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The difference between hub and non-hub airports — An airside capacity perspective

Bojana Mirković [a], [*], Vojin Tošić [a]

[a] University of Belgrade - Faculty of Transport and Traffic Engineering; Division of Airports and Air Traffic Safety, Vojvode Stepe 305, Belgrade 11000, Serbia

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ABSTRACT

Airport airside capacity is limited by the runway system capacity or apron capacity, whichever is more constraining. Sometimes, taxiway system can also impose constraint to airside capacity, but in the case of fully developed taxiway systems (involving parallel taxiway, high speed exits, etc.) that is usually not an issue. To determine which airside element is more constraining it is not always as simple as comparing runway system and apron capacities directly one to another. It is important to understand and take into consideration their relationship. Runway-apron relationship depends on demand characteristics e.g. dominant market segments (e.g. scheduled, charter, low-cost, general aviation, cargo), and/or specific traffic patterns (hubbing or point-to-point services, seasonality in demand, etc.).

The paper brings up the issue of available airside capacity under different traffic characteristics, faced by hubs vs. non-hub airports, and the necessity to understand runway-apron interdependency in order to properly identify the bottleneck on the airside. Referring to earlier findings related to apron capacity analysis, the paper summarizes various factors that affect apron capacity at non-hub and hub airports and uses them to define the runway-apron relationship, as well as its role in the process of analyzing airside capacity under various demand characteristics.

The main finding is that functional relationship between the runway system and aprons is much stronger in the case of hub airports, and should be carefully considered when analyzing airside capacity. Besides runway capacity, few other variables that affect apron capacity at hub airports are discussed. Generic examples are used to support the discussion.

1. Introduction

As a reflection of what occurs in the case of major airports worldwide, the runway system is considered to be the main airside capacity constraint, and airside capacity is usually expressed through the runway system capacity. In this paper airport airside is observed through the runway system (hereinafter: runway) and apron/gate complex (hereinafter: apron). It is assumed that the taxiway system has reached mature phase in its development, and it does not present the capacity constraint.

Services provided to aircraft on the runway and on the apron are different in nature. The runway is entry/exit point to/from the airside system, where service times are the order of magnitude of a few minutes. At apron(s) aircraft are turned-around which requires service times from 20min to as much as several hours (depending on the aircraft class and type of service).

Interaction between arrivals and departures exists at both airside elements, but different flows of arrivals and departures interact at these two, due to difference in service times and the transitional (taxi) times between them. This paper does not address physical runway-apron relationship, i.e. an impact of taxi times on exchange of arrivals and departures between the runway and the apron, but it analyzes their functional relationship, related to specific demand characteristics.

Analytical models (few existing) deliver apron capacity in aircraft/h, while runway capacity is usually expressed in operations/h. The most common relation is to multiply aircraft/h by two to obtain corresponding operation/h, assuming that one aircraft is related to two operations — arrival and departure. Such a calculation is used, for example, in the FAA's graphical method (Federal Aviation

* Corresponding author.
E-mail address: b.mirkovic@sf.bg.ac.rs (B. Mirković).

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Administration - FAA, 1983).[1] De Neufville and Odoni (De Neufville and Odoni, 2003) suggest taking into consideration largest fraction of arrivals in the traffic mix during a certain time interval, instead of applying default 50/50 share of arrivals and departures.

However, such transformation might give a rough approximation, but is it sufficient to capture the connection between apron and runway capacities at all airports? This relationship may depend on demand characteristics e.g. dominant market segments (e.g. scheduled, charter, low-cost, general aviation, cargo), and/or specific traffic patterns (hubbing or point-to-point services, seasonality in demand, etc.). This paper primarily focuses on two airport types, with respect to their role in air transport network: origin-destination (O/D) airports, serving primarily point-to-point[2] (P2P) traffic, resulting in traffic distribution throughout the day, with more or less pronounced peak periods; and hub airports serving temporally coordinated[3] flights concentrated in waves of flights (solely, or in combination with non-coordinated, P2P flights).

Due to various reasons, airports can be exposed to significant changes in their demand characteristics, in both directions. For example, Milan Malpensa is among a number of airports that experienced de-hubbing (Redondi et al., 2012). After Alitalia's decision to abandon it (in 2008), Milan Malpensa became second most important Easy Jet's base and managed to recover in three years. Consequently, the traffic nature has changed from primarily connecting to P2P. On the other hand, successful traditional airlines constantly compete to expand their markets (e.g. Grimme, 2011), aiming to strengthen their major hubs or create new ones. Inter alia, Etihad Airways signed the contract of strategic partnership with former Jat Airways (now Air Serbia) end of 2013. Since then, Belgrade Airport experiences significant increase in number operations and passengers served (about 30% in 2014). Due to that and its favourable location from the perspective of west-east connections, there is a growing potential for Belgrade Airport, being now O/D airport, to transform into a hub (Air Serbia introduced direct flights Belgrade - New York in June 2016). The question to be timely considered in these cases is whether the airside capacity can support such a transformation.

