UNIVERZITET U BEOGRADU

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# BALANSIRANO KORIŠĆENJE KAPACITETA I PLANIRANJE RAZVOJA ELEMENATA AERODROMA

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# AIRPORT AIRSIDE BALANCED CAPACITY USAGE AND PLANNING

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- *Predlog metoda za vrednovanje razvojnih scenarija sistema vazdušnog saobraćaja u Srbiji (prevozioci, aerodromi i kontrola letenja) sa aspekta bezbednosti, efikasnosti, ekonomičnosti i uticaja na životnu sredinu* (broj 15023), 2008-2011; i
- *Podrška održivom razvoju sistema vazdušnog saobraćaja Republike Srbije* (broj TR36033), 2011-2014.

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**Balansirano korišćenje kapaciteta i planiranje razvoja elemenata aerodroma**

**Rezime:**

U doktorskoj disertaciji je predložen postupak za analizu kapaciteta vazdušne strane aerodroma, za zadata fizička i operativna ograničenja, i zadate karakteristike potražnje. Ovaj postupak podrazumeva povezivanje (postojećeg) modela za procenu kapaciteta sistema poletno-sletnih staza sa (proširenim) modelom za procenu kapaciteta pristanišne platforme, kroz njihovu funkcionalnu vezu.

Cilj ove doktorske disertacije je bio vrednovanje i, po potrebi, modifikovanje i proširenje postojećih modela za procenu kapaciteta platforme, kao i definisanje funkcionalne veze između poletno-sletne staze i platforme za različite tipove saobraćaja.

Postojeći modeli su prošireni tako da uzimaju u obzir ograničenja po tipu aviona i korisnicima (npr. aviokompanije), kao i po vrsti saobraćaja. U cilju analize osetljivosti, predlažene su obvojnice za prikazivanje kapaciteta platforme određene konfiguracije, u zavisnosti od strukture potražnje u odnosu na glavne uticajne faktore.

Analiza je obuhvatila dva osnovna tipa aerodroma sa aspekta njihove uloge u mrežama vazdušnog saobraćaja, a to su: izvorno-ciljni aerodromi, sa dominantnim saobraćajem od-tačke-do-tačke, i hub aerodromi, sa dominantnim transfernim saobraćajem za koji je karakteristično da se koncentriše u talase. Dodatno su analizirani i aerodromi na kojima postoje oba tipa saobraćaja.

Rezultati disertacije pokazuju da se za izvorno-ciljne aerodrome može koristiti standardni pristup prilikom analize ukupnog kapaciteta vazdušne strane aerodroma, u kome se poletno-sletna staza i pristanišna platforma posmatraju odvojeno, pri čemu manji kapacitet nameće ograničenje ukupnog kapaciteta. Sa druge strane, u slučaju hub aerodroma kapacitet platforme i kapacitet poletno-sletne staze se ne mogu posmatrati nezavisno jedan od drugog.

S tim u skladu, u ovoj doktorskoj disertaciji predložen je model za procenu kapaciteta platforme na hub aerodromima, koji pored konfiguracije platforme i strukture potražnje uzima u obzir i kapacitet poletno-sletne staze, kao i parametre koji opisuju talasnu strukturu saobraćaja.

Kroz pažljivo definisane primere analizirana je razlika u kapacitetu izvorno-ciljnih i hub aerodroma pod istim uslovima, kao i razlika između teoretskog kapaciteta koji hub aerodrom može da ponudi koordinisanim letovima i iskorišćenog kapaciteta za zadatu talasnu strukturu potražnje. Takođe, kroz primere je prikazana i promena iskorišćenja raspoloživog kapaciteta na hub aerodromu ukoliko bi se dopustilo korišćenje slobodnih resursa i drugim, osim koordinisanim letovima. Dva scenarija su razmatrana: „preferentni“, u kome se dozvoljava korišćenje svih parking pozicija ostalim letovima kada ih ne koriste koordinisani letovi, i „eksluzivni“, koji podrazumeva korišćenje kontaktnih parking pozicija samo za koordinisane letove. Na posebnim primerima se analizira i uticaj promena kapaciteta poletno-sletne staze na kapacitet platforme na hub aerodromu, pod različitim uslovima, kako bi se istakle okolnosti pod kojima je ovaj uticaj jasno vidljiv, a pod kojima ostaje sakriven.

Na kraju, u disertaciji se razmatra i pitanje rezervnog/latentnog kapaciteta platforme, kao potencijala da se prihvati dodatna potražnja, pre odluke o fizičkom proširenju za obezbeđenje dodatnog kapaciteta. Rezervni kapacitet se definiše u funkciji fleksibilnosti kapaciteta platforme. U disertaciji je predloženo izražavanje fleksibilnosti kapaciteta platforme, sa zadatim operativnim ograničenjima, u odnosu na apsolutno fleksibilnu platformu, koja nema operativnih ograničenja u korišćenju parking pozicija.

**Ključne reči:** vazdušna strana aerodroma, aerodromska platforma, analitički modeli, kapacitet u uslovima zasićenja, funkcionalna veza poletno-sletna staza - platforma, izvorno-ciljni aerodrom, hub aerodrom, analiza osetljivosti

**Naučna oblast:** Saobraćajno inženjerstvo

**Uža naučna oblast:** Aerodromi i bezbednost vazdužne plovidbe

**UDK broj:**

**Airport airside balanced capacity usage and planning**

**Abstract:**

The thesis proposes an approach to analyzing the capacity of the existing (built) system under given physical and operational constraints and for given demand characteristics. The approach considers the linking of the (existing) runway capacity model with the (extended) apron capacity model, through the runway-apron functional relationship.

The objective of the thesis was to evaluate and, if necessary, to modify/expand the existing apron capacity estimation models, as well as to define functional relationship between the runway system and apron(s).

Existing apron capacity models are modified to include constraints on both aircraft classes and users (e.g. airlines), considering also different traffic types. The thesis also suggests apron capacity envelopes to illustrate sensitivity of apron capacity to changes in the demand structure with respect to dominant users, provided for a given apron configuration.

Two general airport categories with respect to the role of the airport in the air transport network are analyzed: origin-destination airports (serving primarily point-to-point flights) and hub airports (serving primarily airline/alliance coordinated flights). Furthermore, the thesis also considers the co-existence of point-to-point and coordinated flights at a single airport.

The results of the thesis show that the common approach in the overall airside capacity analysis can be applied at origin-destination airports: the runway system and apron(s) can be observed independently of each other, deriving the conclusion on the overall airside capacity by comparing the two. On the other hand, the finding of the thesis is that capacities of the runway system and apron(s) at the hub airports have to be observed linked to each other.

Consequently, a model to estimate apron capacity at hub airport is offered in the thesis. In addition to apron configuration and demand structure it also takes into consideration: hubbing parameters and the runway system performance.

Different examples are used to analyze the following: the difference between apron capacity for origin-destination airport and hub airport, under the same conditions; the difference between the theoretical capacity hub airport can offer to coordinated flight and the utilized capacity under given wave-system structure; and utilization of the capacity at hub airports when point-to-point traffic is allowed to use idle stands (two scenarios are compared: preferential, assuming that contact stands are available to point-to-point flights between waves, and exclusive, assuming that contact stands are used only by coordinated flights). Additional examples are used to analyze the influence of the runway system performance on apron capacity at hub airports, under different conditions. The aim was to differentiate between the cases where this influence is obvious, from the other cases where it is concealed.

The thesis also addresses the issue of reserve/latent apron capacity, as a potential solution for accepting additional demand prior to physical expansion. Reserve capacity is defined and discussed through apron capacity flexibility, which is expressed in this thesis relative to apron capacity of the absolutely flexible apron (with no operational constraints on stand usage).

**Key words:** airport airside, airport apron, analytical modeling, saturation capacity, runway-apron functional relationship, origin-destination airport, hub airport, sensitivity analysis

**Scientific field:** Transport and Traffic Engineering

**Specific scientific field:** Airports and Air Traffic Safety

**UDK:**

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## Introduction

Airport capacity planning and management is a very challenging task that requires matching capacity (which is neither easy, nor cheap to expand) to fast growing demand which from time to time suffers changes in its characteristics. We are witnessing the transformation from point-to-point networks to hub-and-spoke networks and back, of a new user profile appearance (low-cost), the introduction of new large aircraft into service (A380), etc.

The runway system is considered to be the main airport capacity planning parameter. This is reasonable, considering that building a new runway is a huge infrastructural project for an airport, both in terms of investment, and in terms of capacity gain (in aircraft operations per hour). Another huge infrastructural project is the development of the terminal complex, when the issue of passenger terminal capacity comes to the fore.

In order to provide efficient functioning of the whole system between major infrastructural changes, it is important that the development of other elements (taxiway system, aprons, curb-side, etc.) follows expected demand volume and structure changes. Development of other airport elements can be planned and realized in smaller steps, which is associated with smaller investments, as well as a lower risk of significant capacity/demand mismatch occurrence. However, that is not a justification for these issues to be put aside, or to be very poorly considered.

The objective of the thesis is to evaluate and, where necessary, to modify/expand existing capacity estimation models (of the runway system, aprons and entire airside), with the aim of suggesting an approach for overall airside capacity analysis.

In the process of airside capacity analysis it is important to understand the system as a whole, accounting for physical and operational constraints on airside elements usage and functional relationship between elements. Chapter 1 of the thesis summarizes airport elements usage with respect to different criteria: market segments, physical constraints and operational constraints, together with their impact on the capacity of the entire system. The thesis primarily addresses passenger airports which account for a large share of all market segments.

At passenger airports runway-apron functional relationship is mainly affected by the role of the airport in the air transport network. Chapter 2 discusses different airport categorizations with respect to traffic parameters. It places a special emphasis to airport types with respect to their role in the network.

Chapter 3 summarizes definitions related to airside capacity and the main factors that affect it. Special emphasis is given to characteristics of hub airports with implications on airside capacity utilization, primarily: temporal concentration, ideal wave, wave-system structure and evolutionary phases. This chapter also discusses the issue of peak period. This includes traditional approaches to derive peak hour and design day, together with some of the latest research aimed at deriving typical representative peaks for large international airports, based on the selected traffic parameters.

Chapter 4 provides an overview of the broader literature related to the models for airside capacity assessment and analysis, used for supporting planning studies with a medium- to long-term horizon. A detailed review of the apron capacity modeling is given in the second part of this chapter. It is identified as a research field rather modestly addressed in literature, in comparison to very mature fields such as runway system modeling and simulation modeling of the entire airside.

Chapter 5 proposes an approach for overall airside capacity analysis (Section 5.1). The approach considers linking (one of the) existing runway system capacity models with the apron capacity model (newly developed or modified), through the functional relationship between airside elements (the runway system and aprons), taking into account terminal airspace and passenger terminal processes, to the extent that is necessary.

In Section 5.2 an extension of existing analytical models is proposed, followed (in Section 5.3) by apron capacity representation, using the apron capacity envelope to illustrate how the capacity of a certain apron configuration reacts to changes in demand structure, with respect to dominant users. The significant variables that influence estimated capacity are discussed in Section 5.4.

Section 5.5 addresses the difference in capacity utilization of available resources, depending on the nature of the traffic at the airport. Two main airport types, with respect to their role in air transport network, are analyzed: origin-destination airports, serving primarily point-to-point traffic (resulting in rather “uniform” traffic distribution during the day, with more or less pronounced peak periods) and hub airports serving primarily transfer traffic typically concentrated in waves/banks of flights. Following network evolution, the thesis also addresses the co-existence of coordinated and point-to-point flights at a single airport.

The thesis also addresses the issue of reserve/latent apron capacity (Section 5.6). It is discussed through the concept of apron capacity flexibility. On one hand, apron capacity flexibility is observed as an indicator of ability of the apron(s) to respond on changes in demand structure. At the same time, it is an indicator of latent/reserve capacity that may be “activated” by reallocation of available resources i.e. relaxation of the constraints on stand use.

In addition (Section 5.7) a short discussion is given on possible areas of application of the proposed approach in the field of airport airside capacity analysis.

Concluding remarks are summarized in Chapter 6 of the thesis.

The thesis contains 15 appendices that additionally support certain discussions from the main content. Appendix 14 is an introductory guide for an apron capacity estimation tool provided as a supplementary material to the thesis.

# 1 Airport elements usage with respect to different users

The airport system consists of two sub-systems depending on what/who is served by the system elements. The airside sub-system primarily serves aircraft (and airport ground service vehicles). It considers runway system, taxiway system and apron(s)[1], also referred (all together) as the airfield. The landside sub-system serves passengers and vehicles. It considers terminal buildings, access roads, curbside, parking, etc. The airside and landside sub-systems are connected through terminal complex i.e. through terminal building-apron link.

