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The potential of some of the innovative operational procedures for increasing the airport landing capacity

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Abstract

The ATC (Air Traffic Control) system is established over some designated airspace in order to enable safe, efficient and effective aircraft movements between their origin and destination airports. The main operational performance of these airports has been their airside and landside capacity. In particular, the airport airside capacity includes the capacity of the runway system and surrounding (close) airspace, and the capacities of of taxiways and apron/gate complex. Different concepts of the airport runway system capacity can exist. The first is the concept of the "ultimate" capacity expressed by the maximum number of air transport movements (atms), carried out during a given period of time (usually one hour) under conditions of constant demand for service (atm is either one landing or take-off). The other is the concept of "practical" capacity expressed by the maximum number of atms carried out during a given period of time guaranteeing the average delay per atm within the prescribed limits. Both capacities are calculated respecting the given operational procedures and supportive technologies.

This chapter describes modeling of a potential of some of the innovative operational procedures for safe increasing the "ultimate" runway landing capacity. These are: i) the ATC time-based separation rules applied to landings on a single runway; and ii) the steeper approach procedures applied tp landings on the closely-spaced parallel runways. The modeling implies developing a methodology consisting of the dedicated analytical models for estimating the runway "ultimate" landing capacity under given conditions, which are applied to the selected airports according to the "what-if" traffic scenario approach.

Key words: airport, runway landing capacity, innovative operational procedures, the ATC time-based separation rules, the steeper approach procedures, closely-spaced parallel runways.

1. Introduction

Despite continuous efforts by the air transport system operators, regulators, and researchers (academic and consultants), the problem of providing sufficient airport runway capacity to match continuously growing demand safely, efficiently, and effectively has had rather limited success. A[art from growing demand, the specific environmental (mainly noise) constraints at many large airports both in US and Europe have prevented the full utilization of the designed runway capacity. The sharp concentration of atms (air transport movements) (one atm corresponds to one landing or one take off) within the rather short time periods at the hub airports due to operating the hub-and-spoke networks has created sharp peaks causing further already existing imbalance between demand and the available runway capacity. At some other airports one of which is, for example New York La Guardia airport (US), a high demand/capacity imbalance has been created simply because of their attractiveness and not primarily due the type of airline scheduling practice. In addition, specifically in the US, the operation of airports under IMC (Instrument Meteorological Conditions) and VMC (Visual Meteorological Conditions) and the corresponding difference in the ATC (Air Traffic Control) minimum landing distance-based separation rules (IFR – Instrument Flight Rules, and VFR – Visual Flight Rules, respectively) have inherently created instability of the airports' declared runway landing capacities and consequently their rather high vulnerability to weather conditions. In Europe, such capacity instability caused by weather has also been relatively high, even though the aircraft landings have been carried out exclusively by applying IFR under both IMC and VMC. As well, the shortage of land for expanding the airport runway capacity at many airports has also contributed to the above-mentioned demand/capacity imbalance there in the long-term. In all cases, this imbalance has created congestion, delays and related airline and air passenger costs.
Under such circumstances, the different ultimately short-term measures for mitigating the demand/capacity imbalance by influencing both demand and capacity have been considered. On the demand side, these have generally been demand management by the slot regulation, auction and trading-off of slots, and eventually congestion charging. On the capacity side in addition to building new runways as the long-term measure, these have mainly included introducing the innovative operational procedures supported by the existing and/or innovative technologies. In general, these latter measures have expected to contribute to reducing the ATC separation minimums between landing aircraft and consequently provide the landing capacity gains within the existing airspace and airport infrastructures (Czerny et al., 2008; Janic, 2008, 2008a; CRS, 2008). The ATC separation minimums have mainly been based on the horizontal distances between landing aircraft, which have been modified respecting the impact of the wake-vortices generated behind the large (heavy) aircraft. The landing aircraft have followed the standardized GS (Glide Slope) angle of 3^0 of the ILS (Instrument Landing System). Such rather inflexible but safe operational pattern has provided the runway landing capacity with the above-mentioned characteristics – insufficient and vulnerable to weather. Consequently, the question is whether some innovative operational procedures supported by the existing and/or new technologies could safely increase the airport runway landing capacity and diminish its vulnerability to weather. Some of these considered are the ATC time-based instead of the current ATC distance–based separation rules between landings on a single runway, and the steeper approach procedures to the closely-spaced parallel runways. Both would be supported by the various ATC (Air Traffic Control) decision-support tools at both tactical and operational level. Specifically, in the US, some of these have included Ground Holding Program (GHP),

Airspace Flow Program (AFP), Flight Schedule Monitor (FSM), Flight Schedule Analyzer (FSA), and Traffic Management Advisor (TMA) (CRS, 2008).
In addition to this introductory section, this Chapter consists of five other sections. Section 2 describes the above-mentioned innovative operational procedures for increasing and stabilizing the airport runway landing capacity. Section 3 develops a methodology consisting of the dedicated models for estimating the potential contribution of particular innovative procedures to increasing the runway landing capacity. Section 4 presents application of particular models. The final section (5) summarizes some conclusions.

2. The innovative operational procedures for increasing the runway landing capacity

2.1 Background

The innovative operational procedures for increasing (and stabilizing) the airport runway capacity include the ATC time-based instead of the currently used distance-based separation rules between landings on a single runway and the steeper approach procedures to the closely-spaced parallel runways (Janic, 2008; 2008a).

2.2. The ATC time-based separation rules for landing aircraft

2.2.1 Background

At oresent, at the US airports, depending on weather, the aircraft landings are carried out either under IMC or VMC. Both types of conditions are specified by two parameters - ceiling and visibility - as shown in Figure 1 (FAA, 2004).

