: $\boldsymbol{v_{i/k} \leq v_{j/j}}$



b) Sequences: $v_i > v_j$

Figure 1 Scenarios of landing at closely-spaced parallel runways when the ATC/ATM vertical separation rules are applied

The term $(\varepsilon_{kl}/v_{j/k})$ in Eq.3 (a, b) takes the positive sign ("+") if the leading aircraft *(i)* lands on the closer and the trailing aircraft *(j)* on the staggered runway (Fig. 1a(i), 1b(i)), and the negative sign ("-"), if otherwise (Fig. 1a(ii), 1b(ii)). If the variable $d = 0$, the aircraft *(i)* and *(j)* are assumed to land on the same runway with the displaced threshold. If both variables $d = 0$ and $\varepsilon_{kl} = 0$ in Eq. 3 (a, b), both aircraft *(i)* and *(j)* land on the same runway threshold.

3.3.3.4 The minimum time between take-offs

It is assumed that taking-offs *(m)* and *(n)* in the given sequence are carried out sequentially and always at different runways *(k)* and *(l)*, respectively. Under conditions of no or inconvenient crosswind, the ATC/ATM applies existing time-based wake-vortex separation rules. Under conditions of convenient crosswind and with support of WTMD, the trailing aircraft *(n)* can start its take-off from the runway *(l)* immediately after the leading aircraft *(m)* lifts-off from the runway *(k)*. In order to additionally diminish the impact of wake vortices, the aircraft *(m)* and *(n)* can be assigned diverging departure trajectories immediately after taking-off (Mayer, 2011). Figure 2 shows the corresponding time-space diagram.

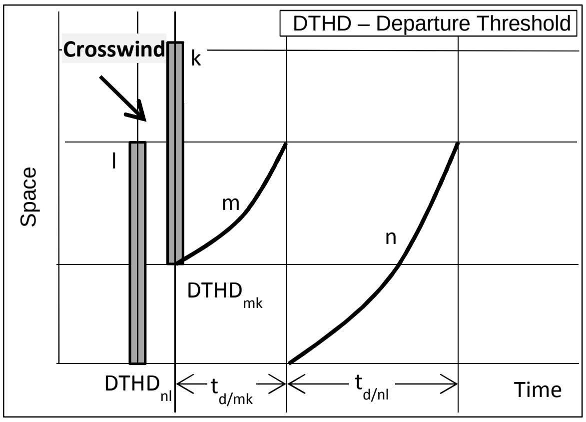


Figure 2 Time space diagram for the taking-off sequence *(m)* and *(n)* from the runways *(k)* and *(l)*, respectively - convenient crosswind

Under the above-mentioned conditions, the minimum time between successive take-offs from the closely-spaced parallel runways can be calculated respecting the use of ATC/ATM time-based separation rules. These depend of the runway occupancy time of the leading aircraft in the given departure sequence, the minimum wake-vortex separation rules (if applicable), and the number of successive departures from the runway of the leading aircraft in the given take-off sequence. Consequently, this minimum time can be estimated as follows:

$$\tau_{d/mk,nl} = [n_{d/mk} * \max(t_{d/mk}; t_{d/mn/\min})] \text{ - without crosswind} \tag{4a}$$

and

$$\tau_{d/mk,nl} = n_{d/mk} * t_{d/mk} \text{ - under crosswind} \tag{4b}$$

where

$t_{d/mk}$, $t_{d/mn}$	is the runway occupancy time of the taking-off aircraft *(m)* and *(n)* from the runways *(k)* and *(l)*, respectively (min);
$t_{d/mn/min}$	is the minimum ATC/ATM time-based separation rules between taking-off aircraft of the category *(m)* and *(n)* (min); and
$n_{d/mk}$	is the number of successive take-offs from the runway *(k)*.

Equation 4(a, b) implies that the number of take-offs $n_{d/mk}$ is always equal or greater than 1. Specifically, if $n_{d/mk} = 1$, then it is considered as the take-off of aircraft *(n)*.

3.3.3.5 The inter-event time between different operations

a) Take-off between successive landings

As mentioned above, the aircraft *(i)* and *(j)* in the landing sequence *(ij)* and/or taking-off sequence *(mn)* are assumed to always land and/or take-off, respectively, on different runways *(k)* and *(l)*, respectively, independently on the applied ATC/ATM separation rules. In addition to the previously mentioned, the following notation is used:

$\delta^{da}{}_{jm}$ is the minimum longitudinal distance of the trailing landing aircraft *(j)* in the landing

$DTHD_m$

sequence *(ij)* from the taking-off aircraft *(m)*.

A take-off between any two landings can be carried out in different combinations as follows:

A) The leading aircraft *(i)* lands on the closer runway *(k)* and the trailing aircraft *(j)* on the staggered runway *(l)* (Figure 1a(i) and 1b(i)) while the aircraft *(m)* take-offs from: the same runway where the aircraft *(i)* landed; or from the runway where aircraft *(j)* is to land; and

B) The leading aircraft *(i)* lands on the staggered runway *(l = 2)* and the trailing aircraft (*j)* on the closer runway *(k = 2)* (Figure 1a(ii) and 1b(ii)) while the aircraft *(m)* takes-off from: The staggered runway *(l = 2)* where the aircraft *(i)* landed or the closer runway *(k = 2)* where the aircraft *(j)* is to land.

Under conditions of operating the closely-spaced parallel runways (as a single runway), the previously landed aircraft *(i)* has to clear its runway and the approaching aircraft *(j)* has to be at the minimum longitudinal distance from the aircraft *(m)* of $\delta_{da/jm}$ at the moment when it starts taking-off, independently on the combination of runways used for landings and taking-offs. Figure 3 shows the time-space diagram of operating closely-spaced parallel runways in the above-mentioned different (crosswind) conditions.