Even when demand changes are not as drastic as those involving de-hubbing or evolution of non-hub to hub, understanding the sensitivity of airside capacity to specific demand characteristics is still very important for efficient utilization of available resources and timely planning of the future expansion.

The hubbing itself does not seem to be endangered, as it is indispensable (at least) for long-haul routes. But the changes in traffic distribution and its evolution through airline business model segmentation driven primarily by constant growth in low-cost segment are evident. In Europe low-cost traffic reached more than 40% of total traffic (almost 50% if we only consider Western Europe). The constantly growing low-cost market is based on successful competiveness with other markets and continuous search for new opportunities. It became evident that they are also prepared to change their initial concept (at least partially) by: entering primary airports, facilitating transfers, engaging in codesharing, entering alliances and acquiring other airlines (De Wit and Zuidberg, 2012). Due to that, airports should be prepared to respond adequately to such changes.

In this work we bring up the issue of available capacity under different demand characteristics faced by hubs vs. non-hub (O/D) airports. This issue, although very important for airport planners, is only sparsely addressed in literature. More than 40 years ago Steuart (1974) analyzed an influence of the flights schedule and flights' behavior relative to the schedule on gate requirements. The emphasis is on bank operations – "the cyclic exchange of a large number of scheduled gate occupancies followed by a small number". Using a stochastic model based on empirical data, he showed that banking tends to increase the number of gates needed, observing the scheduling alternatives where decrease (increase) in number of aircraft in the bank is followed by decrease (increase) in the time interval between banks, under the constant arrival rate. The same issue is addressed in the extension of this work, 25 years ago. Hassounah and Steuart (1993) very briefly discussed the influence of the time interval between banks on gate requirements, aiming to show how close banks could be scheduled without causing an excessive increase in gate requirements. They observed two banks of the same size, and fixed number of aircraft in the banks. In last 10 years, only Burghouwt (2007), in a chapter devoted to impact of airline networks onto airports, observes spatial and temporal concentration from the perspective of wave system structure, connectivity and seat capacity, all being certain indicators of demand characteristics. However, possible repercussions of the specific demand characteristics on airport airside capacity and its utilization were not addressed, which is the main focus of this paper.

Section 2 of this paper summarizes variables that should be taken into account in estimating apron capacity for hub and O/D airports, which is the key in understanding the connection between runway and apron capacities and its impact to overall airside capacity. Generic examples are used in Section 3 to support the discussion related to runway-apron relationship and its interpretation related to airport airside planning. Theoretical approach, rather than empirical, is used, aiming to introduce and explain the "phenomenon", not to analyze specific example(s). Section 4 summarizes the main findings of this work.

2. Apron capacity for different airport types and the factors affecting it

Overview of existing models for apron capacity estimation (Mirkovic and Tosic, 2014) shows that, in general case, apron capacity is derived from the number of aircraft stands (hereinafter: stands) and average stand occupancy times (SOT), taking into account demand structure, not only with respect to aircraft classes (fleet mix), but also apron users (depending on the restrictions that apply on terminal/apron complex: airlines; domestic/international, Schengen/non-Schengen, flights, etc). The minimum of the capacities set by each group of stands is considered as apron capacity:

$$C = \min_{ij} (C_{ij}) \quad (1)$$

i - designates the user, $i \in [1, n]$

j - designates the aircraft class, $j \in [1, m]$ where *1* is the smallest aircraft class, and *m* is the largest aircraft class.

C_{ij}- apron capacity limited by the group of stands available for user *i* and aircraft class *j*.

The capacity limited by the ij^{th} group of stands (C_{ij}) is calculated from the number of stands in ij^{th} group of stands (N_{ij}') and weighted average stand occupancy time demanded by all aircraft allowed to use stands from the ij^{th} group ($\overline{t_{ij}}'$). When deriving N_{ij}' and $\overline{t_{ij}}'$ stand size restriction need to be taken into consideration

[1] Advisory Circular AC 150/5060-5 on Airport Capacity and Delay was updated in 2012, through Airport Cooperative Research Program, Report 79 – Evaluating Airfield Capacity (Transportation Research Board, 2012). It primarily addressed the runway system capacity and delay, while no further improvements on modelling apron/gate capacity were included.

[2] The term "point-to-point" flight/traffic referrers to non-coordinated aircraft carrying origin-destination passengers rather than transfer passengers.

[3] The term "coordinated" aircraft/flight/traffic refers to aircraft carrying significant number of transfer passengers. Coordinated aircraft are concentrated in waves, aimed at providing efficient transfers between flights.