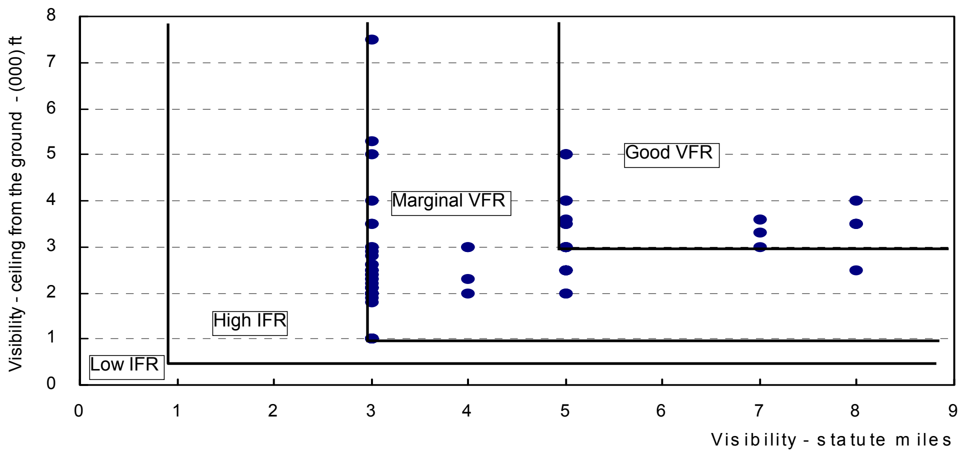


Fig. 1. Characteristics of the meteorological boundary conditions at the 75 selected US airports (Compiled from (FAA, 2004; NASA, 2001)

As can be seen, the critical ceiling is the most diverse when the horizontal visibility is 3 and 5 (statute) miles and relatively homogenous when this visibility is 4, 7 and 8 miles. In addition, most airports operate at the margin between the "high IFR" and the "marginal VFR" (FAA, 2004; NASA, 2001). Depending on the above-mentioned weather conditions (IMC or VMC), the ATC applies the VFR and IFR corresponding minimum separation rules between landing aircraft given in Table 1 (FAA, 2004).

		IFR		
i/j	**Small**	**Large**	**B757**	**Heavy**
Small	2.5(3)	2.5(3)	2,5(3)	2.5(3)
Large	4.0	2.5(3)	2.5(3)	2,5(3)
B757	5.0	4.0	4.0	4.0
Heavy	6.0	5.0	5.0	4.0
		VFR		
i/j	**Small**	**Large**	**B757**	**Heavy**
Small	1.9	1.9	1.9	1.9
Large	2.7	1.9	1.9	1.9
B757	3.5	3.0	3.0	2.7
Heavy	4.5	3.6	3.6	2.7

Table 1. The FAA (ICAO) minimum separation rules between landing aircraft (nm)
Compiled from: (FAA, 2004; NASA, 1999, 2001)

As can be seen, the current IFR separations applied under IMC are for about 40 per cent stricter than the VFR separations applied under VMC. Both separation rules generally eliminate the impact of the wake vortices of the leading aircraft on the trailing aircraft in particular combinations of landing sequences on the same runway. Under an assumption that the potential exposure of the trailing aircraft to the wakes generated by the leading aircraft in a given landing sequence is nearly the same for both types of separations, the question is: ″Why is such a distinction between the VFR and the IFR separations?″. The possible answer could be that under VMC, the trailing aircraft fly on the principle "see and be seen" by keeping just a sufficient distance to avoid the wake vortex hazard from the leading aircraft. Under IMC, in addition to the basic separation rules required to avoid the wake vortices, the ATC introduces the additional "buffers" to compensate the cumulative system error in estimating the aircraft position(s). These positions are visualized for the ATC controllers thanks to the sophisticated radar systems. The influence of the two categories of separation rules on the landing capacities, i.e arrival rates, at the selected US airports are shown in Figure 2.

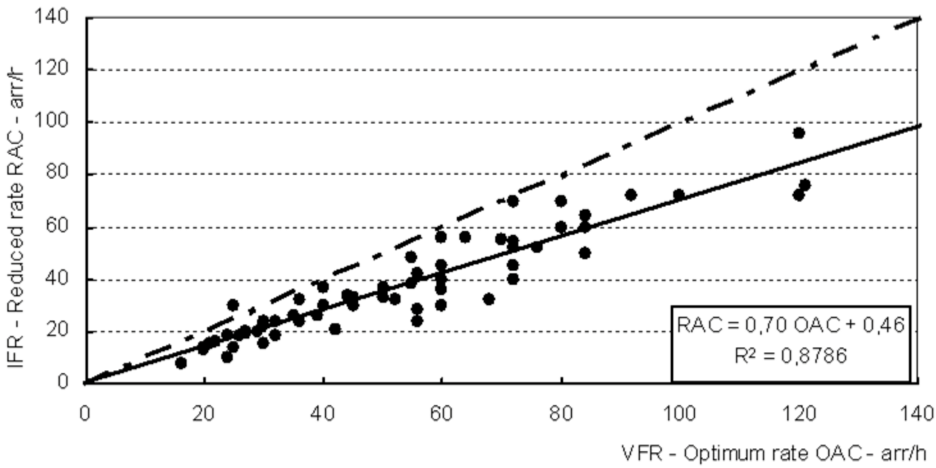


Fig. 2. Relationship between the IFR and VFR landing capacity at the selected US airports (Compiled from: FAA, 2004; NASA, 2001)

As can be seen, a rather strong linear relationship between the IFR and VFR landing capacities (arrival rates), with an average difference of about 30 per cent exists, i.e. the IFR landing capacities generally amount up to about 70 per cent of the corresponding VFR landing capacities. In Europe, independently of the weather conditions, the landings are carried out exclusively according to the IFR separations in Table 1 (EEC, 2005). Consequently, the question is if it is possible to set up the time-based separation rules, which would be standardised respecting the true (dynamic) behaviour of the wake vortices under all weather conditions. In general, these separation rules are expected to provide the shorter minimum time-distance intervals between successive landing aircraft and consequently increase the current distance-dependent runway landing capacity while maintaining it rather stable subject to weather changes. This could be possible if more precise monitoring of the true behaviour of the wake vortices behind particular aircraft would be enabled to pilots, ATC, and/or both.