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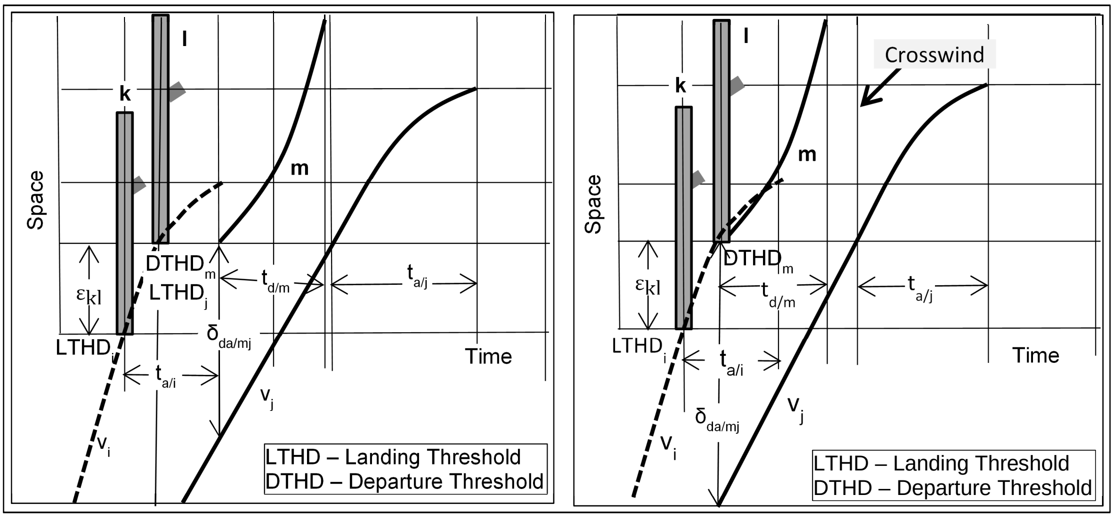


a) Without crosswind (Case A) b) With crosswind (Case A)

Figure 3 Time-space diagram for mixed operations on the closely-spaced parallel runways under different weather conditions

Specifically, Figure 3a shows that the operating Case A is identical to that of a single runway, independently on crosswind conditions. Figure 3b shows the above-mentioned operating Case A under convenient crosswind conditions. With support of WTMD, WTMA, and other above-mentioned technologies, the ATC/ATM may allow the aircraft *(m)* to start taking-off from its runway immediately after the landing aircraft *(i)* touched down the other runway, implying no waiting of aircraft *(k)* for aircraft *(i)* to clear its runway. At the same time the approaching aircraft *(j)* should again be at least at the minimum longitudinal distance from the aircraft *(m)* at the moment when it starts take-off. Similar time-space diagram as in Figure 3 can be drawn for above-mentioned Case B Consequently, the ATC/ATM minimum time interval enabling *(n_d)* take-offs between successive landings *(i)* and *(j)* under the above-mentioned conditions can be calculated as follows:

$$\tau_{d/kj} = \begin{bmatrix} (n_d - 1) * (t_{a/i} + \delta_{ad/mj} / v_j), \ \textit{current and/ or under crosswind if } (i) \textit{ and } (m) \textit{ use the same runway;} \\ (n_d - 1) * [\max(t_{d/m}; \ \delta_{ad/mj} / v_j)], \textit{ with crosswind if } (i) \textit{ and } (m) \textit{ use different runways} \end{bmatrix} \quad (5a)$$

Landing between successive take-offs

A landing can also be carried out between successive taking-offs. According to the above-mentioned notation, the landing *(i)* can be realized between the two successive take-offs *(m)* and *(n)* each departing from different of the two closely-spaced parallel runway, if the sufficient time gap appears as follows:

$$t_{d/kl} = t_{d/m} + t_{ai} \tag{5b}$$

Eq. 5b implies that the take-off *(m)* should, independently on the ATC/ATM separation rules applied, clear its departure runway and the landing *(i)* should clear its arrival runway before the successive take-off *(n)* is allowed.

3.4 "Practical" capacity

When the demand for landings and/or taking-offs generally does not generally exceed the runway system 'ultimate" capacity during the longer period of time, the ACM delays, when happen, are stochastic and not particularly long. In such case, in addition to the "ultimate' capacity, the specified average delay(s) per ACM can be used for determining the "practical" capacity to be declared by the airport in terms of the number of slots per hour (or 15minutes) during the day. For such a purpose the modified expression for the average delay per an ACM derived from the steady-state queuing system theory can be used with the following notation (Newell, 1979):

λ_p is the "practical" landing and/or taking-off capacity (ACM/h);

λ_u is the "ultimate:" landing and/or taking-off capacity as the reciprocal of the corresponding mean service times ($\lambda_u = 1/\bar{t}$, Eq. 1(a, b)) (ACM/h);

σ is the standard deviation of service time of an arrival and/or of departure (h^2); and

D^* is the maximum average delay per landing and/or take-off specified for setting up the 'practical" capacity (min).

The maximum average delay is calculated as follows:

$$D^* = \frac{\lambda_p(\sigma^2 + 1/\lambda_u^2)}{2(1-\lambda_p/\lambda_u)} \tag{6a}$$

Eq 6a is valid if $\lambda_p < \lambda_u$; if it comes closer to 1, i.e. if the difference between two capacities decrease, the average delay grows exponentially. After setting the variable $\sigma = 0$ just for the purpose of simplification, the "practical" capacity can be derived from Eq. 6a as follows:

$$\lambda_p = \frac{2D^*\lambda_u{}^2}{2D^*\lambda_u + 1} \tag{6b}$$

where all symbols are as in the previous Eqs.