(i.e. stands are allowed to be used by design aircraft or any smaller than design aircraft), as well as the restrictions with respect to airlines, destinations, or else, necessarily including the stand-use policy (common, preferential, exclusive).

$$C_{ij} = N_{ij}' \Big/ \bar{t}_{ij}' \tag{2}$$

$$N_{ij}' = \sum_{k \in K} \sum_{l \in L} N_{kl} \tag{3}$$

$$\bar{t}_{ij}' = \sum_{k \in K} \sum_{l \in L} p_{kl} \cdot SOT_{kl} \tag{4}$$

N_{ij}'- number of stands that may be used by aircraft of user i and class j (stands allowed to be used by user i, designed for aircraft class j and for aircraft larger than j).

$\bar{t}_{ij}'$ - expected stand occupancy time demanded by all user/aircraft class combination allowed to use the ij^{th} group of stands.

p_{kl} – share of aircraft of user k and class l in the population of aircraft demanding service.

SOT_{kl} – mean stand occupancy time of the aircraft of user k and class l.

$K = \{k | k \in [1, n]$ and user k allows its stands to be used by user $i\}$, $K \subseteq [1, n]$

$L = \{l | j \in [1, m]$ and aircraft class l is equal or larger than aircraft class j, $l \geq j\}$,$l \in [j, m]$

SOT reflects the time during which a stand is reserved, i.e. blocked, for a particular aircraft regardless whether it physically occupies the stand during entire time. SOT should account for at least the turnaround time (TAT) for different users/aircraft classes and some additional time between two consecutive occupancies of the same stand or apron area. TAT is the reflection of the manufacturer's requirements, airline requirements, as well as the ground handler's performance at particular airport and should be derived from the traffic schedules. Additional time between two consecutive occupancies of the same stand or apron area is included in apron capacity models either through utilization factor or through separation time (ST). ST is the time between a departure from a gate position and the next arrival. It consists of push-out or power-out time, the time required by departing aircraft to clear the apron, and the time required by arriving aircraft to move in from the apron entrance to the gate position (Bandara and Wirasinghe, 1988). ST depends on the apron and terminal layouts. On the other hand, the utilization factor, determined empirically, is a function of number of stands and existing traffic schedule at the airport where it is estimated. Due to that, ST is considered to be more convenient correction than utilization factor.

The general approach for calculating apron capacity applies only for O/D airports. At hub airports, with aim to increase number (and quality) of indirect connections, the dominant airline/alliance coordinate their flights in time by operating waves (banks) of flights. Mirkovic (2014) analyze the impact of concentrating aircraft into waves on airport apron capacity. The models for apron capacity calculation at hub airports, available in (Mirkovic and Tosic, 2016), rather define general relationship between the wave-system parameters and apron capacity instead of analyzing the impact of specific traffic schedules, as it is done by Steuart (1974).

The structure of a wave (Fig. 1) is determined by: the minimum connecting time (MinCT), the maximum acceptable connecting time (MaxCT), and the maximum number of flights that can be scheduled per wave (N), (Burghouwt and de Wit, 2005) and (Danesi, 2006). The time interval between the same points of the consecutive waves is the wave repeat cycle (WRC), and it is characteristics of the airline schedule.

MinCT depends on the airline, type of connection (domestic, continental, intercontinental, etc.), and airport design and its capacity to process transfer passengers and baggage within and between terminals, (Dennis, 1994). European average is clustered around 45min, with small differences between airports. Exceptions are purpose-built terminals e.g. Munich Airport (35min) or Vienna Airport (25min); or connections to long-haul destination, involving changing terminals, e.g. London Heathrow (75min Terminal 1 to Terminal 4), (Dennis, 1994).

MaxCT reflect the "level of service" i.e. the time period that keeps connections attractive to passengers. It depends on the type of connection and quality level provided. For example, for poor quality level MaxCT is considered to be 180min for continental connections, 300min for continental-intercontinental connections and 720min for intercontinental connections, (Burghouwt and de Wit, 2005) and (Danesi, 2006).

In the case of hub airports, under assumption of ideal wave,[4] TAT for coordinated flights (TAT_{cf}), and consequently SOT for coordinated flights (SOT_{cf}), have to account for the time required for facilitating transfers between connecting flights (MinCT) and the duration of the arrival time-window (ARR_{tw}). Both TAT_{cf} and SOT_{cf} depend on the wave-system parameters (N and MinCT) and runway (arrival) capacity.[5]

$$TAT_{cf} = ARR_{tw} + MinCT = N \Big/ C_{rwy}^{arr} + MinCT \tag{5}$$

$$SOT_{cf} = TAT_{cf} + ST = N \Big/ C_{rwy}^{arr} + MinCT + ST \tag{6}$$

As proposed in (Mirkovic and Tosic, 2016), N is limited either by static apron capacity (N_{stat}) or the "target" quality of connections (MaxCT) defined through MaxCT (N_{maxCT}):

$$N = \min(N_{stat}, N_{\max CT}) \tag{7}$$

$$N_{stat} = \min_{ij} (N_{ij}) = \min_{ij} \left(N_{ij}' \Big/ s_{ij}' \right) \tag{8}$$

$$s_{ij}' = \sum_{k \in K} \sum_{l \in L} p_{kl} \tag{9}$$

N_{ij}'- number of stands that may be used by aircraft of user i and class j (stands allowed to be used by user i, designed for aircraft class j and for aircraft larger than j).