2.2.2 The "wake reference airspace"

Monitoring the true behaviour of the wake vortices, i.e. dynamically, requires defining the "wake reference airspace" used for the final approach and landing on a given runway. In general, this space consists of two parts: i) the "wake vortex corridor", i.e. the airspace of shape of a horizontal prism, which spreads along the extended centreline of the runway; and ii) the SHA (Simplified Hazard Area) in which the wake vorteuces generated by a given aircraft remains until they decay and/or vacate the "wake reference airspace" (Janic, 2008; ONERA/DOTA, 2005). The "wake vortex corridor" begins at FAG (Final Approach Gate), which is usually defined as the waypoint or by the radio-navigational aid (VOR/DME). Ur ends at the runway touchdown area. Figure 3 shows the simplified three-dimensional scheme of the "wake reference airspace".

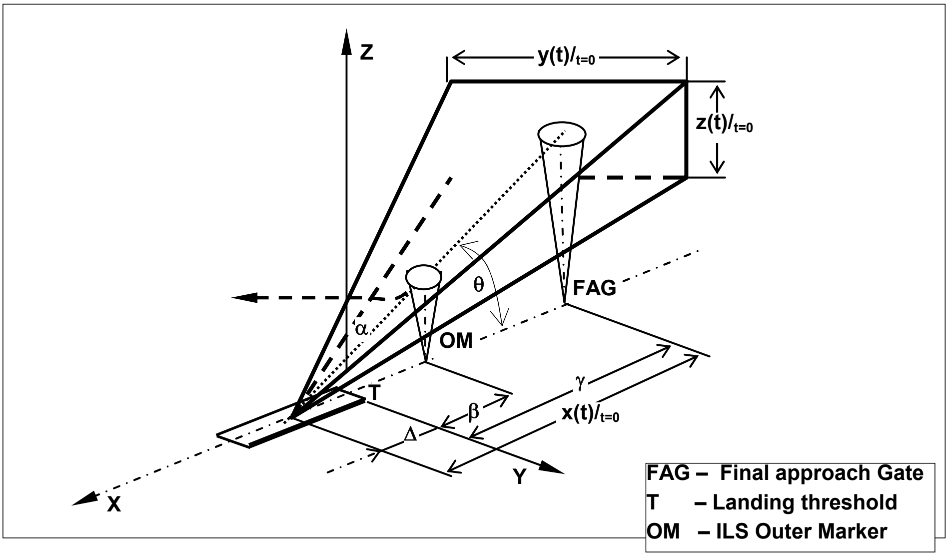


Fig. 3. Three-dimensional scheme of the "wake reference airspace" (Compiled from (Janic, 2008)

where γ is the length of the "wake vortex corridor"; Δ is the horizontal distance between the FAG (Final Approach Gate) at the beginning of the "wake vortex corridor", and the runway landing threshold *T*; OM and MM are Outer and Middle marker, respectively, of ILS (Instrument Landing System); $x(t)$, $y(t)$, and $z(t)$ are longitudinal, horizontal, and vertical coordinates, respectively, of the "wake reference airspace", depending on time (t); β is the horizontal distance between the location of the OM and the runway-landing threshold T α is the angle between the axis of the "wake vortex airspace" and one of its sides in the horizontal plane; and θ is the nominal angle (ILS Glide Slope) of the aircraft approach path in the "wake vortex airspace".

As mentioned above, ILS provides the approaching and landing aircraft with primary navigation. In the future, the Cockpit Display Traffic Information (CDTI) system on-board the aircraft supported by the ADS-B device will be used for easier self-managing the arrival procedure individually and relative to other close traffic. The ATC usually uses the highly sophisticated radar system for monitoring the arriving traffic. For example, the Precision Radar Monitoring (PRM) system is one of them. In addition, monitoring and prediction of the wake vortex behavior in the "wake reference airspace" is and will be carried out by the current and forthcoming technologies and systems both on the ground and on board the aircraft (Choroba, 2003; Wilkenmans and Desenfans, 2006). The most well-known current system on the ground is Aircraft Vortex Spacing System (AVOSS) currently operating at Dallas Fort Worth airport (US). The system provides the dynamic spacing criteria between aircraft approaching the single runway along a pre-defined corridor based on the prediction of the wake vortex position and strength dependent on the current weather conditions. The wake attribute, which first clears the corridor at a certain ("reference") profile, defines the distance separation criterion for a given aircraft. The standardization and operationalization of such ATC distance-based into the ATC time-based separation rules will likely require the full development of the active (dynamic) forthcoming wake vortex advisory systems such as ATC WAKE, WAKEVAS, and WVWS The particular components of these systems both onboard the aircraft and at the ATC working desk will enable monitoring and predicting the wake vortex behavior within the entire "wake reference airspace" and exchanging the information between pilots and controllers online, i.e. automatically via data link. The information on the wake vortex of the preceding aircraft would be presented to the crew either on the Navigational or Primary Flight Display containing the wake's strength and prospective behavior (movement) within the "wake reference airspace". Under such circumstances enabling pilots to monitor the wake vortex of the aircraft they follow on the cockpit screen instead of looking at the aircraft itself, which they cannot see under IMC, the separation between the landing aircraft could become purely the dynamic time-based separation, and, in terms of the distances, closer to the today's VFR minimum distance-based separation intervals mainly applied to the US airports (Choroba, 2003; Wilkenmans and Desenfans, 2006).