The thesis observes airport airside, while the landside is taken into consideration only to the extent to which it is inseparably connected to the airside, e.g. it may impose certain constraints on apron usage.

This chapter summarizes usage of airport airside elements depending on airport users (Mirkovic 2011a; Mirkovic and Tosic, 2012; Mirkovic and Tosic, 2013). Users are classified with respect to different criteria. Section 1.1 discusses airport elements usage with respect to different market segments. Section 1.2 addresses aircraft classes and physical constraints. Section 1.3 addresses operational constraints related to airline/traffic characteristic. The impact of different user constraints on airside capacity is summarized in Section 1.4.

## 1.1 Market segments

When observed in the broadest sense, the users of the airport are associated with various purposes of flying: passenger, cargo, military, business aviation, and other (pilot education, agricultural flying, panoramic flying etc.), summarized in Figure 1.

Eurocontrol (2007) differs between seven market segments: traditional scheduled, low-cost, non-scheduled, business aviation, cargo, military, and other, as given in Table 1. The first three fall under passenger market segments.

[1] Hereinafter, the term apron(s) is used to represent all aircraft stands, including contact aircraft stands (also referred to as gates) and remote stands (also referred to as open stands).

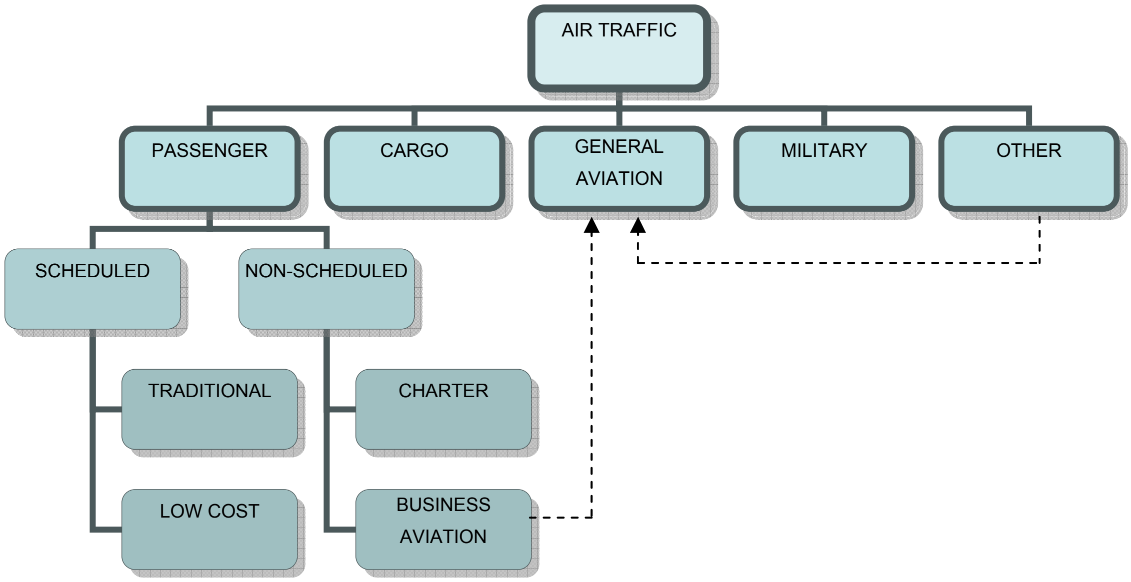


Figure 1. Airport users with respect to type of traffic (Mirkovic and Tosic, 2012)

Table 1. Airports in Europe grouped by dominant market segment (source: Eurocontrol, 2007)

| Single dominant market segment | | Two dominant market segments | |
|---|---|---|---|
| Traditional | 272 | traditional/low-cost | 41 |
| low-cost | 34 | traditional/business | 27 |
| Business | 24 | business/other | 25 |
| Military | 20 | traditional/non-scheduled | 23 |
| Other | 11 | traditional/other | 12 |
| non-scheduled | 7 | low-cost/business | 6 |
| Cargo | 2 | business/military | 6 |
| - | - | traditional/military | 5 |
| - | - | all other combinations | 8 |
| TOTAL | 370 | TOTAL | 153 |

The analysis of 528 airports in Europe shows that 370 airports (70%) have one dominant market segment[2] (see Table 1 for details). At a majority of them (85%) the dominant market segment is one of the passenger market segments (traditional, low-cost or non-scheduled).

[2] The market segment is considered as dominant if it accounts for more than 25% of the total flights.

Of these airports, 153 have two major market segments (see Table 1 for details), of which 42% are passenger-related, i.e. both dominant market segments are passenger market segments. Three dominant market segments were found at five airports only (two traditional/low-cost/business, two traditional/low-cost/non-schedules and one traditional/business other).

Regardless of the market segment, all aircraft use the same runway system and (usually) taxiway system, but, if the volume of traffic justifies it, the passenger aprons can be separated from the cargo and general aviation aprons.

For example, at Munich Airport (MUC), as shown in Figure 2, aprons 1, 2 and 3 are used for passenger traffic, aprons 8 and 9 - for cargo, aprons 10 and 11 - for general aviation (including maintenance). There are additional aprons - 6 and 7 (east of aprons 8 and 9, not visible in Figure 2), located in the maintenance area.

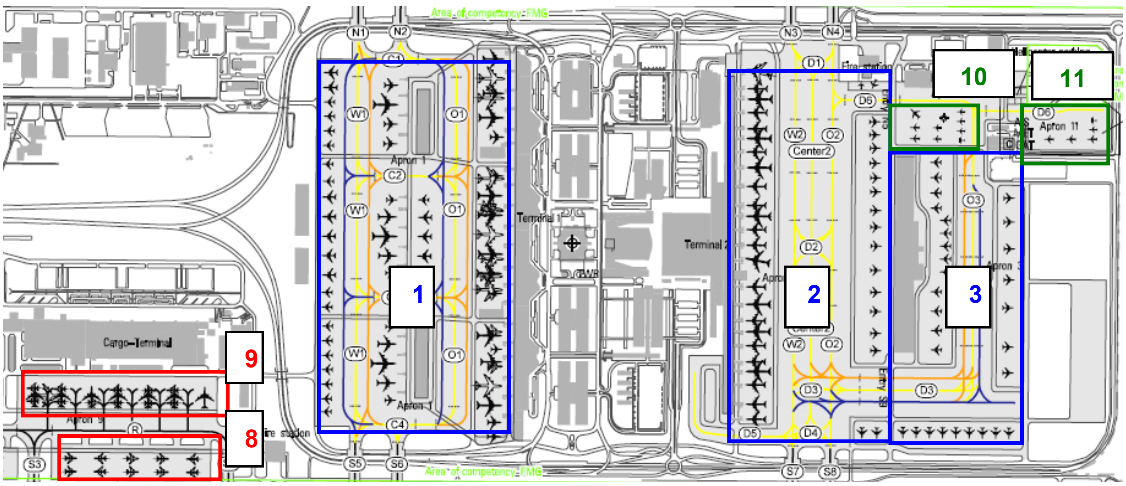


Figure 2. Aprons at Munich Airport, Germany (DFS, 2004)

At joint civil-military airports, civil and military terminal complexes are separated. The taxiway systems can also be separated and used independently, if the terminal complexes are located on opposite sides of the runway system. The number of joint civil-military airports increases, as one of the solutions for the lack of runway system capacity in the air transport network. Instead of building new runways, the idea is to use nearby underutilized existing (military) runways for the overflow from congested civil airports.

For example, an initiative CUMA (Civil Use of Military Aerodromes) has resulted in the transformation of many military airports in Europe for joint use (Siluri, 2008): 34 in France, nine in Spain, three in Italy, two in the Czech Republic, one in Holland, in one in Germany, etc. A similar initiative also exists in U.S. (MAP - Military Airport Programme) under which 21 military airports have been transformed into joint use by 2008 (Siluri, 2008).

Further on, certain segmentation can exist within the apron(s) accommodating passenger traffic. Significant increase in low-cost traffic caused some changes at airports where it became one of dominant market segments. Low-cost carriers (LCCs) may have their own terminal complex separated from traditional airlines. Some airports have built completely new terminal building to meet LCC's requirements (e.g. Marseilles, Geneva, Kuala Lumpur, Singapore, Brussels-not the whole complex, but the new pier with 6 stands). At some airports existing terminal complexes have been adapted for LCCs. For example: Berlin Schoenefeld[3] (the previous charter terminal has been adapted for the LCC Easyjet), Budapest (Terminal 1 has been reconstructed into an exclusive low-cost terminal, serving around 10 LCCs[4]), Warsaw (former Terminal 1 has been adapted for LCCs[5]), Paris Charles de Gaulle (charter Terminal 9, now Terminal 3 is also used for low-cost flights[6]), Amsterdam Schiphol (one pier has been transformed for LCCs), (Radovanovic, 2009).

When the share of low-cost traffic is not significant enough to justify a separate terminal building, LCCs prefer remote over contact stands, in order to avoid high fees for air-bridges use. It is quite similar with the practice of non-scheduled airlines. The rules/constraints related to use of remote stands are not rigid usually. It is easy to deviate from them (which is not always the case with contact stands) if necessary to meet changed requirements.

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[3] Berlin Brandenburg Airport is intended to replace Schoenefeld Airport and Tegel Airport, but it has encountered series of delays and its opening has already been postponed on several occasions.

[4] After the bankruptcy of Malev in 2012, all airlines operating from Budapest Airport are switched to Terminal 2.

[5] Terminals 1 and 2 are now designated as Terminal A. South hall (former Terminal 1) is currently under reconstruction.

[6] EasyJet pretends to operate exclusively from Terminal 2B, after it is reconstructed.

### 1.2 Aircraft classes

Each airport airside element has certain physical dimensions which impose constraints on the aircraft classes (types) that may use it.

In the case of runways, it is their length and width that allow or not certain aircraft classes to use the runway. However, these constraints are not exclusive, since the larger aircraft can be allowed to use shorter runways by decreasing their landing/take-off weight. The mix of aircraft classes has a direct impact on ATC (Air Traffic Control) separation rules applied and related inter-event times between landings and take-offs, and consequently on the runway system capacity.

At an apron, regardless of the market segment, there are physical constraints on aircraft stand usage due to aircraft class/stand size[7] compatibility. Each stand may be occupied by an aircraft for which it is designed, or by any other smaller-than-design aircraft. An apron can consist of a fixed number of stands of a certain size or it can have a flexible structure that enables various arrangements of aircraft in the same area e.g. one large aircraft, or two smaller aircraft instead. International Air Transport Association (IATA) proposed, so called MARS - Multi Aircraft Ramp System concept, (IATA, 2004). The experience so far has indicated that the aprons with a fixed configuration are more sensitive to aircraft fleet mix changes. Consequently, the flexible configuration appeared due to rather frequent changes in fleet mix, and difficulties in coping with it.

### 1.3 Airlines/alliances and flight origin/destination

In addition to the constraints on apron usage with respect to market segments and physical dimensions, there are also operational constraints on terminal building usage that have direct consequence on apron contact stands (also referred as gates) usage.

One of the operational constraints is caused by the necessity to separate domestic and international passengers, as the same processes do not apply to both categories of passengers, either in arrival or departure flow.

[7] The size of the aircraft stand depends on different factors, such as: design aircraft (size and maneuverability), apron configuration, type of ingress and egress, clearances, ground servicing, etc.

International passengers have to pass through additional processes (passport control, customs, and perhaps additional security checks) that do not apply to domestic passengers. That is why terminals are divided into those handling only domestic, only international and mixed domestic/international passengers. This directly influences the allocation of the apron contact stands to particular aircraft/flight. Domestic contact stands can be used only by aircraft coming from and flying to domestic destinations. Similarly, international contact stands are available only for aircraft coming from and flying to international destinations. Aircraft carrying out mixed domestic/international flights can be accommodated at contact stands of the mixed terminals. Contact stands at mixed terminals can also accommodate aircraft operating any other flight origin/destination combination. At the San Francisco Airport (SFO), shown in Figure 3, contact stands A and G are international, while B, C, D, E and F are domestic. There are no mixed domestic/international contact stands (SFO, 2012).