s_{ij}' - cumulative share of user/aircraft class combination allowed to use the ij^{th} group of stands

$$N_{\max CT} = (MaxCT - MinCT) \cdot C_{rwy}^{arr} \Big/ 2 \tag{10}$$

Equation (10) is derived from the condition that wave length of the ideal wave should not be larger than MaxCT:

$$MaxCT = 2 \cdot ARR_{tw} + MinCT \tag{11}$$

It makes N dependent to: number of stands in each group of

[4] Arrival time-window (ARR_{tw}) and departure time-window (DEP_{tw}) are of the same length and sequence of aircraft in arrival flow is the same as the sequence of aircraft in departure flow. Although departure period is shorter than arrival period in reality, the ideal wave is considered to be convenient for defining the modelling approach in general. Once defined, it can be modified later on in accordance with specific runway system operations.

[5] Depending on the runway operating mode it can be either runway arrivals only capacity, or arrival capacity in mixed mode operations (assuming alternating arrivals and departures).

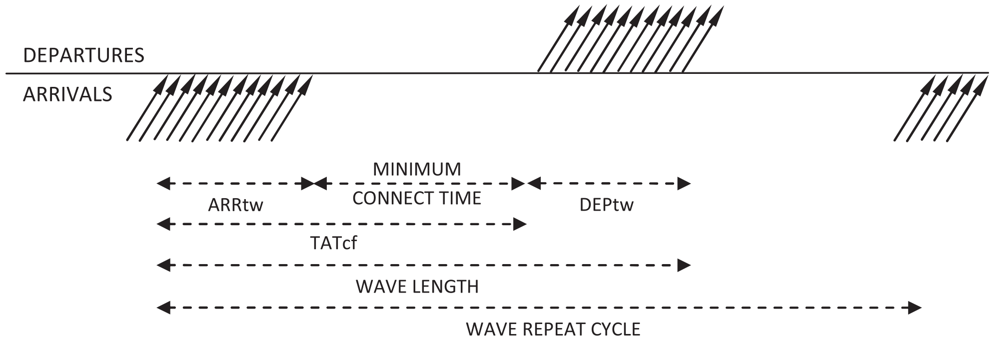

Fig. 1. Wave-system parameters in the case of split waves (WRC ≥ WL).

stands and demand structure (if static apron capacity is more constraining); or the wave-system parameters (MinCT and MaxCT) and runway capacity (if N is constrained by MaxCT).

If we observe pure hub airports, which serve only coordinated flights, (dynamic) apron capacity can be derived from the maximum number of aircraft per wave (N) and the time during which a stand is blocked for the next (Mirkovic and Tosic, 2016). Theoretical apron capacity (C_T) assumes an exchange of aircraft on stands after SOT_{cf}. But, that applies only when ARR_{tw} of the new wave overlaps with DEP_{tw} of the previous wave (in this case runway(s) operate in mix-mode). In general case, an exchange of aircraft on the same stand in pure hub case occurs only after WRC. WRC should be used as stand blocking time to derive utilized apron capacity (C_U) for coordinated flights. Theoretical capacity is nothing but the special case when utilized capacity reaches its maximum, i.e. when WRC= SOT_{cf}.

$$C_T = N \Big/ SOT_{cf} \tag{12}$$

$$C_U = N/WRC \tag{13}$$

Hub airports mainly do not operate as pure hubs, but in addition to coordinated flights there are usually other (non-coordinated P2P) flights operating on strong origin-destination markets on the borders of waves, or in off-wave periods. In the case of mixed hubs, having two types of traffic (coordinated and other flights), apron capacity is defined as the minimum of the capacities set by the group of stands for coordinated flights and the group of stands for other flights, accounting for their shares during WRC period. Mathematical formulation of the model for the case of mixed hub is available in (Mirkovic and Tosic, 2016). It combines the basic model (for O/D case) and the model for the pure hub case, and includes all the variables as used in these two.