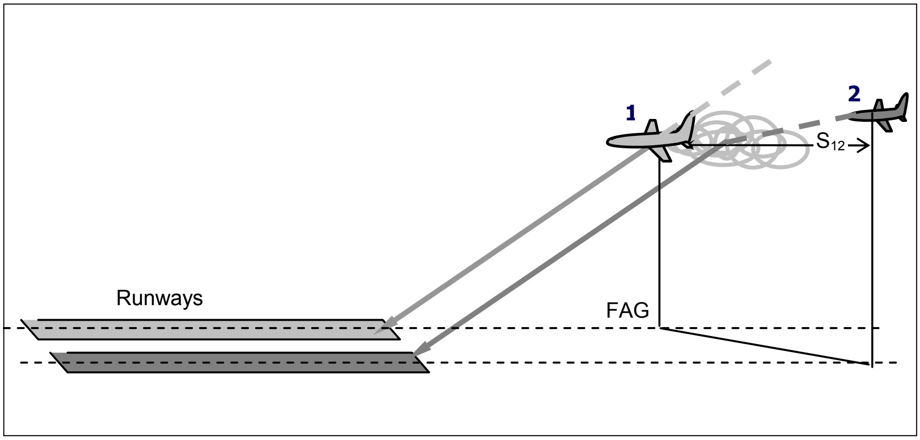
2.3 The steeper approach procedures

2.3.1 Background

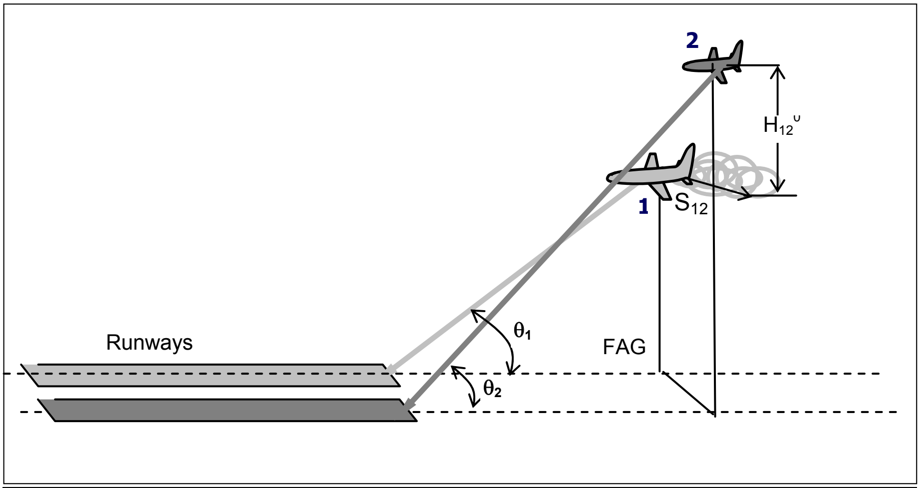
Different configurations of parallel runways are used at busy European and US airports. In Europe, the four busiest continental hubs operate parallel runways: Frankfurt-Main (Germany) a pair of closely-spaced (dependent), and London Heathrow (UK), Paris Charles de Gaulle (France), and Amsterdam Schiphol airport (The Netherlands) a pair, two pairs, and three pairs of the far-spaced (independent) parallel runways, respectively. Currently, at the U.S. the busiest hub airports operate 28 pairs of closely-spaced, 10 pairs of the intermediate-s[aced, and 28 pairs of the far-spaced parallel runways (NASA, 1998). In addition to the above-mentioned characteristics valid for a single runway, in case of parallel runways, the wakes can move from the "wake reference airspace" of one runway to this airspace of the adjacent runway(s) at the speed almost proportional to the speed of crosswind. If the wakes do not sufficiently decay before reaching the adjacent runway, they can create a hazard for the aircraft there, thus making operations on both runways dependent on each other (Burnham, 2002; FAA, 2004; Hammer, 2000; NASA, 2001). Under such circumstances, under VMC, the ATC applies the VFR to the approaches to the parallel runways spaced by 2500 ft (762m) and less by assuming that the wakes generated along the "wake reference airspace" of one runway will never reach this airspace of the adjacent (parallel) runway. This makes the two runways operationally independent on each other (FAA, 2004; Janic, 2008a; LMI, 2004). Under IMC, the ATC exclusively applies the IFR horizontal separation rules in Table 1 between the aircraft approaching to either of the closely-spaced parallel runways, thus making both runways to operate as dependent of each other, i.e. as a single runway. In such case, the CNAP (Conventional Approach Procedure) is performed (Janic, 2008a).

2.3.2 The characteristics of Steeper Approach Procedure (SEAP)

In order to mitigate the above-mentioned dependency of closely-spaced parallel runways the procedures for pairing the arriving aircraft under IMC similarly as under VMC have been considered in both Europe and US. In Europe this has been Staggered Approach Procedure (SGAP) with displaced landing threshold at one of the closely–spaced parallel runways at Frankfurt Mian airport (Germany) (Fraport, 2004). In the US these have been: Simultaneous Offset Instrument Approach/Precision Runway Monitoring (SOIA/PRM), and the most advanced but still under the conceptual development NASA/FAA TACEC (Terminal Area Capacity Enhancing Concept) (Burnham, 2002; Cotton et al., 2001; EEC, 2005), These and an additional innovative procedure called Steeper Approach Procedure (SEAP) use both ATC horizontal and vertical separation rules simultaneously. Figure 4 (a, b) shows the principal difference between CNAP and SEAP performed under IMC (Janic, 2008a).



a) Conventional Approach Procedure (CNAP)



b) Steeper Approach Procedure (SEAP)

Fig. 4. The CNAP and SEAP to the closely spaced parallel runways under IMC (Compiled from: Janic, 2008a)