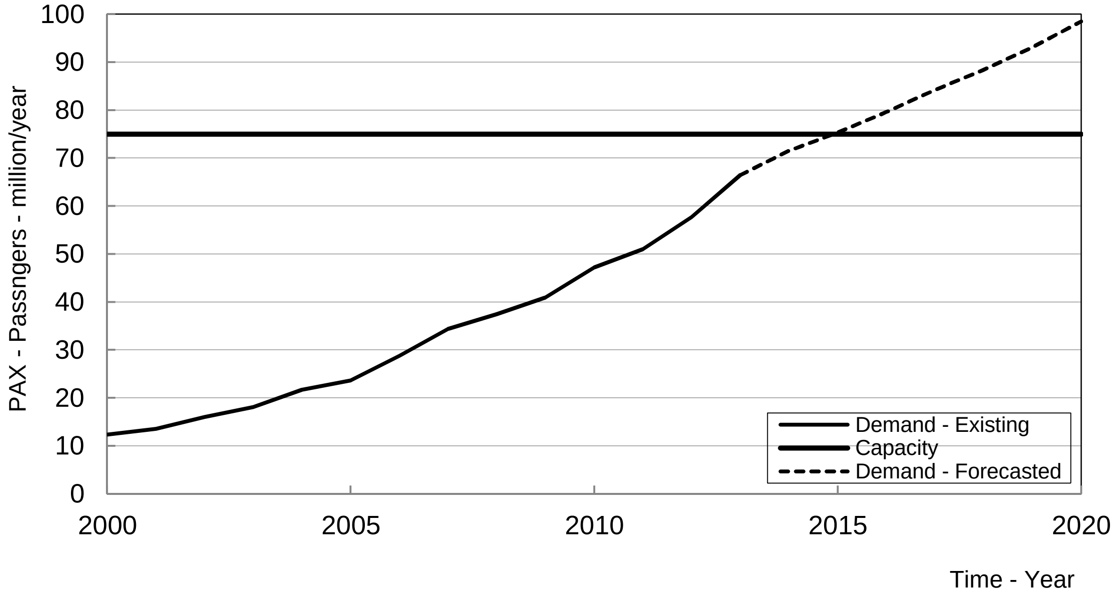
4 AN APPLICATION OF THE MODELS

The above-mentioned capacity models are applied to the case of two closely-spaced parallel runways at DXB (Dubai International) airport. Despite the new airport (DXC) has been build and already taken over most of the DXB's traffic, its case is sufficiently generic to illustrate the potential of the above-mentioned models, and their usefulness to be applied to other similar airport runway system cases.

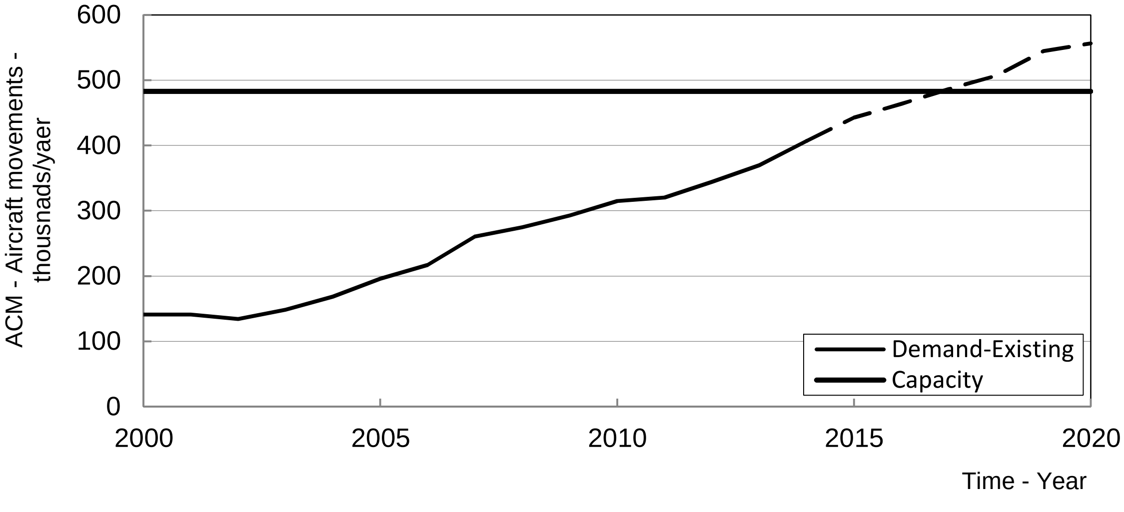
4.1 DXB (Dubai International) Airport

4.1.1 Traffic demand development

The numbers of passengers, volumes of cargo, and aircraft movements at Dubai international airport (DXB) have grown tremendously during the past decade. Figure 4(a, b) shows such growth of the number of passengers and aircraft movements during the period 2000 - 2013 (DA, 2013).



a) Passengers



b) Aircraft movements

Figure 4 Development of Dubai International Airport (Period: 2000 – 2013 and 2013 - 2020) (DA, 2013)

Figure 4a shows nearly an exponential increase in the annual number of passengers from about 12 million in the year 2000 to about 62 million in the year 2013. This has been mainly driven by the development of the main airlines - domestic Emirates and its code-sharing partner Qantas, both using the airport as their primary and secondary hub, respectively, of their long-haul hub and spoke-networks, flydubai operating the short-to medium-haul routes of its point-to-point network, and more than 130 other international airlines, all serving about 215 destinations worldwide. Simple regression analysis using the data from the period 2000-2013 shows a strong relationship between the annual number of passengers and the above-mentioned main driving forces as follows:

$$PAX_{ap} = 4.90 + 1.48 PAX_{al} \qquad R^2 = 0.998$$
$$t - stat \; (4.776)(18.196)$$

where

PAX_{ap} is the annual number of passengers handled at the airport (million); and
PAX_{al} is the annual number of passengers carried out by the main airline (Emirates) (million).