In the mixed hub case two different stand use strategies could apply. Exclusive use case assumes that group of stands for coordinated flights (e.g. contact stands) are exclusively used by coordinated flights, while P2P flights use only other (e.g. remote) stands. Preferential use case assumes that stands for coordinated flights are also available for other flights when they are not used by coordinated flights. The main difference between these two cases is in the time during which group of stands for coordinated flights (e.g. contact stands) are blocked for other flights. In preferential use case exchange of aircraft on group of stands for coordinated flights is allowed after SOT_{cf}, which makes them available to other users in off-wave periods. In exclusive use case, an exchange of aircraft on group of stands for coordinated flights is allowed only after WRC, which makes them available only for coordinated flights i.e. blocked all the time for P2P flights.

Table 1 summarizes variables that should be taken into account in determining apron capacity for different airport types with respect to nature of traffic at the airport. Wider range of variables (eight) should be taken into account to determine apron capacity in the case of hub airports, than it is with the common approach, applicable for O/D airports (first four variables).

In O/D case, runway capacity does not have any impact on apron capacity. Due to that, for O/D airports capacities provided by the apron and the runway can be calculated independently and compared to each other to identify the bottleneck in the airside system and the conditions under which it switches from one element to another. The only matter is to "transform" aircraft/h into operations/h in order to compare them, as it was explained in the introduction.

Table 1
Factors that can affect apron capacity for different types of airports.

	O/D airport	Static apron capacity (N-stat)	Max No. of aircraft in a wave due to MaxCT (N-MaxCT)	Pure HUB (only coordinated flights)		MIXed hub (coordinated + P2P flights)	
				Theoretical	Utilized	Preferential	Exclusive
Number of stands (by a/c class, by apron user, by flight type)	X	X		X	X	X	X
Demand structure (by a/c class, by apron user, by flight type)	X	X		X	X	X	X
Turn-around time[a]	X					X	X
Separation time	X			X		X	X
Maximum acceptable connecting time			X	X	X	X	X
Minimum connecting time			X	X	X	X	X
Wave repeat cycle					X	X	X
Runway capacity			X	X	X	X	X

Bold emphasizes apron-runway interdependence; runway capacity is one of the factors to influence apron capacity.
[a] Refers to turn-around time for P2P flights; coordinated flights require longer turn-around time (TAT_{cf}) derived from equation (5).

Table 2
The relationship between runway and apron capacities – hub cases summary.

Number of aircraft per wave is limited by:	Pure HUB		MIXed hub - Preferential use case, capacity constraint on group of stands for:		MIXed hub - Exclusive use case, capacity constraint on group of stands for:	
	Theoretical	Utilized	Coordinated flights	P2P flights	Coordinated flights	P2P flights
Static apron capacity	+	–	–	+	–	–
MaxCT	+	+	+	+	+	–

"+" - apron capacity depends on runway capacity; "-" - apron capacity does not depend on runway capacity.

On the other hand, in hub cases, the relationship between apron capacity and runway capacity is not as simple as comparing one to another, because apron capacity estimates already include runway capacity in the calculation. It means that, together with runway capacity, apron capacity can also change, which is not the case with O/D airports. Table 2 summarizes interdependency between apron capacity and runway capacity in hub cases, which is not always obvious, because it can be concealed under certain conditions. This is the main contribution to better understand what kind of request a traffic pattern delivers to the supply side, and how that affects airside capacity at hub airports.

If the number of aircraft per wave is limited by the MaxCT (Eq. (10)), not by static apron capacity, this makes apron capacities (both theoretical and utilized) dependant to runway capacity.

If static capacity sets the limit for maximum number of aircraft per wave, then:

- Theoretical apron capacity (Eq. (12)) still depends on runway capacity (Eq. (8)), because SOT_{cf} (Eq. (6)) is a function of runway capacity through the length of ARR_{tw};
- Utilized apron capacity (Eq. (13)) does not depend on runway capacity, since it is derived from WRC, which is a characteristic of the demand itself, not a reflection of runway capacity.

In the case of mixed hubs that serve also P2P traffic in addition to coordinated flights, impact of runway capacity can be obvious, but it can also be concealed. It depends on the policy of stand use (preferential or exclusive) and on the apron area that is more constraining (for coordinated or P2P flights). Until the constraint is on the group of stands for coordinated flights, the same what is summarized above for utilized capacity at pure hub airports applies. Once it switches to the group of stands for other (P2P) flights, runway capacity does not affect apron capacity in exclusive use case, but it does in the preferential use case (through SOT_{cf}).

It means that, in the case of mixed hubs, apron capacity is sensitive to runway capacity:

- When the number of aircraft per wave is limited by the MaxCT – in preferential use case regardless of which group of stands (for coordinated or P2P flights) is more constraining; in exclusive use case only when the constraint is on the group of stands for coordinated flights;
- When the number of aircraft per wave is limited by static apron capacity – in preferential use case only when the constraint is on the group of stands for P2P flights.

In other cases runway capacity does not affect apron capacity.