The Steeper Approach Procedure (SEAP) could be considered as the prospective approach procedure under IMC in cases when it is necessary to avoid obstacles in the final approach airspace, if it is not possible to displace the landing threshold of one of two (closely spaced) parallel runways, but if it is needed to eventually relatively substantively increase the runway system capacity. Currently, the SEAP is applied to some single runway regional airports (six in Europe) mainly for avoiding obstacles and/or eventually reducing the noise burden (EEC, 2005). This procedure has never been considered for application to the closely-spaced parallel runways for any of the above-mentioned purposes and particularly not for eventual increasing of the runway system capacity under IMC. Even the above-mentioned future concept (TACEC) does not consider the final approaches at different (and steeper) GS angles than nowadays. Consequently, at this preliminary stage the SEAP is characterized as follows:

- Technologies

The SEAP applied to the closely-spaced parallel runways can be based on two pairs of ILSs (or GNSS supporting ADS-B in the future) each attached to one of the runways or a pair of MLSs each serving a single runway. For a given runway, one ILS provides the standard GS angle of 3^0 and the other the steeper GS angle of $5\text{-}7^0$. A single MLS provides simultaneously both GS angles within a given range: $3\text{-}7^0$ (This will also be possible when GNSS and ADS-B will be available) (Rossow, 2003;TC, 2004). The ILSs are preferably of the category IIIb or IIIc (i.e. with zero Decision Height (DH) and Runway Visual Range- (RVR) of 50ft or 0ft, respectively) thus enabling also the auto-landing under the worst visibility conditions (ICAO, 1996). Each ILS has different LLZ (Localizer) frequency coupled with the GP (Glide Path) frequency, which prevents interference between the ILSs serving the same runway. Thus, given aircraft can perform either the standard or the steeper approach and landing procedure independently, by using existing ILS avionics and Flight Management (FM) auto-landing system. MLS also enables the similar auto landing opportunities. In addition, the ATC can also use PRM for monitoring the arriving traffic. As well, other technologies improving the situational awareness both at aircraft and on the ground could be gradually implemented (EEC, 2005; ICAO, 1996; Janic, 2006, 2008a). Ub addition, the lighting system on each parallel runway must be appropriately calibrated respecting the different ILS or MLS GS angles. This might appear unfeasible causing the pilot confusion, and thus being considered as insufficiently safe. The auto-landing could mitigate or even eliminate this concern.

- Operations

The SEAP implies that the arriving aircraft can use either the standard or the steeper ILS GS angle while approaching to the closely-spaced parallel runways under IMC. In particular, if the aircraft pairing is made similarly as under VMC or the SOIA/PRM, the leading aircraft can be assigned the standard and the trailing aircraft the steeper GS angle. Figure 4b shows the simplified typical scheme when at the moment of pairing the heavy - leading *(1)* and small - trailing *(2)* aircraft approaching to the closely-spaced parallel runways. As can be seen, the leading aircraft *(1)* approaches to the right parallel runway at the standard GS angle θ_1; the trailing aircraft *(2)* approaches to the left runway at the steeper GS angle θ_2 ($\theta_1 < \theta_2$). The leading aircraft *(1)* and trailing aircraft *(2)* are appropriately vertically separated by the ATC vertical separation rules H_{12}^0 at the moment of pairing at FAG (Final Approach Gate) of aircraft *(1)*. This initial vertical separation does not exclude some horizontal separation S_{12}, which might be unnecessary. In addition, when the condition regarding the aircraft speeds and GS angles is fulfilled (i.e. $v_1 > v_2 sin\theta_2/sin\theta_1$), the initial minimum vertical separation H_{12}^0 continuously increases - until the leading aircraft *(1)* lands. Under such circumstances the aircraft *(2)* will always stay above the aircraft *(1)*, thus completely avoiding the hazard of its wakes staying all the time below its final approach trajectory. Nevertheless, the hazard from wakes along the same approach path still requires application of the ATC longitudinal (in-trail) separation rules.

- Traffic complexity

Performing the SEAP and CNAP simultaneously on the same runway(s) may increase the traffic complexity and consequently the workload of ATC controllers and pilots. However, the updated decision supporting tools such as CTAS (Centre/TRACON Automation System) and Integrated Arrival/Departure manager on the one hand, and CDTI on the other, may compensate such increased workload, respectively (Janic, 2006).

- Standardization

The SEAP is not the standardized ICAO procedure such as CNAP. Therefore, it needs approval from the local airport and national aviation.

- The aircraft certification

Specifically, the aircraft should be technically capable and consequently certified for SEAP similarly as they are currently certificated for CEAP. The certification could include only discrete but also the continuous GS angles within a given range. Since most Boeing and Airbus aircraft do not have such certification, the related costs of additional certification might be relatively high, of course if the aircraft are considered capable for being certified for the SEAP safely[1]. While following the steeper approach trajectory, the aircraft need higher descent speed, which in turn reduces the horizontal component of the resultant speed and thus seemingly increases the wake-vortex. In order to prevent the impact the resultant approach speed should be increased to compensate the higher vertical component authorities.

- Training the staff

The pilots and ATC controllers must be appropriately trained. One aspect of training of pilots is preparation of the aircraft full landing configuration in the SEAP earlier than in the CNAP, which includes intercepting the steeper GS angle, and stabilizing and keeping the constant approach speed at the lower thrust. Training of the ATC controllers implies familiarizing with application of different combinations of separation rules and eventually with a potential for handling an increased number of missed approaches.

- Passenger comfort

The vertical speed during CNAP of about 500-800ft/min currently appears comfortable for passengers. Under the same circumstances, increase in the vertical speed during SEAP for about 80% as compared to CNAP might be uncomfortable.