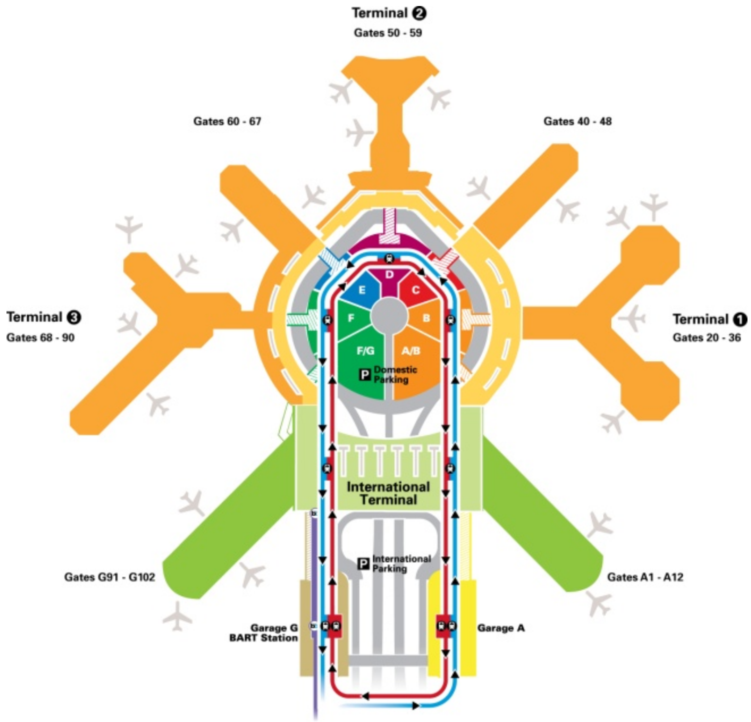


Figure 3. Layout of the terminal complex at San Francisco Airport, United States (SFO, 2012)

European airports experience a somewhat more specific situation, since part of Europe belongs to the Schengen area inside of which a free flow of passengers and goods applies. Domestic passengers are those traveling not only to/from a particular country but to/from the entire Schengen area. Non-Schengen passengers have their origin and/or destination outside the Schengen area. Within this group it is often the case to separate the sub-group of international (intercontinental or special countries) passengers traveling to/from the countries that require some additional passenger checks (usually related to security). The Schengen area of the terminal building has to enable the free flow of passengers, and the non-Schengen area has to provide entry/exit separation from the Schengen area. Depending on the passenger terminal building, the apron contact stands can be available only for Schengen flights, only for non-Schengen/international flights and/or for mixed flights with respect to their origin/destination. If separation between non-Schengen and Schengen flows is achieved vertically (by levels) in the same building, contact stands can be for mixed usage. Unlike U.S. airports, there are many more mixed terminals at European airports, aiming to shorten connecting times between the flights on mixed routes that account for a great share of the total number of connections.

For example, at Zurich Airport (Figure 4) Pier A is for Schengen flights, while Pier B and Pier E are for mixed Schengen and non-Schengen flights (vertical separation within the terminal). Terminal E has separate areas for international flights with special security requirements. Earlier (before Switzerland joined the Schengen Agreement), all terminals were international. Remote stands are now used for Schengen-flights overflow, primarily for airlines other then Star Alliance members. They are also engaged (in the midday peak) for Pier E long-haul flights overflow (ZRH, 2012a).

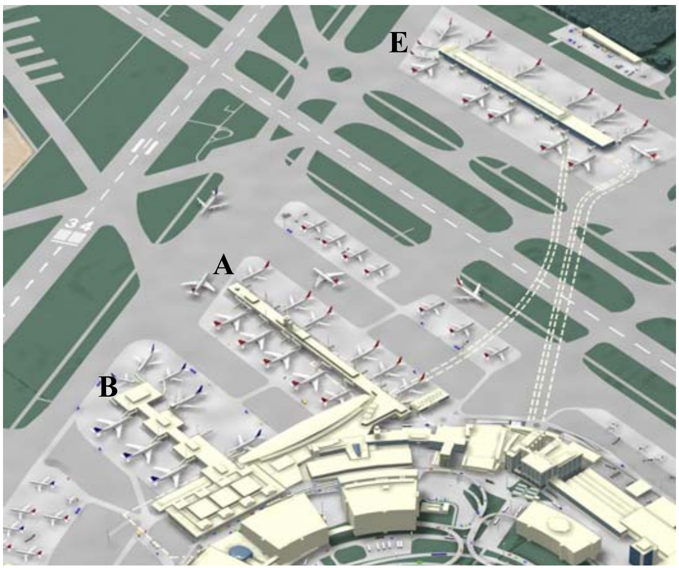


Figure 4. Layout of the terminal complex at Zurich Airport, Switzerland (ZRH, 2012a)

At Munich Airport both terminals are for mixed flights. The separation of the flows is horizontal (dedicated modules) in Terminal 1, while in Terminal 2 vertical separation applies (dedicated levels), Figure 5. In Terminal 1 modules A and C are for Schengen, modules B and D for non-Schengen (B higher risk), and module E for extremely high-risk destinations (e.g. Israel). In Terminal 2, one level for Schengen and the other for non-Schengen allow contact stands to be used flexibly by all flights with respect to their origin/destination combination[8].

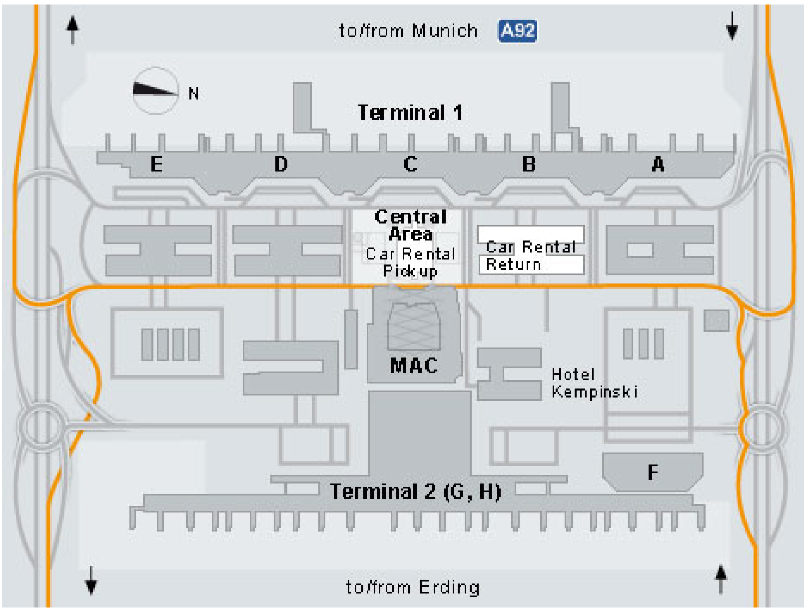


Figure 5. Layout of the terminal complex at Munich Airport, Germany (MUC, 2013)

If there are more dominant classes of passengers accounting for a significant share, different segmentation may apply, e.g. at Palma de Mallorca Airport, Spain there is an additional module for inter-island flights.

Operational constraints in using passenger apron(s) may also stem from the stand assignment policy with respect to different airlines. In Europe, it is typical that stand assignment policy is entirely the matter of airport operator's decision[9], a so-called a common-use strategy. On the other hand, at U.S. airports, stand assignment is typically passed on the airlines. There is a difference between exclusive, preferential and joint use

[8] Only for Lufthansa and Star Alliance

[9] One of the exceptions is Terminal 2 at Munich Airport, as a joint investment of the Munich Airport and Lufthansa, which is used only by Lufthansa and Star Alliance.

of stands/gates. Exclusive use signifies that a single airline has complete use and control of stands/gates[10]. Preferential use implies leasing stands/gates by a particular airline, while the airport operator retains the right to assign available resources to other airlines when they are not used by the leasing airline. Joint use assumes leasing the same stands by various airlines.

For example, at John F. Kennedy Airport (JFK), shown in Figure 6, Terminal 5 is used exclusively by JetBlue, Terminals 2 and 3 by Delta, while other terminals (1, 4, 7 and 8) are jointly used by several airlines (JFK, 2012).

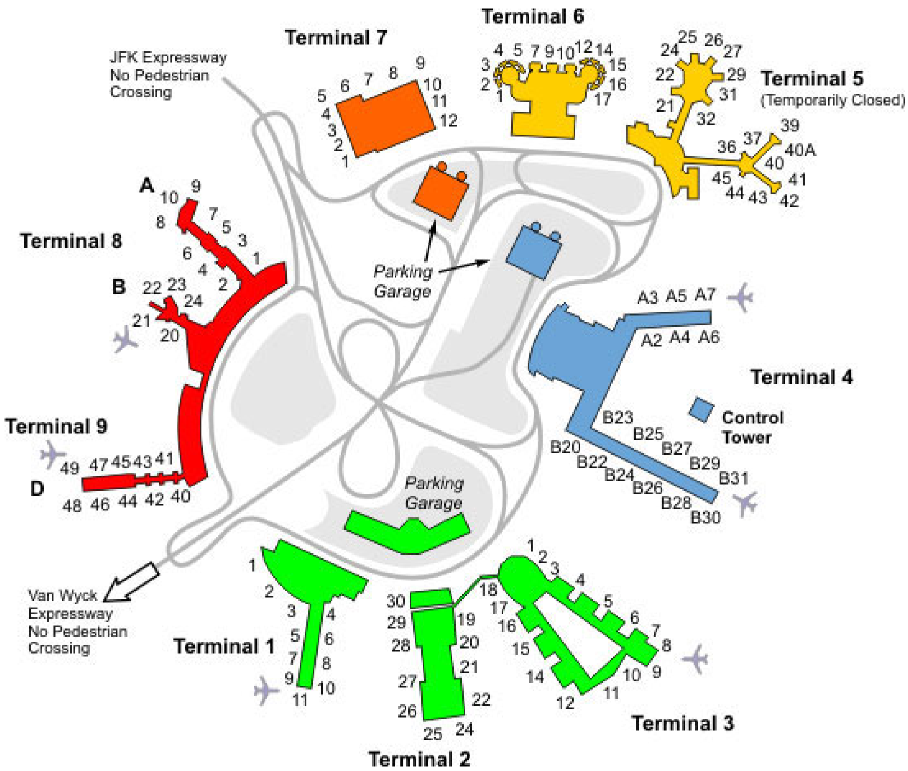


Figure 6. Layout of the terminal complex at John F. Kennedy Airport, United States (JFK, 2012)

At the San Francisco Airport (Figure 3) all terminals are used jointly by several airlines[11].

[10] Lease agreements may give the airport operator the right to negotiate for underutilized gates.

[11] Terminal 1 is used by AirTran Airways, Alaska, Delta, Frontier, Southwest and US Airways; Terminal 2 – by American and Virgin America; Terminal 3 - by Continental, United and United Express; and the international area is used by all international flights, plus Hawaiian, JetBlue and Sun Country (SFO, 2012).

### 1.4 Impact of different user constraints on airport airside capacity

Considering the impact on the runway system capacity (through the imposed ATC separation rules), the main users of the runway system are arriving and/or departing flights[12] (regardless of airline) operated by different aircraft classes.

On the other hand, the situation is more complex when the apron(s) are considered. In addition to physical constraints imposed by aircraft classes, there are other categories of users that can impose constraints on apron stands usage and consequently affect apron capacity (market segments, airlines and flight origin/destination).

More constraints on the use of certain infrastructure element make it less flexible in absorbing changes in the demand characteristics. Inflexibility of one element affects the inflexibility of the entire system. In an inflexible system, changes in demand characteristics may lead to a decrease in the efficiency of overall capacity utilization.

When an apron appears to be a bottleneck in the airport airside sub-system, it is necessary to detect whether there is an objective lack of capacity, or whether the capacity shortage appears as a result of operational imbalance between the supply (apron configuration and constraints applied) and the demand (demand volume and structure)? In the first case, the only solution to the problem is infrastructure expansion. In the second case, it is possible to mitigate or remove a bottleneck through adequate reallocation of the apron (contact and remote) stands among the users by changes and/or relaxation of the current constraints.

The thesis aims in analyzing capacity of the current apron and its impact on the overall airside capacity at passenger airports. It also analyzes the potential to gain additional capacity by means of changing constraints on apron stands usage.

[12] The runway may be designated only for arrivals, only for departures, or for mixed operations.

# 2 Airport categorizations with respect to traffic parameters

## 2.1 General

Airport categorizations are based mainly on size of airport (volume of traffic served) also taking into account: hubbing, presence of LCCs and, for small airports, dominance of regional (short-to-medium haul) traffic/routes (EC, 2008; Malighetti et al., 2009; Oetl and Boeck, 2012).

Official categorizations of airports adopted by international institutions are primarily based on airport size, referring to traffic volume served (mainly annual number of passengers). In addition to that they are further classified based on dominant market segment(s) and traffic pattern (to split hub from non-hub type of service).