Furthermore, apron capacity is also sensitive to hubbing parameters. Changing the quality of service provided to transfer passengers, defined through MaxCT and MinCT, may result in different throughputs. Providing the connections for which passengers are willing to wait longer (increased MaxCT) or speeding up the transfer process (decrease in MinCT) can result in higher apron throughputs. But, not all cases are sensitive to these changes. Similar relations from Table 2 apply in this case. Namely, if N is limited by static apron capacity, (dynamic) apron capacity is not sensitive to changes in MaxCT, but it is to MinCT in two cases only: theoretical capacity for pure hubs and mixed hubs, preferential use case, when the constraining group is for P2P flights. When N is limited by the MaxCT than in all cases, apron capacity is sensitive both to MaxCT and MinCT, except for mixed hubs, exclusive use case, limiting groups is for P2P flights. As a characteristic of the wave-system traffic pattern, WRC also affects apron capacity i.e. its utilization, but that particular aspect is not addressed in this work.

Generic examples are used in Section 3 to illustrate these findings and support the discussion about runway-apron relationship and sensitivity of apron capacity at hub airports to other variables.

3. Numerical example and discussion

Let us observe an airport with 30 aircraft stands on the apron: 22 contact stands (of which 4 for class 1, 12 for class 2, and 6 for class 3 aircraft)[6] and 8 remote stands (of which 3 for class 1, and 3 for class 2, and 2 for class 3 aircraft).

Demand structure for pure hub, hub with mixed coordinated and P2P flights and O/D airport are summarized in Table 3. Demand structure in pure hub case is: 20% class 1, 60% class 2, and 20% class 3 aircraft. In mixed hub cases share of coordinated is 50% (the same structure by aircraft classes applies as in pure hub case). Other 50% are P2P flights (of which 20% class 1, 70% class 2 and 10% class 3 aircraft). In order to make the O/D case comparable to hub (mainly preferential) cases, the same (total) fleet mix from exclusive/preferential cases applies for the O/D case (20% class 1, 65% class 2 and 15% class 3 aircraft).

Wave-system parameters for hub cases are: WRC 190min; MinCT 40min and MaxCT 140min. TATs for non-coordinated flights are: 35 min for class 1, 45 min for class 2, and 55 min for class 3 aircraft. ST of 5 min applies for all stands.

In order to show the sensitivity of apron capacity to runway capacity, four scenarios are compared, which assume different runway capacities, while apron structure and demand structure remain the same. In Scenario 1 runway capacity is 21 arrivals/h, in Scenario 2–25 arrivals/h, in Scenario 3–27 arrivals/h and in Scenario 4–33 arrivals/h. In Fig. 2, the red, green, blue and violet lines represent runway capacity (arrivals/h) for Scenarios 1–4, respectively. Furthermore, using Scenario 2 as the baseline, MinCT and MaxCT are varied to show the sensitivity of apron capacity to hubbing parameters, see Fig. 3.

Table 4 summarizes all the values from Figs. 2 and 3. Extra rows are for the maximum number of aircraft per wave (N), SOT_{cf} and note about the group of stands that imposes the constraint to apron capacity in the case of mixed hubs. Runway capacity affects apron capacity, at hub airports, but in some cases this impact can be concealed. This is due to fact that not all variables, apron capacity is

[6] 1 – light; 2 – medium; 3 - heavy.

Table 3
Demand structure for pure hub, hub with additional P2P traffic and O/D airport.

Type of flight	a/c class	Pure HUB	MIXed hub	O/D
Coordinated	1	0,2	0,1	0
	2	0,6	0,3	0
	3	0,2	0,1	0
Other (P2P)	1	0	0,1	0,2
	2	0	0,35	0,65
	3	0	0,05	0,15

derived from, are necessarily dependent to runway capacity. The most constraining group of stands holds the explanation whether certain impact is concealed or obvious.

In the O/D case apron capacity remains the same in all four scenarios (row 2, Table 4), regardless of runway capacity, only the difference between the two is getting lower as the runway capacity increases.

Number of aircraft in a wave of flights limited by the maximum acceptable connecting time (N_{maxCT}, row 4, Table 4), increases together with the runway capacity increase, in all cases. In Scenario 1 and Scenario 2 MaxCT determines maximum number of aircraft in a wave ($N=N_{maxCT}$), while in Scenario 3 and Scenario 4 static apron capacity becomes more constraining ($N=N_{stat}$), see row 5 in Table 4.

With the change in N (Scenarios 1–3), theoretical and utilized apron capacities, in the pure hub case, also change (rows 7&8, Table 4). When N remains the same (Scenarios 3 and 4), hub utilized capacity does not react on changes in runway capacity, any more, being derived from static apron capacity and WRC, where neither of the two is a function of runway capacity. The theoretical capacity of the hub to handle coordinated flights continues to increase, due to decrease in SOT_{cf} (row 6, Table 4).