3. A methodology for estimating the potential of innovative procedures to increasing the runway landing capacity

3.1 Background

The methodology for estimating the potential contribution of the above-mentioned innovative procedures to the airport runway landing capacity consists of two dedicated models: i) the model when the ATC time-based separation rules are applied; and ii) the model when the SEAP

[1] The earliest, De Havilland DHC-6 and DHC-8 had been certified as the STOL (Short Take Off and Landing) aircraft. Later, the regional aircraft Cessna Citation, BAe RJ 85/100, Fokker 50, Dornier 328, Embraer ERJ 135/170, and recently the larger Airbus A318/319 have been certified for the SEAP (EEC, 2005; TC, 2004).

in addition to CNAP is applied to the closely-spaced parallel runways. The models have the analytical structure enabling carrying out the sensitivity analysis with respect to changes of the most influencing factors.

3.2 Previous research

Modelling of the airport ultimate (runway) capacity has occupied the airport, ATC, and airline operators, planners, analysts and academics for a long time. These efforts have resulted in developing the numerous analytical and simulation models, which could be classified into two broad classes for: i) calculating the (runway) capacity of individual airports and of the airport network(s) (Odoni and Bowman, 1997); and ii) optimization of utilization of the airport (runway) available capacity under changing influencing factors and conditions (Andreatta and Romanin-Jacur, 1987; Bianco and Bielli, 1993; Richetta and Odoni, 1993, 1994; Richetta, 1995; Terrab and Odoni, 1993; Vranas et al., 1994).

Specifically, the analytical models for calculation of the airport runway capacity have provided the two-value parameter – one for the arrival and another for the departure capacity (Blumstein, 1959; Donahue, 1999; Gilbo, 1993; Harris, 1972; Hockaday and Kanafani, 1974; Janic and Tosic, 1982; Janic, 2006; Newell, 1979; Swedish, 1981). Some other models such as the FAA Airport Capacity Model, LMI Runway Capacity Model, and DELAYS as 'Quasi-Analytical Models of Airport Capacity and Delay', developed mainly for the airport (runway) planning purposes and based on the analytical single-runway capacity model, have calculated the so-called "capacity coverage curve" including the associated aircraft delays (Gilbo, 1993; Newell, 1979). In parallel, separate models of the ultimate capacity of the airport apron/gate complex and the system of taxiways have been developed. Recently, these analytical models have been integrated into the 'airport integrated-strategic planning tool' (EEC, 2005). An additional integration has however been achieved by developing the computer-supported simulation models for calculating the airport capacity and delay at i) Low (HERMES and The Airport Machine), ii) Intermediate (NASPAC, FLOWSIM and TMAC), and iii) High Level of Detail (TAAM and SIMMOD) (Ignaccolo, 1993; Janic, 2001; Odoni and Bowman, 1997; Swedish, 1981; Wu and Caves, 2002). In comparison to the analytical models, these models have studied the airport airside operations in much greater details. In some cases, they have seemed to require relatively long time for familiarization, time-consuming preparation of input, consequently relatively high cost, and produced too detailed output, which paradoxically made the strategic planning choices more complex and time consuming than otherwise (Odoni and Bowman, 1997; Stamatopoulos et al., 2004). However, the efforts on further refining existing and developing new models offering estimation of the potential of some of the innovative operational procedures and technologies for increasing the airport runway landing capacity have been made. They have resulted in developing the analytical models for estimating the "ultimate" landing capacity for the cases elaborated in this Chapter, i.e. the ATC time-based separation rules and and the steeper approach procedures, both considered as elements of the current NextGen (US) and SESAR (Europe) programmes (http://vams.arc.nasa.gov/activities/tacec.html). (Janic, 2006, 2008, 2008a).

3.3 Objectives and assumptions

The objectives of the research described in this Chapter are to develop the methodology consisted of the dedicated analytical models, which will enable estimating the potential of the selected innovative operational procedures and technologies to increase the airport runway landing capacity under given conditions. In addition, each model should enable carrying out the sensitivity analysis of the capacity with respect to changes of the most important influencing factors. Consequently, the methodology is based on the following assumptions (Janic, 2006, 2008; 2008a, 2009):

- The runway system consisting of a single and/or a pair of the closely-spaced parallel runways with the specified geometry used exclusively for landings is considered;
- The aircraft arrive at the specified locations of their prescribed arrival paths almost precisely when the ATC (controller) expects them, i.e. the system is considered as "the error free";
- The occurrence of particular aircraft categories in particular parts are mutually independent events;
- The arrival mix characterized by the weight (i.e. the wake-vortex category) and approach speed of particular aircraft categories is given;
- The aircraft approach speeds along particular segments of the "wake reference airspace" are constant.
- The influence of the weather conditions on the wake vortex behavior for a given landing sequence is constant during the aircraft staying in the "wake reference airspace";
- The ATC uses the radar-based longitudinal and horizontal-diagonal, and vertical separation rules between the arriving aircraft;
- Assignment of CNAP/SEAP depends on type of the arrival sequence(s) in terms of the aircraft wake-vortex category, approach speed, and capability to perform SEAP in the latter case;
- The successive arrival aircraft approaching to the closely-spaced parallel runways, are paired and alternated on each runway; and
- Monitoring of the current, and prediction of the prospective behavior of the wake vortices in the "wake reference airspace" is reliable thanks to the advanced technologies;

3.4 Basic structure of the models

The models developed possess a common basic structure, which implies determining the "ultimate" landing capacity of a given runway(s) as the reciprocal of the minimum average "inter-arrival" time of passing of all combinations of pairs of landing aircraft through a given "reference location" selected for their counting during a given period of time (Bluemstein, 1959). In the given context, the minimum average inter-arrival time enables maximization of the number of passes through the "reference location", which is usually the runway landing threshold. The period of time is ¼, ½, and/or most usually 1 hour.

Consequently, the basic structure of the model using the ATC time-based instead of the ATC distance-based separation rules between landing aircraft on a single runway is based on the traditional analytical model for calculating the "ultimate" runway landing capacity as follows(Blumstein, 1959; Janic, 2001):

$$\lambda_a = T / \sum_{ij} p_{i\,a} t_{ij\,\min} p_j \quad (1)$$

where

$_at_{ijmin}$ is the minimum inter-arrival time of the aircraft pair *(i)* and *(j)* at the runway landing threshold selected as the "reference location" for counting the operations;

p_i, p_j is the proportion of aircraft types *(i)* and *(j)* in the landing mix, respectively;

T are the periods of time (usually one hour).