Figure 4b shows that the annual number of aircraft movements (ACM) has similarly grown supporting growth of the number of passengers, i.e., it increased from about 141 thousands in the year 2000 to about 370 thousands in the year 2013. Derived from the previous two, the average number of passengers per aircraft movement has grown more than proportionally with an average of 207 PAX/ACM during the observed period (2000 - 2013). This has be mainly due to a relatively substantive proportion of heavy and supper heavy long-haul aircraft in the airport's fleet mix.

If the above-mentioned developments continue similarly in the future as used to be in the past, i.e., over the period 2013 - 2020, the airport's "practical" annual passenger terminal capacity of 75 million passengers and the "practical" runway system capacity of 483 thousands aircraft movements will be saturated already in the year 2015 and 2017, respectively, as shown on Figure 4(a, b).

4.1.2 Terminal airspace, runway system, and capacity

The above-mentioned aircraft movements have been accommodated in the DXB airport's airside area including terminal airspace, the runway system consisting of two closely-spaced staggered parallel runways, the network of taxiways, and 157 apron/gate aircraft parking stands (DA, 2013).

In particular, the terminal airspace of DXB airport is equipped with four WPs (Way Points) supported by VOR/DME DXB, all used to define the holding pattern of arriving aircraft (Jeppsen, 2007). Figure 5 shows that the holding points are WP UKRIM and PEDOW for approaches and landings on RWY (Runway) 12L or 12R, respectively, and WPs SEDPO and LOVOL for approaches and landings on RWY 30L or 30R, respectively.

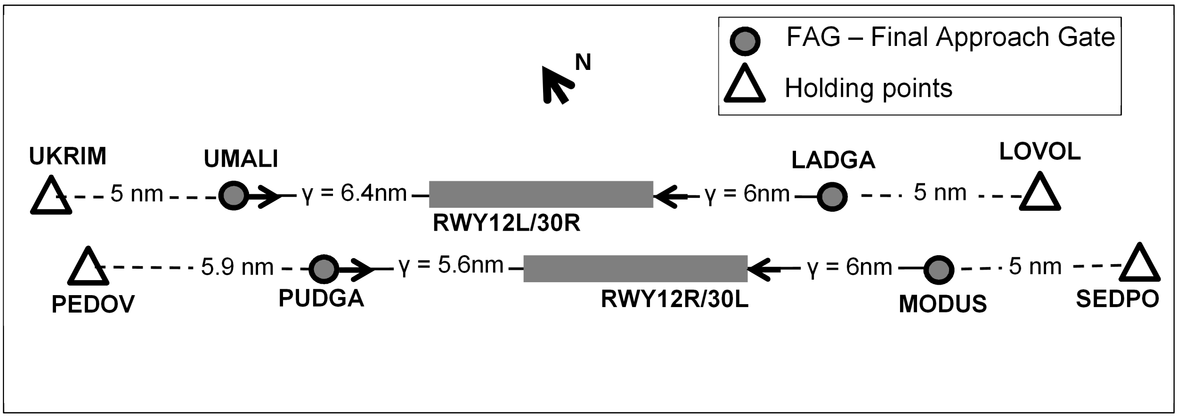


Figure 5 Simplified geometry of the terminal airspace of Dubai International airport (DXB) (Jeppsen, 2007)

In the former case, the distance UKRIM - RWY12L is 11.4nm (nautical mile) and that WP PEDOV - RWY12R is 11.5nm. In the latter case, distances between WPs SEDPO and LOVOL and corresponding RWYs (thresholds) 30L/30R are 11.0nm. The approaching and landing aircraft on

RWY12R/12L, after leaving the holding pattern, fly between WPs PEDOV and PUDGA, and WPs UKRIM and UMALI, respectively, at the constant altitude of 2000ft (600m). The WPs PUDGA and UMALI represent the FAGs (Final Approach Gate(s)) for starting the final approach and landing, always along the ILS (Instrument Landing System) 3-D defined trajectory. The procedure is similar for approaches and landings on RWYs30L/30R, where WPs MODUS and WP LADGA, respectively, are the FAGs. The holding procedure of 4min is performed around all WPs at the altitudes between 2000ft and 4000ft (Jeppsen, 2007)

The length of RWY12L/30R and RWY12R/30L in Figure 5 is 4000m and 4447m, respectively, and their width is 60m. These enable accommodation of all large/heavy, including the largest/super heavy A380 aircraft. The lateral spacing between the two runways is: 385m, i.e., less than 760m (2500ft), which categorizes them as the closely-spaced parallel runways, currently safely operating as a single runway (DA, 2013; Janic, 2008). The runways are staggered for 1553m in courses 12L/30R and 2000m in courses 12R/30L, respectively.

The "practical" runway system capacity of DXB airport is specified by the declared number of daily slots for the year 2014 - 661/661 for landings/taking-offs, respectively. This makes the daily total of 1322 ACMs and the annual total of 482530 ACMs, if assumed that the airport continuously operates over the whole year without any constraints affecting the capacity (DA, 2013). At the same time, the capacity of the apron/gate complex where the gate/stands are exclusively used by particular aircraft categories amounts 91aircraft/h. This gives the total capacity of 2184 aircraft/day and the annual capacity of 797160 aircraft/year implying continuous operations during the year. The assumption on the continuity of airport operation over the year is introduced only for the illustrative purposes. Actually, at most airports including this one it is highly unrealistic (DA, 2013; deNeufville and Odoni, 2003).

4.2 Inputs

The proposed models of "ultimate" and 'practical" capacities are applied to calculating the capacity of two closely-spaced parallel runways at Dubai International airport (DXB). The inputs used are geometry of the terminal airspace and the runway system (Figure 5), characteristics of the current and future aircraft fleet mix, and the ATC/ATM current and innovative operational procedures applied to both landings and taking-offs (Figures 1-3).