It is similar in the case of hubs with mixed coordinated and other P2P flights. Apron capacity changes with runway capacity only under the conditions when constraining group of stands is sensitive to runway capacity. Otherwise, it remains unchanged. In the exclusive use case (row 9, Table 4). in Scenarios 2–4, apron capacity is limited by the group of stands for P2P-flights/aircraft-class-2, which operates as O/D case, thus it is not affected by runway capacity. However, in the preferential use case (row 10, Table 4). apron capacity is constrained by the group of stand for coordinated flights, and due to that shows the same "behaviour" as utilized capacity for pure hubs (increases from Scenario 1 to Scenario 3, with no further increase in Scenario 4).

In all four scenarios airside capacity appears limited by runway capacity in the O/D case and by apron capacity for hub cases. Although it seems that apron capacity imposes the constraint to airside capacity in all hub cases, the conclusion is different if these two are observed as a system. Since apron capacity already includes runway capacity in its calculation, it means that until apron capacity reacts to runway capacity, the real constraint for airside capacity is on the runway system. When it stops reacting to runway capacity changes (Scenario 4), it indicates that the constraint switches to apron area. Unlike O/D case, simple (direct) comparison between apron and runway capacity to discover the bottleneck on the airside does not apply in the case of hubs, and can even be misleading. When it comes to decision when and where to expand, it is crucial to carefully analyze all possible interdependencies, aiming to define expansion plan that suits the best given traffic pattern, traffic structure in terms of coordinated and P2P flights, fleet mix, strategy of stand use and quality of connections provided.

For example, apron capacity can be enhanced by changing the strategy of stand use. Preferential strategy, allowing P2P flights to use contact stands when they are not occupied by coordinated flights, is expected to bring extra apron throughput in comparison to exclusive use strategy (no contacts stands are only available to P2P flights). But, that is not necessarily the case. Here it can be noticed that in Scenarios 2–4, preferential use strategy results in higher throughput than exclusive use. But, in Scenario 1 they do not differ. It means that different strategies of stand use do not necessarily bring higher throughput, but only under certain conditions. While apron capacity is limited by the group of stands for coordinated flights in both use strategies, there is no difference in apron capacity provided under exclusive vs. preferential stand use. But, when the group of stands for P2P flights becomes the constraining group, the relaxation of the stand use strategy from exclusive to preferential should result in higher apron throughputs, under the same conditions.

Furthermore, Fig. 3 shows the sensitivity of apron capacity at hubs to quality of connections provided. (Apron capacity in O/D case is also given, only to keep it comparable to Fig. 2). Scenario 2 is used as the baseline. In the first variation (Scenario 2a) it was assumed that worst case connections (between flights on the border of the wave) are increased, MaxCT 160min. In addition to that, in the second variation (Scenario 2b) shorter connecting times for the best case connections are assumed, MinCT 30min. Both are

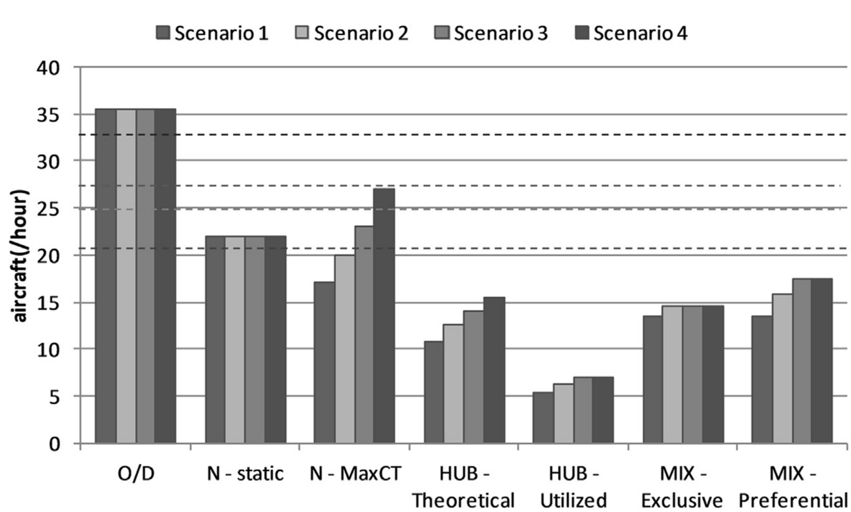

Fig. 2. Sensitivity of apron capacity to runway capacity – O/D, pure hub and mixed hub cases.