In the case of the SEAP on the closely-spaced parallel runways, let's assume yajy yjere are two aircraft landing sequences: i) the aircraft sequence *(ij)* is to land on RWY1; and ii) the aircraft sequence *(kl)* is to land on RWY2. Since the occurrences of particular aircraft categories are mutually independent events on both runways, the probability of occurrence of the "strings" of aircraft *(ikj)* and *(kjl)* can be determined as follows (Janic, 2006, 2008a):

$$p_{ij/k} = p_i p_k p_j \text{ and } p_{kl/j} = p_k p_j p_l \tag{2}$$

where

p_i, p_k, p_j, p_l is the proportion of aircraft categories *(i)*, *(k)*, *(j)* and *(l)* in the mix, respectively.

Given the minimum inter-arrival time at the landing threshold of RWY1 and RWY2 as $_at_{ij/k/min}$, and $_at_{kl/j/min}$, respectively, and the probabilities $p_{ij/k}$ and $p_{kl/j}$ for all combinations of the aircraft sequences *(ikj)* and *(kjl)*, respectively, the average inter-arrival time at the threshold of RWY1 and RWY2 in Figure 4b as the "capacity calculating locations" can be computed as follows (Janic, 2006, 2008s):

$$\bar{t}_{a1} = \sum_{ikjk} {_a t_{ij/k/\min}} p_{ij/k} \text{ and } \bar{t}_{a2} = \sum_{kjl} {_a t_{kl/j/\min}} p_{kl/j} \tag{3}$$

Then, the "ultimate" arrival capacity of a given pair of the closely-spaced parallel runways can be calculated separately for each runway as (Janic, 2006):

$$\lambda_{a1} = T / \bar{t}_{a1} \text{ and } \lambda_{a2} = T / \bar{t}_{a2} \tag{4}$$

The total landing capacity for the runway system can be calculated as the sum of the individual capacities of each runway.

3.5 Determining the minimum interarrival time(s) at the "reference location"

3.5.1 The ATC time-based separation rules

The minimum time-based separation rules for the aircraft landing on a single runway are determined by modeling the wake-vortex behavior in the "wake reference airspace", setting up the dynamic time-based separation rules, and calculating the inter-arrival times of particular sequences of landing aircraft at the "reference location", i.e. the runway landing threshold *T* in Figure 3 (Janic, 2008).

3.5.1.1 The wake vortex behavior

The wake vortex appears as soon as the lift on the aircraft wings is created. The investigations so far have shown that the wakes behind the aircraft decay over time generally at more than proportional rate, while simultaneously descending below the aircraft trajectory at a certain descent speed. Without crosswind they also move from the aircraft trajectory at a self-induced speed of about 5kt (knots). Otherwise, they move according to the direction and speed of the crosswind (Shortle and Jeddi, 2007).

Modeling the wake-vortex behavior includes determining its strength, i.e. the root circulation, the "reference time", decaying pattern, decent speed, and the movement influenced by the ambient weather.

The wake strength – the root circulation at time (t). This can be estainated as follows:

$$\Gamma_0(t) = \frac{4Mg}{\rho v(t) B \pi} \tag{5a}$$

The wake reference time, i.e. the time for the wake to descend for one wing span at time (t). This can be estimated as follows:

$$t^*(t) = \frac{\pi^3 B^2}{8\Gamma_0(t)} = \frac{\rho \pi^4 B^3 v(t)}{32Mg} \tag{5b}$$

The wake-decaying pattern. This is estimated as follows:

$$\Gamma(t) = \Gamma_0(t)\left(1 - \frac{t}{kt^*(t)}\right) \tag{5c}$$

If the safe wake strength is Γ^*, the time the wake needs to decay to this level, $\tau_d\ (\Gamma^*)$ can be determined from expression (5c) as follows:

$$\tau_d(t, \Gamma^*) = kt^*(t)\left(1 - \frac{\Gamma^*(t)}{\Gamma_0(t)}\right) \tag{5d}$$

The wake's self-induced descent speed. This is determined as follows:

$$w(t) = \frac{2\Gamma(t)}{\pi^2 B} = \frac{2\Gamma_0(t)\left[1 - t / kt^*(t)\right]}{\pi^2 B} \tag{5e}$$

where

M is the aircraft (landing) mass (kg);

g is the gravitational acceleration (m/s^2);

ρ is the air density near the ground (kg/m^3);

$v(t)$ is the aircraft speed at time *(t)* (m/s);

B is the aircraft wingspan (m); and

k is the number of the reference time periods after the wakes decay to the level of the natural turbulence near the ground (70 m^2/s) (k = *8* - *9*).

The impact of ambient weather

The ambient weather is characterized by the ambient wind, which can influence the wake vortex behaviour in the "wake reference airspace". This wind is characterized by the crosswind and headwind components as follows.

- Crosswind:

The crosswind can be determined as follows:

$$V_{cw}(t) = V_w(t)\sin(\varphi_w - \varphi_a) \tag{5f}$$

The wake vacates the "reference profile" at almost the same speed as the crosswind.

- Headwind:

The headwind can be determined as follows:

$$V_{hw}(t) = V_w(t)\cos(\varphi_w - \varphi_a) \tag{5g}$$

where

$V_w(t)$ is the wind reported by the ATC at time *(t)*;

φ_w is the course of the wind (^{0});

φ_a is the course of the aircraft (^{0}).