The characteristics of the terminal airspace and of the runway system are synthesized in Table 1.

Table 1 Characteristics of terminal airspace and runway system at DXB airport
(DA, 2013, Jepssen, 2007)

Runway	**Length/width** (m/m)	**Lateral separation** d (m)	**Staggering distance** ε_{kl} (m)	**Length of the final approach path** γ_{ik}/γ_{jl} (nm)
12L/30R	4000/60	385	1533	6.4/5.6
12R/30L	4447/60	385	2000	6.0/6.0

The characteristics of current and future aircraft fleet mix are given in Table 2...

Table 2 Characteristics of aircraft fleet at DXB airport (DA, 2013)

Aircraft category[1]	**Type**	**Proportion (c/f)**[2] (%)	**Approach speed**[3] (kts)	**Runway landing occupancy time** (s)	**Take-off run (lift-off) time**[4] (s)	**Runway take-off occupancy time**[5] (s)
A/Super Heavy	A380	17/23	145	60	44	60
B/Heavy	A300-600, A330, A340, A350, B747, B767, B777, B787,	69/77	140	60	44	60
D/Large	B737, A320, 321s	14/0	130	55	37	50

[1] RECAT/ ICAO categorization; [2] current/future; [3] Ground speed based on IAS (Indicated Air Speed + headwind of 10 kts); [4] Average (typical) time to lift-off; [5] Time for passing the runway during take-off

The aircraft category C/B757 and E/Small are not considered due to not operating at the airport.
The ATC/ATM minimum longitudinal/diagonal distance- and time-based wake-vortex separation rules between landings and taking-offs, respectively, are given in Table 3 and 4.

Table 3 The FAA/RECAT minimum IFR wake vortex longitudinal separation rules for landings - δ^{l}_{ij} and δ^{d}_{ij} (nm) (CAA, 2014; ICAO, 2001, 2008; EEC/FAA, 2008; FAA, 2012)

A/C sequence	A/Super Heavy	B/Heavy	D/Large
A/Super Heavy	2.5[1]	5	7
B/Heavy	2.5	4	5
D/Large	2.5 (1.5)[2]	2.5 (1.5)[2]	2.5 (1.5)[2]

[1] RECAT (Tittsworth et al., 2012); [2] Diagonal separation rules

Table 4 The ICAO/FAA minimum wake vortex time-based separation Rules for take-offs - $t_{d/kl/min}$ (min) (CAA, 2014; FAA, 2012; ICAO, 2001)

A/C sequence	A/Super Heavy	B/Heavy	D/Large
A/Super Heavy	2.0	2.0	2.0
B/Heavy	1.5	1.5	2.0
D/Large	1.0	1.0	1.0

In Table 3, it is assumed that the ATC/ATM minimum diagonal separation rules applied between paired landings on the closely-spaced parallel runways without any wind conditions/restrictions are:

δ_{dij} = 1.5nm, if the leading aircraft *(i)* belongs to D/Large and/or E/Small and the trailing aircraft *(j)* to any wake vortex category. The minimum vertical separation rules applied to any landing sequence are: H_{ij}^{0} = 1000ft. In addition, the ATC/ATM longitudinal separation rules enabling a take-off between any two landings are: $\delta_{d/jk}$= 2nm (CAA, 2014; EEC/FAA, 2008; FAA, 2012; ICAO, 2001, 2008). As well, the ILS GS (Glide Slope), i.e., final approach and landing angle for all aircraft categories is adopted to be: $\alpha = 3^{0}$ (Jeppsen, 2007)

4.3 Scenarios for calculating capacity

The "ultimate" capacity of the runway system at Dubai International airport (DXB) is calculated by using the above-inputs for the calculating scenarios given in Table 4:

Table 5 Scenarios for calculating the runway system capacity at Dubai International airport (DXB)

Capacity	Element	Description
	• The runways in use	• 12L/12R; 30L/30R ($\varepsilon_{kl} > 0$; $\varepsilon_{kl} < 0$)
Landings		
	• The ATC/ATM minimum separation rules	• Longitudinal FAA/RECAT only • Vertical only • Longitudinal FAA/RECAT + FAA diagonal • Vertical + FAA diagonal
Taking-offs		
	• The ATC/ATM minimum separation rules	• Current • Weather (crosswind) dependent
Mixed		
	• The ATC/ATM minimum separation rules	• Current • Weather (crosswind) dependent

In scenarios in Table 5, the current and future aircraft fleet mix is considered. The "practical" capacity is calculated as based on the "ultimate" capacity in particular scenarios in Table 5.

4.4 Results

The above-mentioned capacity models are applied to calculating the "ultimate" and "practical" capacity using the above-mentioned inputs and scenarios of operating closely-spaced parallel runways at DXB airport. Based on the mentioned "ultimate" capacities, the "practical" or "declared" capacity is additionally calculated and compared to the corresponding current airport-specified capacity values (declared number of slots for the year 2014).

4.4.1 "Ultimate" capacity

The calculated runway system "ultimate" capacity is calculated for the scenarios of using two parallel runways shown in Figures 1-3. The results have shown that the landing capacity, independently on applied ATC/ATM separation rules, is higher if the leading aircraft lands on the staggered and the trailing aircraft on the closer runway, than vice versa. As well, this difference increases with increasing of the runway staggering distance. The take-off capacity and the capacity for mixed operations remain the same independently on the pattern of runway use. Assuming that different above-mentioned cases of using runways are practiced in equal proportions over longer period of time, the average runway system capacity, to be used for both planning and operational purposes, is synthesized as the capacity envelopes shown on Figure 6, 7, 8, and 9.