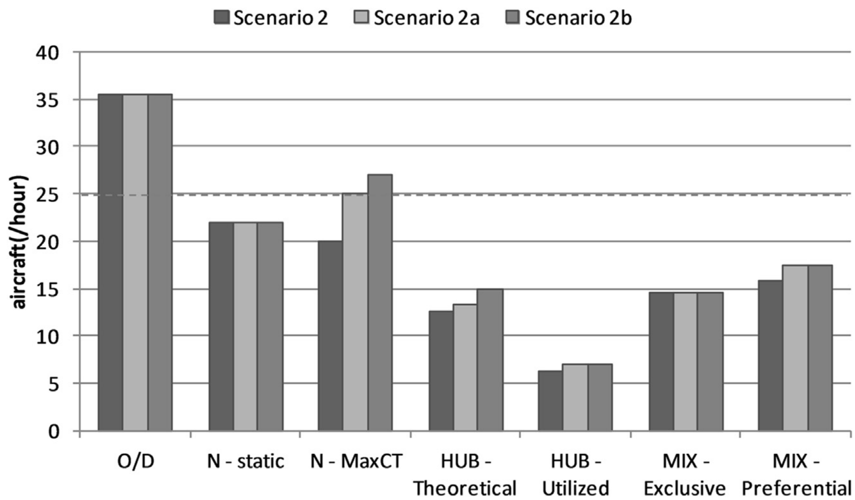

Fig. 3. Sensitivity of apron capacity to hubbing parameters MinCT and MaxCT.

Table 4
Apron capacities for O/D, pure hub (theoretical and utilized), mixed hub (exclusive and preferential) cases, number of aircraft in a wave and stand occupancy time for coordinated flights.

1		Sc.1	Sc.2	Sc.3	Sc.4	Sc.2a	Sc.2b
2	O/D	36	36	36	36	36	36
3	N_{stat}	22	22	22	22	22	22
4	N_{maxCT}	17	20	23	27	25	27
5	N	17	20	22	22	22	22
6	SOT_{cf}	90	90	88,8	80,5	93,8	83,8
7	C_T	10,7	12,6	14,1	15,4	13,4	14,9
8	C_U	5,4	6,3	6,9	6,9	6,9	6,9
9	C_{mixE} limited by the group	13,4 coordinated	14,6 P2P - class 2	14,6 P2P - class 2	14,6 P2P - class 2	14,6 P2P - class 2	14,6 P2P - class 2
10	C_{mixP} limited by the group	13,4 coordinated	15,8 coordinated	17,4 cordinated	17,4 coordinated	17,4 Coordinated	17,4 coordinated

expected to enable extra flights to be scheduled per wave. But, changing the quality or number of connections in such way does not necessarily mean that it will result in higher apron throughput. In this case, in variant scenarios static apron capacity becomes more constraining than MaxCT (row 5, Table 4). Due to that, having the same N, hub utilized capacity does not change. The same happens in the case of hub airports serving mixed coordinated and P2P traffic in the preferential use case (row 10, Table 4). There, it is constrained by the (utilized) capacity of the group of stands for coordinated flights, and it does not change if N remains unchanged, as it is explained earlier. In the exclusive use case, the influence of quality of service is not visible since apron capacity is limited by the capacity of the group of stands for P2P-flights/aircraft-class-2, which operates on O/D principle (row 9, Table 4).

4. Conclusion

The aim of this paper is to show the importance of understanding the impact of traffic characteristics, faced by hubs vs. non-hub airports, on overall airside capacity. The main finding is that the functional relationship between the runway system and apron/gate area is much stronger in the case of hub airports, and should be carefully considered in order to properly identify the bottleneck on the airside.

Depending on the type of traffic and constraining factors, apron capacity may or may not react to changes in runway capacity. Apron capacity at hub airports changes along with runway capacity (Table 2), which requires the two to be observed as a system in the process of airside capacity analysis. Observing them separately (common approach) is applicable only in the case of O/D airports. Such an approach could even lead to the incorrect conclusion regarding the overall airside capacity at hub airports.

Furthermore, the fact that apron capacity at hub airports is dependent on a wide range of factors (including hubbing parameters and runway capacity, Table 1) is important when considering possible improvements of services and/or changes in resource allocation strategy. It was shown that shorter MinCT, longer MaxCT and changing stand/gate use strategy from exclusive to preferential do not necessarily lead to higher apron throughputs. Prior to making the decision, key factors and their interdependencies should be taken into consideration when checking whether expected benefits (i.e. capacity gain) are likely to occur under the given traffic characteristics.

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Abbreviations

ARR_{tw}	arrival time-window
C	apron capacity
C_{rwy}	runway capacity

C_T	theoretical apron capacity
C_U	utilized apron capacity
DEP_{tw}	departure time window
MaxCT	maximum acceptable connecting time
MinCT	minimum connecting time
N	the maximum number of aircraft in a wave
N_{maxCT}	the maximum number of aircraft in a wave limited by the level of service
N_{stat}	static apron capacity
SOT	stand occupancy time
SOT_{cf}	stand occupancy time for coordinated flights
ST	separation time
TAT	turnaround time
TAT_{cf}	turnaround time for coordinated flights
WL	wave length
WRC	wave repeat cycle

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