The headwind does not directly influence the wake descent speed (rate) but does move the wake from the ILS GS and thus increases its vertical distance from the path of the trailing aircraft. This vertical distance increases linearly over time and in proportion to the headwind as follows:

$$\Delta z_{hw}(t) = V_{hw}(t) * t * tg\,\theta \tag{5h}$$

where all symbols are as in the previous expressions.

3.5.1.2 The dynamic time-based separation rules

Let $\tau_{ij/min}(t)$ be the minimum time-based separation rules between the leading aircraft *(i)* and aircraft *(j)* in the landing sequence *(ij)* at time *(t)*. Currently, this time depends on the ATC distance-based separation rules (either IFR or VFR) implicitly including the characteristics of the wake vortex behavior, and the aircraft approach speeds (see Table 1). The main idea is to make these time separations explicitly based on the current and predicted characteristics and behavior of the wake vortex generated by the leading aircraft *(i)* in the given sequence *(ij)*. The characteristics and behavior of the wake vortex include its initial strength and time of decay to a reasonable (i.e. safe) level, and/or the time of clearing the given profile of the "wake reference airspace" either by the self-induced descend speed, headwind, self-induced lateral speed, and/or crosswind.

Let $\tau_{ij}(t)$, $\tau_{iy}(t)$ and $\tau_{iz}(t)$, respectively, be the time separation intervals between the aircraft *(i)* and *(j)* based on the current ATC distance-based separation rules in Table 1, and the predicted times of moving the wakes of the leading aircraft *(i)* either horizontally or vertically at time *(t)*, out of the "wake reference airspace" at a given location. In addition, let $\tau_{id/j}(t)$ be the predicted time of decay of the wake of the leading aircraft *(i)* to the level acceptable for the trailing aircraft *(j)* at time *(t)*. Refering to Figure 3, these times can be estimated as follows:

$$\begin{aligned}
&\tau_{ij}(t) = \delta_{ij}(t)/v(t) \\
&\tau_{iy}(t) = Y_i(t)/V_{cw}(t) \\
&\tau_{iz}(t) = \min[Z_i(t)/w_i(t); \Delta z_{ij/\min}(t)/V_{hw}(t)tg\theta] \\
&\tau_{id/j}(t,\Gamma^*) = kt_i^*(t)\left[1 - \Gamma_j^*/\Gamma_{0i}(t)\right]
\end{aligned} \tag{6a}$$

where

$\delta_{ij}(t)$ is the minimum ATC distance-based separation rules applied to the landing sequence *(ij)* at time *(t)*;

$v_j(t)$ is the average approach speed of the trailing aircraft *(j)* at time *(t)*; and

$\Delta z_{ij/min}(t)$ is the minimum vertical separation rule between the aircraft *(i)* and *(j)* at time *(t)*.

Other symbols are analogous to those in the previous expressions. Expression (6a) indicates that the time the wakes of the leading aircraft *(i)* take to move out of the given "reference profile" does not depend on the type of trailing aircraft *(j)*. However, the decaying time of the wakes from the leading aircraft *(i)* depends on its strength, which has to be acceptable (i.e. safe) for the trailing aircraft *(i)*. Consequently, at time *(t)*, the trailing aircraft *(j)* can be separated from the leading aircraft *(i)* by the minimum time separation rules as follows:

$$\tau_{ij/\min}(t) = \min\left[\tau_{ij}(t); \tau_{iy}(t); \tau_{iz}(t); \tau_{id/j}(t,\Gamma^*)\right] \tag{6b}$$

- If $v_i \le v_j$, the minimum time separation rule $\tau_{ij/min}(t)$ should be established when the leading aircraft *(i)* is at the runway landing threshold *T* in Figure 3, i.e. at time $t = \gamma/v_i$. In addition, the following condition must be fulfilled: $\tau_{ij/min}$ *(t)* ≥ t_{ai}, where t_{ai} is the runway occupancy time of the leading aircraft *(i)*.

- If $v_i > v_j$, the minimum time separation rule $\tau_{ij/min}$ *(t)* should be established when the leading aircraft *(i)* is just at FAG (Final Approach Gate) in Figure 3, i.e. at time *t = 0*. This is based on the fact that the faster leading aircraft *(i)* will continuously increase the distance from the slower trailing aircraft *(j)* during the time of approaching the runway.

3.5.1.3 The minimum inter-arrival times between landings

The minimum inter-arrival times for the aircraft sequences *(i)* and *(j)* at the landing threshold can be determined based on expression (6b) as follows:

$$ {}_a t_{ij/\min} = \begin{cases} \tau_{ij/\min}(t=0) + \gamma\left(1/v_j - 1/v_i\right) & \text{for} \quad v_i > v_j \\ \max\left[t_{ai};\; \tau_{ij/\min}(t = \gamma / v_i)\right] & \text{for} \quad v_i \le v_j \end{cases} \tag{6c} $$

where $\tau_{ij/min}(t)$ is determined according to expression 6(a, b).

At time *t = 0*, when the leading aircraft *(i)* is at FAG, the "wake reference profile" is as its greatest, which implies that the wakes need the longest time to vacate it by any means. At time *t* = γ/v_i, when the leading aircraft *(i)* is at the landing threshold, the "wake reference profile" is the smallest, which implies that the wakes need much shorter time to vacate it (see Figure 3).

3.5.2 The Steeper Approach Procedure (SEAP)

The minimum inter-arrival times between the aircraft landing on the closely-spaced parallel runways are estimated respecting the fact that they can perform both CNAP (Conventional Approach Procedures) and SEAP (Steeper Approach Procedures). At both, the ATC applies the longitudinal (i.e., in-trail) separation rules to the aircraft on the same and the horizontal-diagonal and/or the vertical separation rules to the aircraft on the different (parallel) approach trajectories.

3.2.2.1 Scenario for performing SEAP

Simultaneous performing of CNAP and SEAP at a given pair of the closely-spaced parallel runway is carried out according to the traffic scenario shown in Figure 5.