Official categorizations (by the U.S. Federal Aviation Administration - FAA and the European Commission - EC) are referred to in the relevant literature on airport planning and design (Horonjeff et al., 2010; Ashford et al., 2011). An example is categorization by the Committee of the Regions, in its Outlook opinion of 2nd July 2003 on regional airport capacities (EC, 2005). It suggests five categories of European airports:

1. *Major Hub Airport* with more than 25 million passengers per annum (4 airports, accounting for approximately 30% of European traffic),
2. *National Airport* with 10 to 25 million passengers per annum (16 airports, accounting for approximately 35% of European traffic),
3. *Airport* with 5 to 10 million passengers per annum (15 airports, accounting for approximately 14% of European traffic),
4. *Airport* with 1 to 5 million passengers per annum (57 airports, accounting for approximately 17% of European traffic), and
5. *Airport* with 200 000 to 1 million passengers per annum (67 airports, accounting for approximately 4% of European traffic).

Some other categorizations based on number of passengers (or volume of cargo) are available in the sources e.g. FAA (2013), Office of the Federal Register (2011) and EC (2005).

It is important to distinguish between the term “hub” that is misused in majority of categorization referring to airports that handle large volumes of traffic and/or to airports being large airline operational bases, and the real concept of a hub, referring not only to a large airport, but more closely associated to transfer traffic through strong connectivity between flights achieved by inbound and outbound flight schedule coordination (Dennis, 1994). Similarly, the term “national” is also misused. It is not used to differ between national and international, but it is again strictly connected to a certain volume of traffic.

## 2.2 The role of airports in air transport networks

Deregulation and liberalization in air transport had twofold effect. Traditional (also in referred to in literature as: full-service, ex-flag, legacy) airlines begin to concentrate their flights spatially and temporally at hub airports, therefore offering wider coverage of the routes to all “spokes” being connected to hub airport. On the other hand, low-cost model came into the service. In U.S. the low-cost model was established by Southwest, even before deregulation (in 1973) while Europe waited almost 20 years for Ryanair (in 1995) to establish its low-cost service in the liberalized market (Dobruszkes, 2006). Traditional airlines organize their networks in line with the hub-and-spoke concept, while on the other hand LCCs operate on the point-to-point principle.

In the hub-and-spoke network, a distinction is made between hub and non-hub airports, based on their role in the network. The main characteristic of hub airports is strong connectivity between flights. In order to achieve connectivity, one or more airlines concentrate their flights and operate waves (banks) of flights at hubs, enabling them to function as the point of exchange. They experience several (alternating arrival/departure) peaks of demand each day. Understanding of hub airport accounting for spatial concentration and temporal coordination is now widely accepted in literature (Dennis, 1994; Danesi, 2006; Burghouwt and de Wit, 2005; Kraus and Koch, 2006; Burghouwt, 2007; etc.).

Non-hub airports of the hub-and-spoke network are origin-destination (O/D) airports connected to hub airport(s), operating as their feeders. The term feeder is commonly used for these O/D airports, implying an exchange of flights/traffic in both directions, to and from the hub(s). In addition to feeder flights, there are other point-to-point flights operating from these airports. At these airports demand is not concentrated in waves, but spread out throughout the day, with existence of more or less pronounced peak periods (usually morning and late evening, and possibly a midday peak). There is no coordination between particular incoming and outgoing flights with the aim of facilitating passenger transfers at the airport. Airports connected to hub-and-spoke networks are usually (but not necessarily) those with predominantly traditional scheduled traffic.

In addition to O/D airports operating as hub feeders in hub-and-spoke networks, some other airports included into point-to-point networks are also O/D airports. They mainly serve LCCs and/or charter airlines. Similarly as the “spoke” airports, these airports do not coordinate inbound and outbound flights in order to enable effective and efficient passenger transfers between the flights, nor they play the role of feeder airports (at least not as a general rule). In point-to-point network certain spatial concentration exists, naturally created at the strongest base airport(s) of LCCs. Usually, there is no temporal concentration intentionally created to facilitate transfers between flights, but it can consequently exist at airports with high traffic density.

Burghouwt (2007) gives some general categorization of airports based on their temporal and spatial concentration, as in Table 2.

In Table 2, airline stations refer to non-hub airports, i.e. “spokes”, traffic nodes are core nodes of the point-to-point networks, hubs are divided into several sub-groups (see following section for details) one of which is continuous (rolling) hub, which has “lost” wave-system structure of demand due to saturation.

The current state of the European air transport i.e. airline/alliances networks (primarily hub-and-spoke and low-cost) and their foreseen evaluation are summarized in Appendix 1. The aim is to show that, despite permanent networks evolution, airport categories based on spatial and temporal concentration of traffic are not likely to change. However, particular cases can undergo transformation from one role in the network to another, depending on the base airline strategy.

Table 2. Airport categorization based on spatial and temporal concentration of traffic (Burghouwt, 2007)

<table>
<tr><td colspan="2"></td><td colspan="2">Spatial configuration of the node</td></tr>
<tr><td colspan="2"></td><td>Decentral</td><td>Central</td></tr>
<tr><td rowspan="2">Temporal configuration of the node</td><td>No wave-system structure in airline flight schedule</td><td>Airline station<br>Feeder destination/spoke/<br>/non-hub</td><td>Traffic node<br>Continuous (rolling) hub</td></tr>
<tr><td>Wave-system structure in airline flight schedule</td><td>(Intermediate node)</td><td>Hub<br>Hinterland,<br>Directional/Hourglass,<br>All-around, Euro,<br>Specialized, Global,<br>Hyper, Mega, Super</td></tr>
</table>

The role of the airport in the air transport network has significant impact on the traffic pattern (mainly its temporal concentration) and together with that, on utilization of the airport airside capacity.

This issue is rather poorly addressed in literature, with some exceptions. Burghouwt (2007) devoted a chapter in the book discussing the impact of airline networks onto airports. He observed spatial and temporal concentration from the perspective of wave-system structure, connectivity and seat capacity (all being certain indicators of demand characteristics). However, he did not address possible repercussions of the specific demand characteristics on airport airside capacity, which is the main issue addressed in this thesis.

### 2.2.1 Selected airport categorizations with respect to role of airport in the network

Selected airport categorizations, considering hubbing in the real sense, as summarized in (EC, 2008) and produced for the purpose of different studies, are given in Appendix 2.

Deutche Bank Research (2006) differentiated between three categories among European airports (mega-hubs, secondary hubs and secondary airports).

Buyck (EC, 2008) considered worldwide airports, and classifies them into four categories (primary hubs, secondary hubs, regional platforms and LCC bases).

Burghouwt, G. (2007) differed between five categories (ranked 1$^{st}$ to 5$^{th}$) of airports in hub-and-spoke networks, with respect to indirect connectivity in combination with presence of the wave-system structure. Although based on very important characteristics of hubbing, he gave the state of the network from the year 1999, which cannot be accepted as a good approximation of the current state due to constant networks evolution. For example, almost none of the categories had wave-system structures in 1999, which is definitely not the case at the present.

Malighetti et al. (2009) categorized European airports accounting for volume of traffic, destinations of connections, connectivity and type of service. They clustered 467 European Airports[13] into eight categories (worldwide hubs, hubs, secondary gates, airports with 3-5 million pax, no low-cost gates, regional airports, airports for LCCs and local airports). However, cluster analyses should be taken with caution as they are based on exact performance indicators and reflect current network state, but not necessarily future changes. Different subgroups may result from different traffic parameters.

Munich Airport categorization (cited in: Oettle and Boeck, 2012) defers between five airport categories of which two are hubs (international and secondary) and three are O/D airports (international, regional and secondary).

## 2.3 Market segments differentiation

Categorization of (European) airports with respect to dominant market segments is addressed in Chapter 1 (Section 1.1), showing the dominance of the passenger market segment.

[13] With at least one passenger flight scheduled in autumn 2007

## 2.4 Other considerations

Demand for airports is rarely distributed evenly throughout the year, month and/or day. Instead, it is normally characterized by temporal imbalance that can be described in terms of hourly, daily or monthly variations in passenger, cargo or aircraft movements (Ashford et al, 1997; Ashford et al, 2013). Nonetheless, it is important to take into consideration peaking patterns on different levels (daily, weekly and yearly).

A special sub-group of O/D airports are seasonal airports characterized by highly concentrated traffic during the high season, and the very low traffic during off-season periods. Seasonal traffic concentration is the outcome from additional demand, typically related to summer and winter vacation periods and related destinations, but it can also be imposed by events related to important holidays that may differ depending on the country, region, religion, etc. (Halpern, 2011).

In Appendix 3, a list of 39 European seasonal airports is given (as of 2006; source: Eurocontrol, 2007). The seasonality factor is calculated as the ratio between the maximum number of departures during the peak day and the mean number of daily departures. Except "regular" seasonal airports at which seasonality is driven by the tourist season (summer or winter) there are several airports that have experienced seasonality due to special events in 2006. The majority of European seasonal airports experience summer peaks, in combination with common weekly peaking, so called "hedgehog" airports.

Seasonal traffic patterns are illustrated on the example of several Spanish i.e. AENA's, airports, given in Appendix 3.

General principles on airside capacity analysis addressed in this thesis apply also for seasonal airports, but additional implications of seasonality on airport airside resource planning are not further elaborated.

Airport categorization with respect to hourly and daily variations will be addressed in Chapter 3 (Section 3.4).

# 3 Airport airside capacity - definitions and factors that affect it

## 3.1 Definitions of airside capacity

Capacity is the ability of a component of the airside to accommodate aircraft. It is expressed in operations (arrivals and departures) per unit of time, typically in operations per hour (Ashford and Wright, 1992).

In dependence on the dominant factors affecting capacity, different concepts of capacity may exist. Broadly, there can be operational, economic and environmental factors. They may work together, but in the most cases only one type of factors is dominant and thus determines airport airside capacity under given conditions (Janic, 2004). This thesis refers to operational capacity, assuming that the dominant constraining factors are operational.

In general, there are two basic capacity concepts: ultimate and practical capacity. Saturation capacity is also known as ultimate capacity or maximum throughput capacity. Both capacity concepts refer to conditions of saturation (the continuous demand for operations is assumed) and adherence to separation requirements specified by the ATC. The main difference is that saturation capacity does not take into account the level of service (in other words it is determined regardless of delay), while practical capacity considers a certain acceptable level of service (specified average acceptable delay, usually four minutes).

Both concepts of saturation and practical capacity are used in most relevant literature (Ashford and Wright, 1992; De Neufville and Odoni, 2002; FAA, 1983; Hockaday and Kanafani, 1974; Janic, 2009).

As a reflection of what occurs in the case of the most congested airports in the world today, the runway system is considered to be the major capacity constraint. That is the main reason why airside capacity is usually expressed through runway system capacity. The definitions of ultimate and practical airport airside capacity are as it follows (De Neufville and Odoni, 2002):

- *Saturation capacity* indicates the average number of operations that can be performed on the runway system in 1h in the presence of continuous demand, while adhering to all the separation requirements imposed by the ATM (Air Traffic Management) system.

- *Practical hourly capacity*, originally proposed by the FAA in the early 1960s, is defined as the expected number of operations that can be performed in 1h on a runway system, with an average delay per operation of four minutes. The runway system reaches its capacity when this threshold is exceeded. The practical hourly capacity of a runway system is approximately 80-90% of its saturation capacity, depending on the specific conditions.

These two capacity concepts are commonly used in the process of airport planning and development. They are delivered by all capacity estimation models for supporting decision making in these areas.

It is not always suitable to express capacity in a 1-hour period, like it is typically done for saturation capacity or practical capacity. Other time units (smaller or larger) can, and probably should, be used for better description of available resources potential to meet particular demand requirements. This is an especially sensitive question at hub airports, where demand comes in waves of successive arrivals followed by a wave of successive departures. Hubbing parameters that may affect airside capacity are discussed in Section 3.3, followed by the discussion about representative peak periods in Section 3.4.

In addition to above-mentioned basic capacity concepts, there are also, sustained capacity and declared capacity, defined as it follows (De Neufville and Odoni, 2002):

- *Sustained capacity* of a runway system is defined as the number of operations per hour that can be reasonably sustained over a period of several hours. Maximum performance often cannot be sustained in practice for a period of more than one or two consecutive hours.

- *Declared capacity* is defined as the number of aircraft operations per hour that an airport can accommodate at a "reasonable" level of service (LOS). There is no accepted definition of "reasonable" LOS and no standard methodology for setting it[14]. The declared capacity is roughly 85-90% of the saturation capacity of the runway system[15].

These two concepts are meant rather for describing reasonable capabilities of existing systems. Declared capacity is used in specifying the number of slots available for schedule coordination purposes, based on specific LOS that airport aims to meet. In addition, it is widely used for airport benchmarking, although many different understandings of this capacity concept can leads to inconsistency in comparison.