Figure 6 shows the runway system capacity envelopes when different ATC/ATM separation rules are applied to landings of the current aircraft fleet mix given in Table 2. The capacity envelope of a single runway and the airport-specified "practical" capacity are also shown as the benchmarking cases, i.e., for the comparative purposes (DA, 2013).

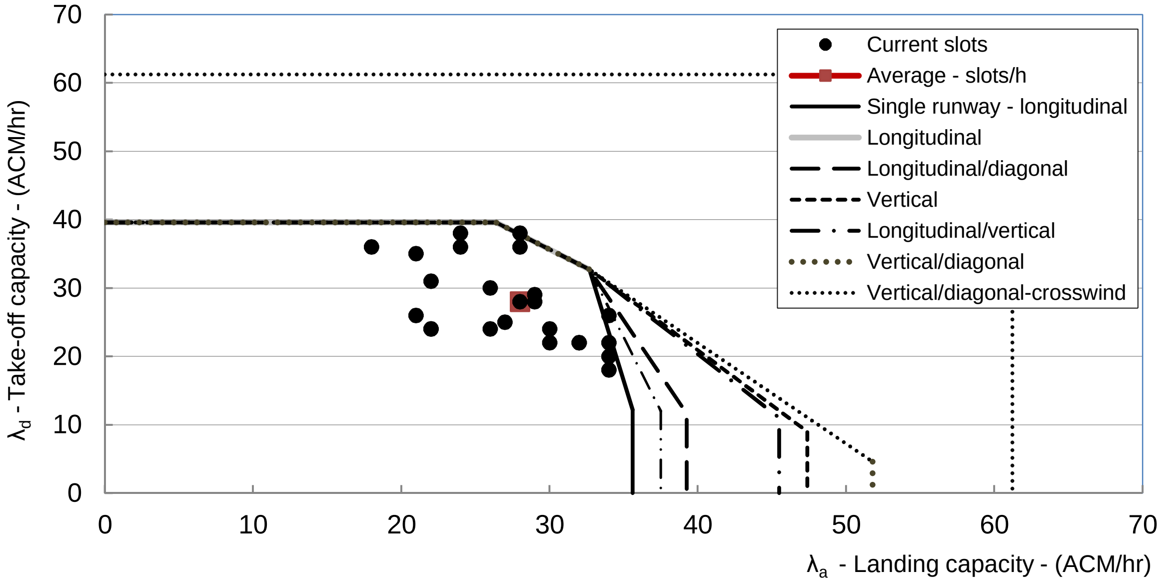


Figure 6 The runway system capacity envelopes at DXB airport when different ATC/ATTM separation rules are applied to landings of the current aircraft fleet mix

As can be seen, the runway system take off and mixed operation capacity remain the same independently on the ATC/ATM separation rules applied between landings as intuitively expected. However, the landing capacity appears very sensitive to type of the ATC/ATM separation rules applied. As compared to the landing capacity of a single runway and that of two closely-spaced parallel runways operating as a single runway when the ATC/ATM current longitudinal distance based-separation rules are applied, the landing capacity increases when the paired landings are realized successively on different runways. This increase amounts 5.3% when longitudinal, 10.3% when mixed longitudinal/diagonal, 33.1% when vertical, 27.8% when mixed longitudinal/vertical, and 45.5% when mixed vertical/diagonal ATC/ATM separation rules are applied. At the same time, with increasing of the landing capacity, the taking-off capacity decreases. Specifically, under convenient crosswind conditions, the landing, take-off, and mixed operation capacity could "explode", implying carrying out an ACM every minute or a half of minute (but this is just a hypothetical hardly realistic situation in the given case). In addition, the "ultimate" capacity envelopes lie above the airport-specified "practical" capacity figures as expected (DA, 2013). For example, the average "ultimate" capacity for mixed operations is for about 18% higher than its "practical" airport-specified counterpart. If the airport operates 24 hours during 365 days per year, the annual "ultimate" capacity will increase from the current 483 to about 578 thousands ACMs. Consequently, respecting development of demand in Figure 4b, such "ultimate" capacity will be saturated up to about 96% in the year 2020.

Figure 7 shows the capacity envelopes when different ATC/ATM separation rules are applied to landings of the future aircraft fleet mix given in Table 2. The capacity envelope for a single runway serving the current aircraft fleet mix is again provided as a benchmark, i.e., for the comparative purposes.