In addition to capacity in absolute terms, its utilization has shown to be particularly important performance indicator, not only for peak periods, but also for longer time horizons (day, week and season). The level of capacity utilization can indicate underutilization of the capacity (as a consequence of traffic demand being lower than capacity), or inefficiency in capacity management, particularly at congested airports (when delays occur due to inability to accept all scheduled operations on time). Cherniavsky and Abrahamsen (2000) defined airport utilization metrics (as a subset of FAA Aviation System Performance Metrics) and explained an approach to calculate them. In brief, arrival/departure/airport utilization represents a degree to which arrival/departure/mixed demand was satisfied for a given period, taking into account the airport's target capacity in that time period. These measurements taken over 15-minute periods are then combined to produce utilization performance (arrival, departure and overall) for the day.

## 3.2 Factors that affect airside capacity

Different approaches to classifying factors affecting airside capacity have been used in the literature (Ashford and Wright, 1992; De Neufville and Odoni, 2002; Janic, 2009; Newell, 1979).

Based on research and practice, major factors affecting runway system capacity are classified in four groups in this thesis. The factors belonging to each group are listed below.

[14] Such as four minutes typicaly used for practical capacity

[15] The declared capacity is not necessarily imposed by the runway system LOS. It can also be affected by the LOS specified for apron(s) and terminal building.

1. *Runway system layout* – number of runways, runway length and runways' mutual position (parallel, crossing, extended runway centerlines crossing (V configuration)), number of simultaneously active runways, available runway configuration with respect to type of operations (departures/arrivals/mixed operations), number and location of runway exits, existence and position of crossing taxiways;
2. *Demand characteristics* – traffic distribution, exchange of operations (arrivals/departures), fleet mix, mix of market segments (scheduled, low-cost, charter, cargo, business, etc.);
3. *Operational constraints* – separation rules set by ATC requirements, runway occupancy times;
4. *Local conditions* – meteorological conditions, environmental conditions.

These four groups of factors are not strictly separated, but they overlap to some extent. For example, runway exit location is an infrastructural factor, but at the same time it is also an operational factor, because it directly affects runway occupancy time, which then affects arrival-arrival and arrival-departure separation at a particular airport; or local meteorological conditions, especially wind and visibility, have direct impact on configuration of the runway system in use.

Although the runway system is identified as the major airport scarce resource, the capacity of other infrastructure elements should also be taken into account.

The taxiway system at major airports is most often designed to provide capacity which exceeds the capacity of the runway system and thus not be the factor limiting airside capacity (De Neufville and Odoni, 2002). This does not necessarily mean that some local constraints cannot be identified, especially in the areas of taxiway intersections, points where taxiways cross an active runway(s) or where high-speed exits merge with taxiways. The general rule is that taxiway capacity problems are specific for each airport and must be resolved at the local level, for the specific configuration and under the local conditions.

On the other hand, apron capacity can be a limiting factor of the overall airside capacity. Airports have lately been facing this more often. Apron capacity depends on similar factors as the runway system capacity. The factors can be classified in four groups, similarly as those for the runway system:

1. *Apron layout* – number of parking stands, number of stands per market segment and per aircraft class, number of stands that can be simultaneously used with respect to lateral separation, apron taxiway layout;
2. *Demand characteristics* – traffic distribution, exchange of operations (arrivals/departures), fleet mix, mix of users (classified by different criteria - airlines, or flights O/D combination), mix of market segments (scheduled, low-cost, charter, cargo, business, etc.);
3. *Operational constraints* – turnaround times, buffer times between aircraft which use the same or laterally endangered stand, policy of parking stand usage (e.g. by airline in U.S., or by flight O/D in Europe);
4. *Local conditions* – meteorological conditions (particularly visibility).

The factors that affect runway system and apron capacity are summarized in Table 3.

Although capacities of the runway system and apron depend on similar factors (see Table 3), it does not imply that both of them reach their capacities under the same conditions. By assessing capacity of the runway system and capacity of the apron complex we have a certain, but rather incomplete, picture of the overall airside capacity and its sensitivity on demand changes. It is necessary to consider their functional relationship in order to create the overall airside capacity scheme.

The thesis places a special emphasis on apron capacity, which is modestly addressed in academic and professional literature, including the explicit consideration of the functional relationship to the runway system and the differences induced by demand characteristics, particularly traffic distribution depending on the role of the airport in air transport networks (O/D airports vs. hubs).

The characteristics of hub airports with implication on airside capacity utilization are discussed in the reminder of this chapter (Section 3.3).

Table 3. Factors that affect runway system and apron capacity

| ***Factors that affect capacity*** | **RUNWAY SYSTEM** | **APRON** |
|---|---|---|
| ***Design parameters*** | Runway system layout (number of runways, runway lengths and runways' mutual position: parallel, diverging/converging, crossing);<br><br>Runway system configurations (number of simultaneously active runways, runway allocation with respect to type of operations: departures/ arrivals/ mixed operations);<br><br>Number and location of runway exits; existence and location of crossing taxiways | Number of parking stands;<br><br>Apron layout (number of stands per market segment, and per aircraft class);<br><br>Available apron configurations in terms of number of stands that can be simultaneously used with respect to lateral separation (for aprons with MARS stands);<br><br>Apron taxiway system layout; |
| ***Demand characteristics*** | Traffic distribution and exchange of operations (arrivals/departures);<br><br>Fleet mix;<br><br>Mix of market segments (scheduled, charter, cargo, business, etc.) | Traffic distribution and exchange of operations (arrivals/departures);<br><br>Fleet mix;<br><br>Mix of users (classified by different criteria - airline, or type of service);<br><br>Mix of market segments (scheduled, charter, cargo, business, etc.) |
| ***Operational considerations*** | Separation rules set by ATC requirements;<br><br>Runway occupancy times | Turnaround times;<br><br>Buffer times between aircraft using the same or laterally endangered stands;<br><br>Policy of stands usage |
| ***Local conditions*** | Meteorological conditions (visibility, ceiling, wind);<br>Environmental conditions (emissions, noise) | Meteorological conditions (particularly visibility) |

## 3.3 Characteristics of hub airports with implication on airport airside capacity

### 3.3.1 Spatial and temporal concentration at hub airports

At hub airports, the core nodes of the hub-and-spoke networks, the dominant airlines concentrate their flights and operate waves (banks) of flights (Figure 7) in order to achieve strong connectivity between flights.

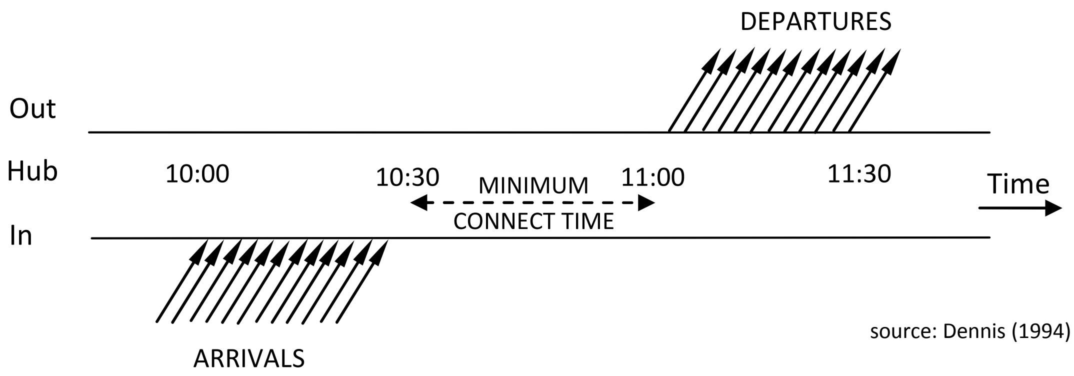


Figure 7. A wave of flights at a hub airport (Dennis, 1994)

The main characteristics of hub-and-spoke networks are their spatial and temporal concentration.

Spatial concentration can be defined by the level of airline network concentration around one or a few hub airports (Burghouwt and de Wit, 2005). It is mainly determined by the geographical location of the hub airport, especially in Europe. For example the Paris and Brussels area is favorable for intra-European connections, while for long-haul connections the entire area between London and Zurich may be considered as competitive (Dennis, 2005). In other markets local demand may additionally induce spatial concentration.

Temporal concentration assumes coordination between inbound and outbound flight schedules aimed at achieving higher number and quality of indirect connections. Demand at hub airports comes in a wave of arriving flights, followed by a wave of departing flights, allowing sufficient time for transfers between them. Usually, several waves are scheduled during a day.

Another vital requirement for effective airline hub operation is sufficient airport airside and landside capacity, to handle a large number of aircraft simultaneously and process transfer passengers in a short period of time, providing some margin to absorb delays (Dennis, 1994).

### 3.3.2 Ideal wave

An ideal wave assumes a complex of incoming and outgoing flights, structured such that all incoming flights connect to all outgoing flights. The wave starts with the arrival time window, followed by transfer period and completed with departure time window (Danesi, 2006).

The structure of the wave is determined by:

1. The minimum connecting time – MCT, which depends on the category of connections),
2. The maximum acceptable connecting time – MaxCT, and
3. The maximum number of flights that can be scheduled per time period - N.

The structure of an ideal wave containing intercontinental and continental connections is shown in Figure 8.

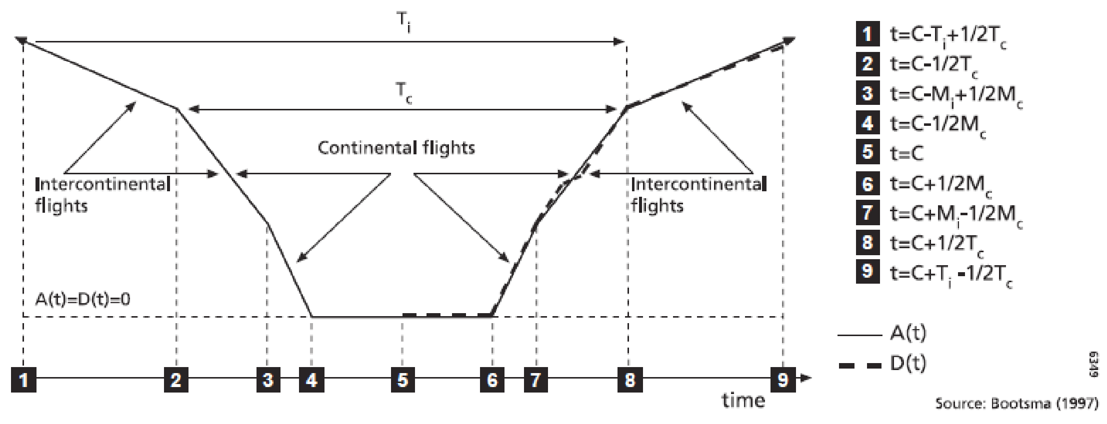


Figure 8. Ideal wave (Bootsma, 1997, cited in: Burghouwt, 2007)

In this case, time windows for arriving intercontinental (ICA) and continental (EUR) flights and departing continental and intercontinental flights, are defined as (Burghouwt, 2007):

- ICA arriving window: [C-Ti+0.5Tc, C-Mi+0.5Mc],
- ICA departing window: [C+Mi-0.5Mc, C+Ti-0.5Tc],
- EUR arriving window: [C-0.5Tc, C-0.5Mc],
- EUR departing window: [C+0.5Mc, C+0.5Tc],

where:

C – the wave center (point 5, Figure 8),

$T_c$ – the MaxCT for continental connections (2-8, Figure 8),

$T_{i/c}$ –the MaxCT involving intercontinental connections (1-8, Figure 8),

$M_c$ – the MCT for continental connections (4-6, Figure 8), and

$M_{i/c}$ – the MCT involving intercontinental connections (3-6, Figure 8).

Connections have to meet MCT in order to be viable. MCT depends on the airline, type of connection (domestic, continental, intercontinental, or other) and airport design and performance (i.e. capacity to process transfer passengers and baggage within and between terminals). Typical MCTs at world airports are given in Appendix 4. European average is clustered around 45min, with small differences between airports (Dennis, 1994). Exceptions are modern terminals (purpose-built) where these times are decreased to 35min (Munich Airport) or even 25min (Vienna Airport). Connections to long-haul destination, involving changing terminals, require longer times (75min Terminal 1 to Terminal 4 at London Heathrow).

MaxCT reflect the LOS thresholds that keep connections attractive to passengers. It depends on the type of connection. For example, long-haul passengers are generally ready to wait longer than short-haul passengers. Bootsma (1997) (cited in: Danesi (2006)) has defined MaxCT for different types of flights and different quality thresholds. For poor quality level MaxCT is considered to be 180min for continental connections, 300min for continental-intercontinental connections and 720min for intercontinental connections.

A trade-off has to be made between the maximum acceptable connecting time and the maximum number of flights that can be scheduled in arrival/departure time windows (Burghouwt and de Wit, 2006). The one that is more critical, determines the size (duration) of the wave. In other words, the size of the wave depends mainly on the runway system capacity, apron capacity and on the LOS threshold (i.e. MaxCT).

As a reflection of the practice at major European hubs, the typical wave size is around 50-60 aircraft, with an arrival and departure time-wave of approximately one hour for each. In typical U.S. wave 60 aircraft arrive in 30 minutes interval, and after being on the ground for at least 30 minutes, they all depart within 30 minutes (Dennis, 2005).

Ideal wave is unlikely to exist in practice due to different reasons (Burghouwt and de Wit, 2005). Some of them are that the “spokes” are too close, or too far, to fit in the wave structure, strong O/D market that attracts flying off-wave, fleet utilization or other reasons airlines choose not to adopt wave-system structure, and last but not least, capacity constraints.

Concentration of flights in waves affects turnaround times and consequently apron capacity. Furthermore, underutilized periods between consecutive waves affect efficiency of airport airside capacity utilization.

For example, if the runway system capacity is 60 arrivals or departures per hour and MCT is 30 minutes, the most of 90-minutes connections (MaxCT=90min) are achievable with 30 flights/aircraft per wave. The average turnaround time increases at a linear rate, and reaches 60 minutes for a 30-flights wave and 90 minutes for a 60-flights wave (Dennis, 2005). This has a direct impact on apron capacity.

### 3.3.3 Hubbing performance

When it comes to indication of hubbing performance, i.e. an influence of temporal concentration on airport performance, indirect connectivity is often addressed in the literature as a global measure of temporal concentration at hub airports.

Different approaches are used to evaluate indirect connectivity. They are all based on the analysis of the number and quality of connections, but the criteria that define quality of connections differ between them.

For example, Burghouwt and de Wit (2005) calculate weighted indirect connectivity index as the sum of weighted indirect connections at an airline hub. For all possible connections between arriving and departing flights during the same day, they calculate the weighted indirect connection number (WNX) as a function of the quality of the connection at the hub airport (calculated based on: MCT, MaxCT and transfer time) and the quality of the indirect flight compared to direct flight (ratio of the actual indirect flight time and estimated direct flight time). Hub connectivity is judged as high if WNX is over 2500, medium if it is between 500 and 2500 and low if less than 500.

Some other indirect connectivity measures are briefly described in Appendix 5.

This thesis does not observe temporal concentration of flights in the context of indirect connectivity, but it rather focuses on implications of temporal concentration of flights on airside capacity.

### 3.3.4 Wave-system structure

Wave-system structure is specified by (Danesi, 2006, Burghouwt and de Wit, 2005):

1. Number of waves,
2. Wave repeat cycle (WRC) - the time interval between the same points of the consecutive waves, and
3. Wave-system structure which may be broken or complete, depending on where short and medium haul fleet is located overnight, at hubs, spokes or both.

Analysis of the European hub airports since 1990s shows changes of the traffic patterns at hub airports from rather “uniform”, i.e. spread out throughout a day with more or less pronounced peaks, to wave-system structure (Borghouwt, 2007). An example of Munich Airport is given in Appendix 6.

Burghouwt (2007) has used a theoretical approach[16] to analyze wave-system structures at main European hubs, i.e. to identify its presence, the number of waves, and the timing

[16] Explanation is given in Appendix 6.

of the waves[17]. However, his approach has omitted to catch an exchange between arrivals and departures, which is rather important from the perspective of airside capacity utilization efficiency.

An exchange of arriving and departing segments of the wave-system is clearly visible on real traffic data. It can be more or less pronounced depending on the type of hub airport, i.e. of the maturity level it approached in its transformation from an O/D airport.

The wave-system structure is much more obvious at small airports which try to improve connectivity between flights through better coordination between inbound and outbound flights (Danesi, 2006). Figure 9 gives an example of clear wave-system structure[18] at Milan Malpensa Airport (before withdrawal of Alitalia).

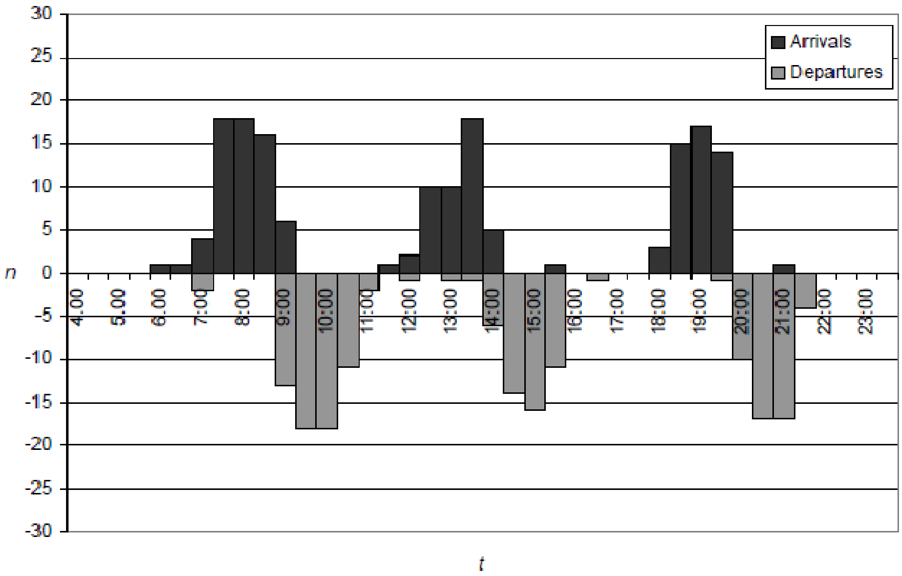


Figure 9. Daily traffic at Milano Malpensa, Italy, 19th January 2005 (Danesi, 2006)

However, at some large hubs, the wave-system structure is difficult to recognize, as is the case at London Heathrow, see Figure 10.

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[17] Some examples of airports with good wave-system structures (at that time, year 2003) are: Amsterdam - KLM operated 5 waves; Frankfurt - Lufthansa operates 5 waves; Munich - Lufthansa operated 4 waves; Zurich - Swiss operated 6-7 waves and Vienna - Austrian operated 5 waves.

[18] It is described as $(3, 5^{1/2}, 1)$ standing for three waves with repeat cycle on 5.5h and fleet stabled at "spokes" (Danesi, 2006).

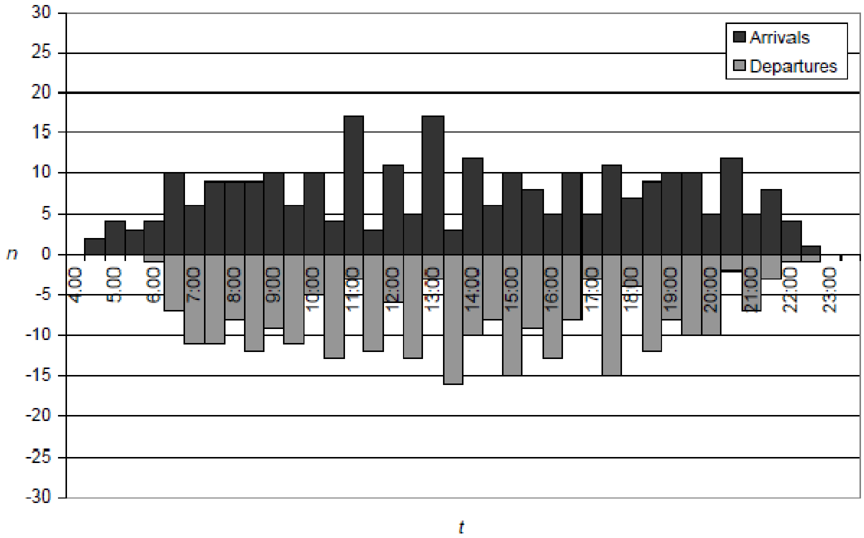


Figure 10. Daily traffic at London Heathrow, United Kingdom, 19th January 2005 (Danesi, 2006)

### 3.3.5 Evolutionary phases

Kraus and Koch (2006) argue that strict separation between O/D and hub airports does not reflect the full range of airport roles in air transport networks. They analyzed arriving and departing seat capacity both for the entire airport and for its hub airline, or the strongest airline at the airport[19]. They identified five different evolutionary stages i.e. types of airports:

1. O/D airports (without hub characteristics), e.g. Tunis (Figure 11),
2. O/D airports with first hub characteristics, e.g. Johannesburg (Figure 12),
3. Long-haul transfer hub airports, e.g. Doha (Figure 13),
4. Mature hub airports, e.g. Paris Charles De Gaulle (Figure 14), and
5. Hub airports with de-peaking strategy (rolling hubs, continuous hubs), e.g. Dallas Fort Worth (Figure 15).

At type 1 airports, the seat capacities offered are in line with the demand. Several peaks may occur during the day. At Tunis Airport (Figure 11) morning departure peak results from the airline strategy to base almost its entire fleet at home base overnight. Midday

[19] The entire flight schedule data (for calendar week 10 in 2006), including departure and arrival times, offered capacity per flight and operating airlines, has been analyzed and clustered into 48 time periods of 30 minutes.

peak results from the airline strategy to serve destinations reachable in 2.5 hours flying time implying that aircraft return to the base airport within approximately the same time-frame. The second peak is created when aircraft leave for their second daily rotations.

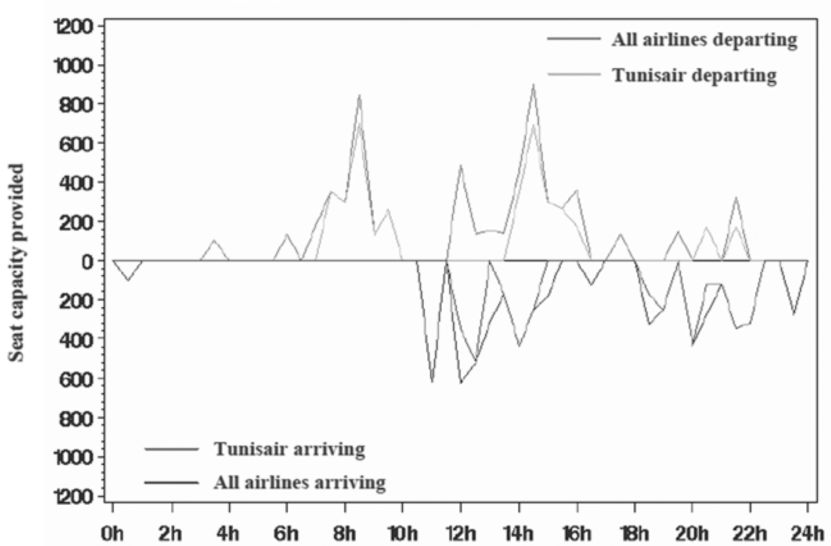


Figure 11. Type 1, O/D airport: Tunis Airport, Tunis (Kraus and Koch, 2006)

At type 2 airports (Figure 12) demand is characterized by a limited overall share of home base airline, as a result of the competition by other airlines in the liberalized market with still strong O/D market. In such case, home base airlines concentrate their flights in one or two waves per day.

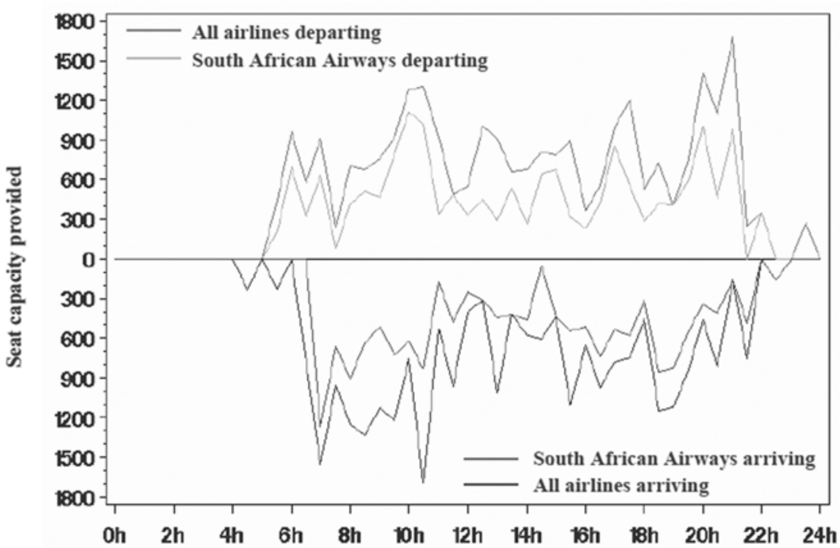


Figure 12. Type 2, O/D airport with first hub characteristics: Johannesburg Airport, South Africa (Kraus and Koch, 2006)

At type 3 airports (Figure 13) wave-system structure is clearly visible. Long-haul routes are served at a lower frequency than short- and medium-haul routes, thus requiring longer times for passenger transfers. This results in a smaller number of “wider” waves. Airport infrastructure is highly utilized during peak periods, while during off-peak periods it remains underutilized.