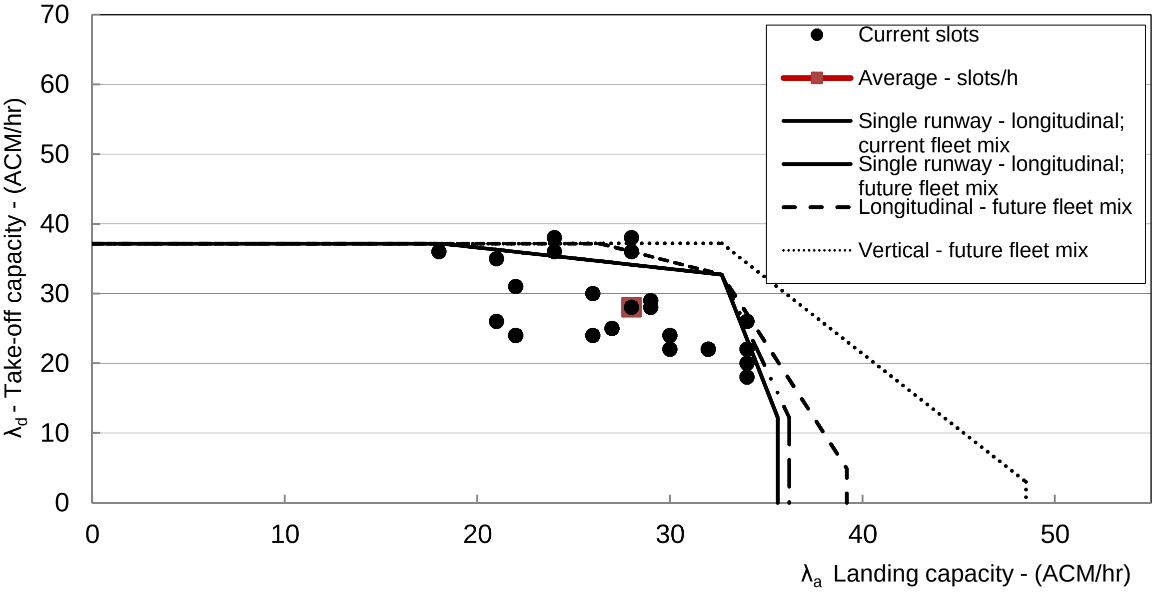


Figure 7 The runway system capacity envelopes at DXB airport when different ATC/ATTM separation rules are applied to landings of the future aircraft fleet mix

As can be seen, in this case the “ultimate” take-off capacity for the future aircraft fleet mix is lower than that for the present one for about 6.6% while the capacity for mixed (50/50%) operations remains the same. The landing capacity of a single runway will increase negligibly, for 1.7%, just due to lower heterogeneity of the future landing aircraft fleet mix. However, the landing capacity of dual runways will increase for 8.3% if the longitudinal and 34% if the vertical ATC/ATM separation rules are applied as compared to their single runway counterpart. At the same time, with increasing of landing capacity, its taking-offs counterpart will decrease. The other above-mentioned combinations of ATC/ATM separation rules between landings are not applicable to the future fleet mix expected to exclusively consist of heavy and supper heavy aircraft.

In addition, the capacity envelopes again stay above but very close to the airport-specified “practical” capacity figures with few exceptions for cases when the vertical separation rules are applied. The average capacity for mixed operations is again greater than its “practical” airport-specified counterpart. Consequently, the effects on the total annual capacity and its saturation until the year 2020 could be similar as those on Figure 6.

Figure 8 shows the capacity envelopes when the ATC/ATM vertical separation rules are exclusively applied to landings of the current and future aircraft fleet mix. The capacity envelope for a single runway, current aircraft fleet mix, and the ATC/ATM existing wake-vortex longitudinal separation rules is given as a benchmark, i.e., for the comparative purposes.

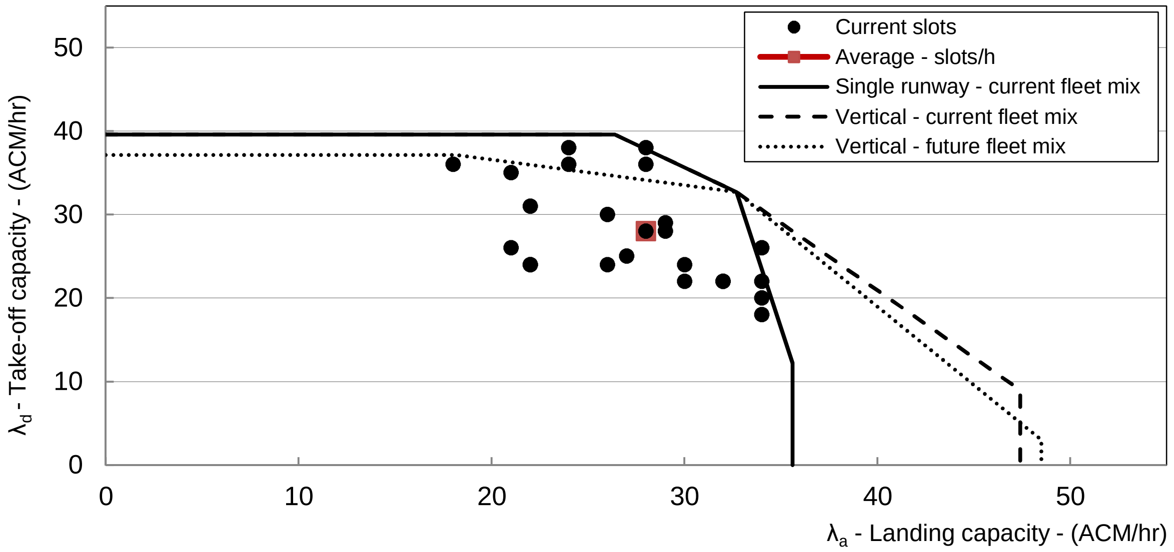


Figure 8 The runway system capacity envelopes at DXB airport when the ATC/ATTM vertical separation rules are applied to the current and future aircraft fleet mix

As can be seen, the take-off capacity and that for mixed operations are the same as their single runway counterpart. If the ATC/ATM vertical separation rules are applied to the current and future aircraft fleet mix, the corresponding landing capacities will increase for about 31% and 34%, respectively, as compared to their single runway counterpart. Again, its taking-off counterpart will decrease. The airport-specified "practical" capacity is again below the calculated capacity envelopes. The effects of the capacity gains for mixed operations at the annual scale have the very similar effects to saturation of the overall runway system capacity as those explained in Figures 6 and 7.

4.4.2 "Practical" capacity

The average number of slots for mixed operations as the "practical" or "declared" and calculated "ultimate" capacity for mixed operations shown in Figures 6, 7, and 8 are used to estimate the specified average delay per an ACM (landing and/or take-off) under given conditions. Based on Eq. 6a, this amounts 4.85min per ACM. With increasing of the average delay per ACM, which implies deterioration of the specified service quality, the "practical" capacity could shift closer to its "ultimate" counterpart. This is illustrated means by relationship between the "ultimate" and "practical" landing capacity shown in Figure 9.