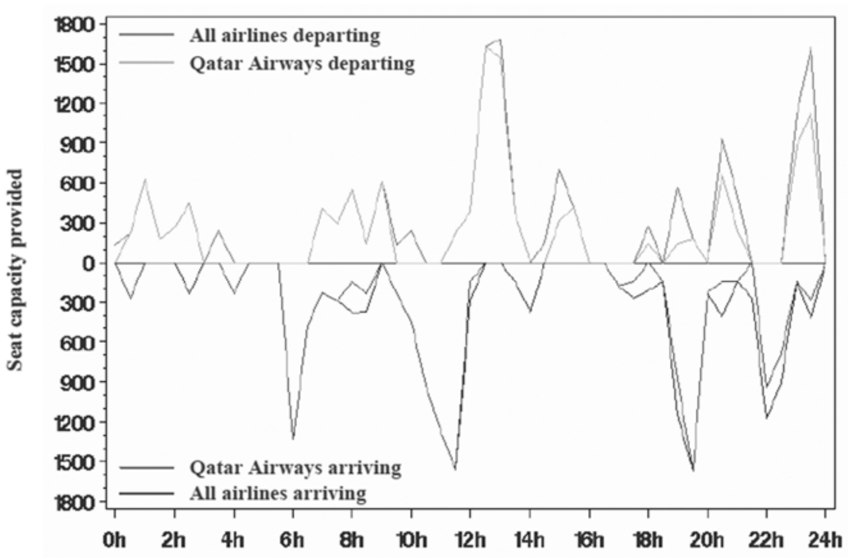


Figure 13. Type 3, long-haul hub: Doha Airport, Qatar (Kraus and Koch, 2006)

At well-established hub airports, type 4 (Figure 14), strong home base airline clearly dominates, operating several waves (5-6) during the day, each with a 1.5-2.0 hours duration. At these airports waves follow each other at short intervals (towards their overlapping), which leads to more or less stable utilization of airport infrastructure. Waves are interrupted by short periods of lower traffic loads, which are sometimes useful for recovery after disturbances.

At type 5 airports (Figure 15) the home base airline dominates. Due to the increase in traffic, not followed by an increase in capacity accordingly, the system cannot continue to function efficiently by keeping a clear wave-system structure, allowing for underutilized periods (idle slacks between waves). In order to increase the overall utilization of airside capacity through its permanent utilization, the traffic pattern changes accounting for larger number of shorter waves that follow each other in shorter time periods, leading to their overlapping after a further increase in the number of waves. So, over the time wave-system structure disappears, and the traffic pattern appears to be rather “uniform” at these airports.

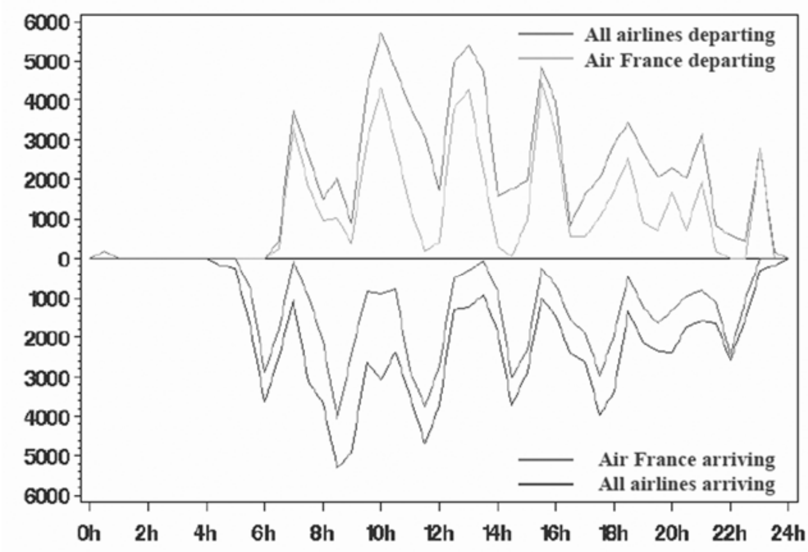


Figure 14. Type 4, mature hub: Paris Charles de Gaulle Airport, France (Kraus and Koch, 2006)

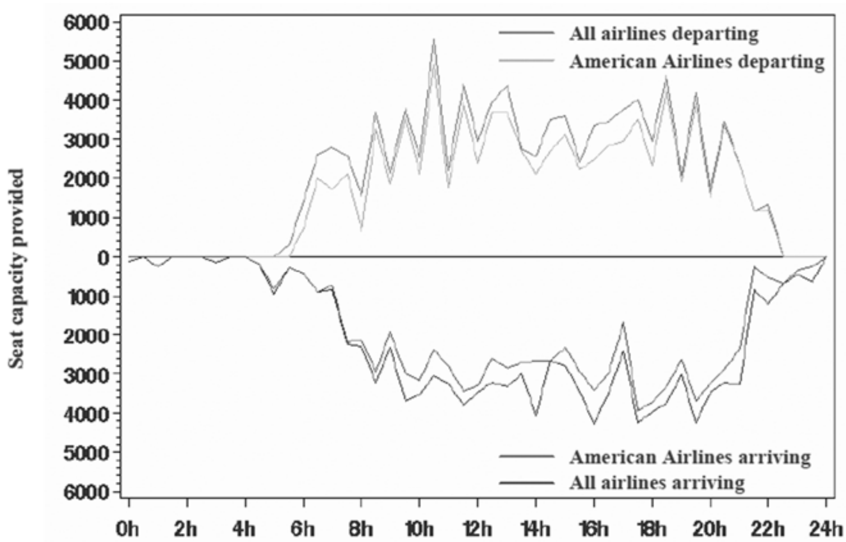


Figure 15. Type 5, rolling (continuous) hub: Dallas Fort Worth Airport, United States (source: Kraus and Koch, 2006)

This process of “destroying” the wave-system and returning to “uniform” pattern during the day is known as continuous or rolling hubbing.

It is not a new concept, but it preceded when connections were not created "artificially", but naturally, as a consequence of high volume of flight activity at busy airports (Dennis, 2005). By keeping the aircraft moving all day instead of concentrating them into fixed waves, it certainly increases utilization and productivity of the airport. On the other hand, it decreases connecting opportunities by offering a lower number of quality connections. Due to that, this may be a "solution" for LCCs, as the difference in price they offer may stimulate passengers to accept longer waiting times between connecting flights (Dennis, 2005).

### 3.4 Peak period

Airport airside capacity analysis and planning can be based on annual, daily and hourly traffic volumes and structures[20]. Which traffic data should be used depends on the type of question asked and the time horizon (planning level) considered.

Annual figures[21] are typically used to illustrate (describe) overall airport performance, and to draw a rough conclusion about whether the airport is capable of handling forecasted traffic volume(s) in particular year(s) in the future, usually in a time-frame of 15-20 years ahead (de Neufville and Odoni, 2002).

For a more detailed analysis daily and hourly traffic figures are far more important. Depending on the type of capacity analysis, peak day and peak hour also referred to as design or typical day/hour, are commonly used. Runway system capacity analysis is typically based on peak-hour traffic. On the other hand, determining whether available contact and remote stands have adequate capacity to accept demand requirements, asks for working with the design day.

Peak hour is not the busiest hour of the year, but it is a busy hour that is exceeded for an acceptably small number of hours during the year. Depending on the country or region,

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[20] Passenger figures are commonly used for landside planning and design, while for the purpose of airside planning and design it is air traffic operations that are of importance.

[21] They are commonly expressed in number of passengers, number of aircraft operations and a cargo volume.

different approaches to defining peak hour apply. The most common ones are given in Appendix 7 (de Neufville and Odoni, 2002).

Similarly the design day is not the busiest day of the year, but it is exceeded for an acceptably small number of days during the year. Common practices in determining peak day volume are given in Appendix 7 (de Neufville and Odoni, 2002).

For the analysis of the available resources utilization it is important to take into consideration arrival and departure distribution in time, as well as changes in traffic structure throughout the day. The Transportation Research Board (TRB) Airport Cooperative Research Program (ACRP) report (TRB, 2012a) on "Preparing peak period and operational profiles – guidebook", differs between design day profiles that assume arrival and departure distributions, and design day schedule that contain flight-by-flight information on airline, aircraft type, flight time, origin or destination, etc. The format of the schedules depends on their intended use. Design day schedules are necessary for the analysis on the highest level of detail (airfield simulations). For the purpose of tactical and strategic planning airside capacity analysis does not necessarily require detailed design daily schedules, as they are usually performed throughout less detailed models, thus requiring less detailed input (arrival rates, fleet mix, user mix for typical peak periods, but also certain schedule parameters, such as wave-system characteristics at hub airports).

In some cases, instead of using peak hour and design day, a more convenient approach would be identification of representative peak periods that best describe design day traffic. Namely, a single peak period or design day may not catch fluctuations in traffic structures during the day or week (e.g. waves centered on long-haul intercontinental connections vs. waves centered on medium-haul continental connections or short-haul regional connections) and traffic patterns during the week or season (e.g. only jumbo-jets during Hajj period vs. mixed fleet during off-Hajj periods at Medina Airport).

Depending on the airport, daily traffic patterns may have different number, duration and level of peak periods. Thus, design day may be described with one or more representative peak periods. This applies both to the runway system and apron capacity modeling, assessment and analysis.

Ashford et al. (2013) discuss the nature of peaking with respect to the most important factors affecting the distribution of peaks throughout the day: domestic/international ratio; charter and low-cost/scheduled ratio; long-haul/short-haul ratio; geographical location and nature of catchment area. Although the timing of the peaks is important for capacity analysis it is also important to know the structure of the peaks. Parameters describing peak periods are their duration and traffic structure with respect to aircraft types (for runway system) and both aircraft types and airlines/other users (for apron capacity analysis).

Oettl and Reeb (2012) suggested an approach to categorizing airports based on traffic parameters, mainly for the purpose of the runway system related capacity evaluations. An overview of the approach to deriving representative airport categories based on traffic parameters is shown in Figure 16.

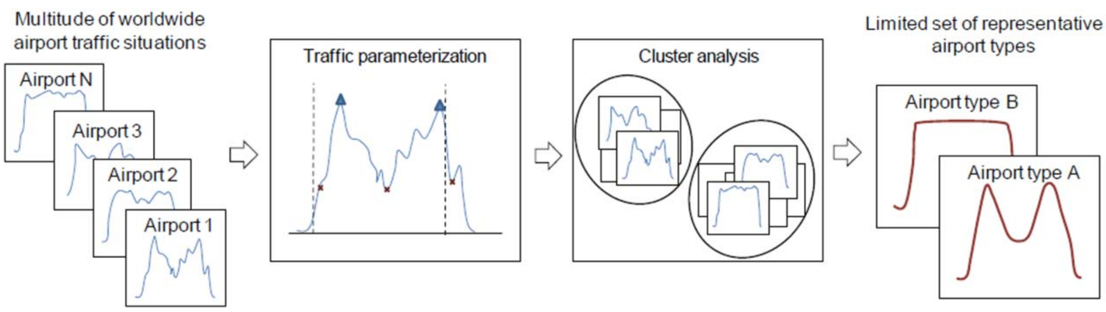


Figure 16. An approach to identifying airport types based on traffic parameters (Oettl and Reeb, 2012)

Main traffic parameters for airport categorization were adopted to be traffic peaking and related parameters. Each traffic peak is described with its aircraft type structure (with respect to 10 aircraft weight classes) and peak shape related parameters: peak duration in hours, peak fill factor (as ration between area under the peak and area of the rectangle) and peak amplitude (as percentage of the maximum peak at the respective airport), as it is illustrated in Figure 17.

Appendix 8 shows 11,936 traffic peak situations clustered in 19 representative traffic peak situations.