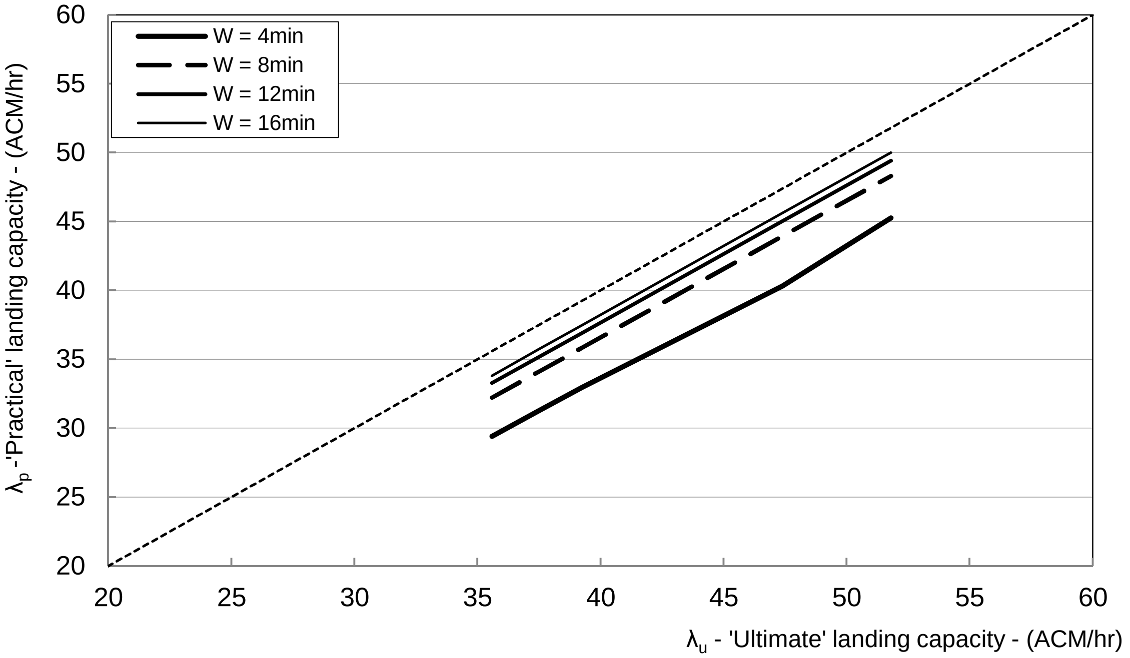


Figure 9 Relationship between "practical" and "ultimate" capacity and maximum average delay imposed on ACM (landing) at DXB airport

The "ultimate" landing capacities are based on the above-mentioned application of different ATC/ATM separation rules. As can be seen, the "practical" capacity increases in line with increasing of the "ultimate" capacity for given average delay per ACM. As well, a gap between two capacities decreases with increasing of the average delay. This implies that the airport can generally use the average delay as an instrument for increasing the number of declared landing slots but only on the account on deteriorating the quality of service due to prolonging landing delay(s).

5 CONCLUSIONS

This paper has dealt an analysis and modelling of the short- and medium-term solutions for matching the airport runway capacity to demand. The solutions have assumed to be new technologies supporting innovative procedures supporting landings and taking-offs at closely spaced parallel runways. These have otherwise commonly operated as a single runway. For such a purpose, the existing analytical models of both "ultimate" and "practical" capacity of the closely-spaced parallel runways have been appropriately modified by taking into account the ATC/ATM (Air Traffic Control/Air Traffic Management) current longitudinal and diagonal, and prospective vertical separation rules between landings, time-based separation rules between taking-offs, and the mixed time-distance based separation rules between mixed operations. The models have been applied to Dubai International airport ((DXB) (Dubai, UAE). The main reasons have been twofold: On the one hand the airport had in the past and is expected in the future to experience continuous growth of air transport demand leading to saturation of its current runway capacity by the year 2015/16 (The building of new airport DXC has not been considered). On the other, it has been to assess the potential of innovative operational procedures supported by the new technologies (under development in European SESAR and U.S. NextGen programs) to eventual increasing of the runway system capacity under given conditions. In addition, a "what-if" scenario of operating the runway system under convenient crosswind conditions has been considered As well, the "ultimate" and "practical" capacity have been interrelated means by an average delay per ACM (landing and/or take-off).

The results presented as the runway system capacity envelopes including that for single runway used as a benchmarking case have shown the following:

- The models applied under given circumstances have realistically reflected operations at given airport by indicating obvious differences between the "ultimate" and "practical" (or "declared") capacity;
- Increase in the landing and taking-off "ultimate" capacity as compared to that of a single runway counterpart thanks to the paired use of two parallel runways, while performing innovative operational procedures supported by the new technologies in combination with different ATC/ATM longitudinal/diagonal separation rules applied to the current aircraft fleet mix;
- Substantive increase in the "ultimate" landing capacity by applying the ATC/ATM vertical separation rules to the paired landings of the current and future aircraft fleet mix. However, except in the balanced case (50/50%), increase in the landing capacity generally causes decrease in the corresponding taking-offs capacity, and vice versa;
- Tremendous increase in the landing, taking-off, and mixed operation "ultimate" capacity under convenient crosswind conditions; as compared to the previous counterparts should be considered as the hypothetical case;
- Increase in the "practical" capacity by increasing the "ultimate" capacity and balancing between the two by the specified average delay per ACM (landing and/or taking-off); and
- An obvious potential of innovative procedures supported by the new technologies for increasing the "ultimate" and consequently "practical" or "declared" capacity of closely-spaced parallel runways at DXB airport, thus enabling postponing its forecasted saturation at least until the year 2020 and maybe beyond, when the new airport (DXC) is expected to be fully operationalized.

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