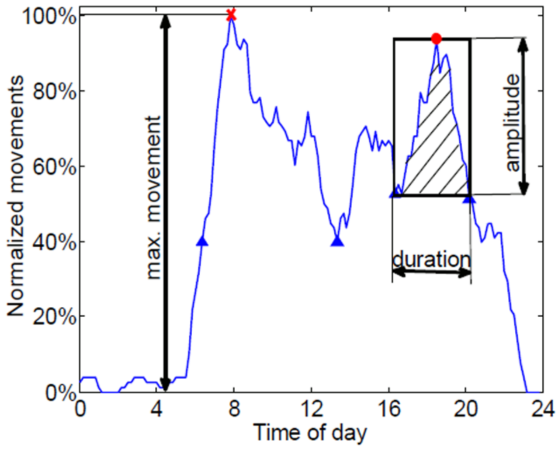


Figure 17. Traffic parameters (Oettl and Reeb, 2012)

Apart from parameters that characterize traffic peak situations, authors also categorized airports with respect to parameters describing daily traffic. These are: distribution of traffic throughout the day and daily traffic mix. Parameters describing distribution of traffic during the day are: number of peaks, number of arrival and departure peaks, fill factor (as ratio between the area under the traffic distribution graph between 7h and 23h and the area of the rectangle given by the maximum number of operations during the day), relative load (as ratio between the time period of flight activities at or above 80% of the maximum number of operations and the time period of flight activities at or above 20% of the maximum number of operations) and relative night rest (as ratio between total time period with number of operations below 5 in 30min period and 8h default nighttime period 23h to 7h). Figure 18 illustrates fill factor and relative load.

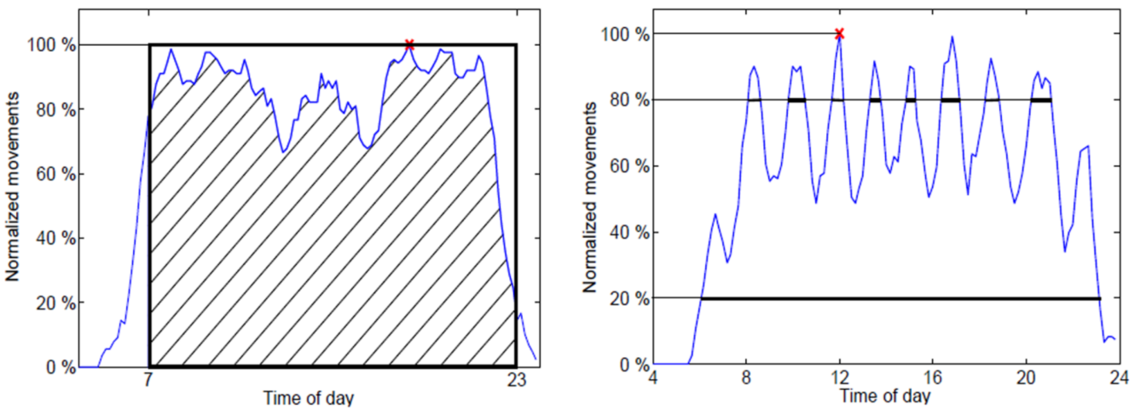


Figure 18. Fill factor and relative load (Oettl and Reeb, 2012)

Cluster analysis of 203 world airports[22] with respect to traffic peak parameters resulted in 16 representative airport categories. They are given in Appendix 8.

It is important to notice that duration of peak periods ranges between 2.5h and 3.5h with only two exceptions over 5h. This confirms the above-mentioned discussion about using representative traffic peak periods instead peak hours. It is supported by Table 4 which gives the typical representatives for all 16 categories of airports. Each airport is represented with three main peak periods, e.g. airport category 11 has first representative peak type 9, second peak type 3 and third peak type 10.

Table 4. The first thee representative peaks for each airport category (Oettl and Reeb, 2012)

| Representative airport | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st relevant peak | 1 | 2 | 1 | 1 | 1 | 9 | 1 | 2 | 6 | 1 | 9 | 11 | 10 | 12 | 17 | 18 |
| 2nd relevant peak | 4 | 5 | 2 | 6 | 2 | 10 | 2 | 5 | 8 | 13 | 3 | 14 | 11 | 13 | 16 | 19 |
| 3rd relevant peak | 7 | 7 | 3 | 8 | 4 | 3 | 7 | 1 | 7 | 3 | 10 | 6 | 13 | 15 | 9 | 14 |

Airport categorization based on traffic parameters, as explained above, does not consider exchange/mix of arrivals and departures in peak periods. The number of total, arrival and departure peaks result from the separate analysis of total, arrival and departure traffic, respectively. With this approach information about slack between arrival and departure peaks (important for hub airport's capacity analysis), or share of each in overlapped peaks (at O/D airports and saturated hubs) is not captured. However, this would be another traffic parameter useful for the analysis of capacity utilization both of the runway system and of the apron(s).

Furthermore, this airports and peak periods categorization does not consider the characteristics of airlines/other users. The criteria for "users" depend on the region in which airport is located, its role in air transport network, dominant market segments at the airport, etc. (e.g. airlines, O/D, type of service, etc.). Due to that, it is not easy to categorize airports with respect to user mixes as an additional traffic parameter.

Oettl and Bock (2012) addressed the issue of airport categorization with respect to other traffic parameters (in addition to aircraft fleet mix), such as: hubbing characteristics, flight distances and share of airlines. They used the example of secondary European

[22] With more than 18 operations per hour in the dataset analyzed (June 2008)

hubs to create representative scenarios. The results are given in Appendix 8. All parameters were observed independently of each other, which caused the loss of important information about traffic characteristics. The authors themselves argue that this approach is not promising. The differences may be quite significant, even in the similar group of airports, and thus difficult to generalize.

The bottom line is that it is difficult to generalize representative peak periods for apron capacity analysis. They should be defined on case-to-case basis.

# 4 Airport airside modeling - literature review

A broader literature overview of the airside modeling is given in Mirkovic (2010). Updated findings are summarized in this chapter.

The first part provides an overview of the models for airside capacity assessments and analysis. It addresses modeling of the runway system, taxiway system, apron(s) and the entire airside, which are mainly used for supporting airport planning in the medium- and long-term. Broader literature overview has shown that the most mature areas are runway system modeling and simulation modeling of the entire airside.

Additionally, an overview of the models/tools for optimizing available resource utilization is given in Appendix 9. These models and tools are primarily designed for and implemented at major airports, aiming to support airside short-term decision making (capacity management). The overview of the literature has shown that the overall emphasis is again on optimization of the runway system utilization, regardless of whether they treat runway system solely, or as a part of the entire airside. Regarding the apron complex, the gate assignment problem is widely addressed in the literature. However it considers gates mainly in the context of the landside.

Second part of this chapter addresses the issue of apron capacity modeling, which is not often referred to in literature. Apron is considered as a component of the airside (but still not separating it from the operational constraints imposed by the landside). Special emphasis is placed on apron analytical modeling.

## 4.1 Airport airside capacity models for supporting planning studies

The history of analytical (macroscopic) runway system modeling started in 1959, by Blumstein. Blumstein (1959) set the method for calculating landing capacity for a single runway. Since Harris (1972), many extensions and improvements of the Blumstein's method have been developed. They have included capacity of mixed operations, capacity of different runway system configuration, introduction of new technologies and procedures, etc. One of the first was Tosic and Horonjeff (1976). They analyzed the effects of the microwave landing system (MLS) introduction on runway system landing capacity. One of the latest papers on runway system analytical modeling is: Janic (2008). Janic (2008) developed analytical models for calculating the ultimate arrival, departure, and mixed operation capacity of closely-spaced parallel runways using innovative approach procedures - staggered approach procedure (SGAP) and the steeper approach procedure (SEAP).

The basic runway system capacity estimation method set by Blumstein and its extensions served as the basis for FAA Airfield Capacity Model (Swedish, 1981) and LMI Capacity and Delays Model, which represent the same method translated into computer language, enabling faster calculation and thus being more convenient for the analysis of different scenarios. Modern, improved versions in this category are: Airport Capacity Analysis Through Simulation (ACATS), described by Barrer and Kuzminski (2005) and runwaySimulator, by Barrer (2007). The advantage of the latest models is their flexibility. They can be easily applied to any airport in the world (any configuration and set of separation rules) without changing the simulation code itself.

Regarding taxiway and apron modeling, not much was done in the field of macroscopic modeling. (Detailed literature review on apron modeling in given in the next section.) Although they depend on almost the same factors as the runway system, the operational constraints and relations to other airside elements are very locally specific and very difficult to generalize and observe isolated from the entire airside system, as can be done for the runway system. Therefore aprons are usually observed, modeled and resolved on a case-by-case basis and they usually exist as one of the modules of integrated high- level-of-detail simulation models.

The most common simulation tools being used nowadays for airside analysis are: TAAM[23], SIMMOD[24]Plus/Pro and RAMS[25]Plus. All three are complete gate-to-gate models, while some others, such as: The Airport Machine and HERMES[26] (developed for Heathrow and Gatwick Airports) are limited only to the airport airside area. A detailed description and evaluation of these models can be found in: Odoni and Simpson (1979); Odoni (1991), Gass (1992); Odoni *et al.* (1997), and up-to-date coverage at

[23] Total Airspace and Airport Modeler
[24] Airport and Aispace SIMulation MODeler
[25] Reorganized ATC Mathematical Simulator
[26] Heuristic Runway Movement Event Simulation

Ashford *et al*. (2011). Updates of new features are available on the websites of companies currently in charge of the development and distribution of the tools: TAAM – Jeppesen, (2013), SIMMOD – ATAC (2013) and for RAMSPlus – ISASoftware (2013). AirTOpsoft (2013) represents a new generation of gate-to-gate fast-time simulation tools. It does not introduce much innovation in modeling the airside itself, but has the advantage of integrating future or customer-specific ATC concepts much faster. IATA's Total AirportSim includes terminal buildings within its scope in addition to airspace, runway system, aprons and gates (IATA, 2008).

Fast-time simulation models are of significant importance to airport planning. They enable definition of the system in high detail, by including physical and operational constraints that apply at the airport. Once the model is built, which requires a major effort, one can determine the effects caused by demand changes (demand increase, demand characteristics changes, temporary changes caused by the occurrence of certain events, etc.), by changes on the supply side (new runway, new parking stands, new runway exits, closure of a runway or an apron due to reconstruction, etc.), or by operational changes (procedural or technological improvements, new concepts introduction, etc.) in a relatively quick and reliable way, which makes it possible to analyze different scenarios and to choose the optimal solution based on that.

Simulation models are designed to deliver highly detailed output data, which is very useful and required in some stages of planning, but not necessary every time, especially in the case of strategic planning. Although capable of delivering a high level of output, it is important to remember that the quality of output depends on the quality (amount and level of detail) of input data provided. The more uncertain the input data are, the less we can trust the delivered output data. It is often the case that there is a lack of available input data for feeding into the simulation. In such cases, simulations are not the solution that decision makers should reach for and rely on. It is something that is often neglected by airport planners, and the reason why these tools are sometimes misused.

Due to that, when we have to calculate with rough input data macroscopic models are more convenient. Dealing with the uncertain future, planners, managers and designers need to recognize the wide range of situations that may occur, examine the implications of these scenarios, and develop strategies that enable them to seize opportunities and protect them from risk (TRB, 1987). In such situations we can gain more from macroscopic models. An advantage of macroscopic models, in comparison to simulation models, is their capability to deliver good enough output very quickly, with less detailed input that is usually all that is available to the planner (e.g. arrival rates instead of the flight schedule). "Quickly" does not refer to calculation time, which is also quite small in simulations, but to the preparation period which is much more time-consuming for simulation modeling. That makes them more suitable for analysis of a great number of scenarios and allows their relative comparison. Such models are not necessarily used as a support to final decision-making. It is desirable to use them for the selection of candidate scenarios that will further be analyzed through high-level-of-detail simulation tools.

One of the rare integrated airside macroscopic models is MACAD - Mantea Airfield Capacity and Delay. It was introduced by: Andreatta *et al.* (1999); further elaborated in: Stomatopulos *et al.* (2004); suggested as a component of the advanced decision support tool for total airport performance assessment and capacity management by EC (2006). MACAD integrates macroscopic airside models to provide approximate estimates of the capacity, utilization and delays associated with every element of the airside. It is primarily meant for studies that require only approximate answers while examining a wide range of hypotheses and scenarios regarding future conditions at an airport. MACAD obtains reliable approximations quickly, even with a limited set of inputs (which is usually all we can provide/obtain for the analysis). It consists of five modules: airside, weather, detailed schedule generation, coordination and user interface. The airside module consists of a runway system capacity model (a generalized stochastic analytical model for the estimation of the capacity envelope of the runway system, for a wide variety of runway system configurations), a runway system delay model (an analytical model for computing the distributions of delays throughout the time interval of interest), and an apron/taxiway macroscopic simulation model (in which taxiways are represented by probability distributions for the taxi-in and taxi-out times for each configuration of the runway system). There are no specific details given on apron modeling, but it is stated that the this module identifies the stands which are most limiting (depending on the aircraft types, the type of flights, and the handler/airline that they serve) as well as the ones that are underutilized for the examined configuration and demand scenarios.

In 2009, the project "Evaluating Airfield Capacity" was initiated under the TRB - ACRP. The aim was to produce a new manual for capacity analysis intended for airport planners. The report (TRB, 2012b) was released in December 2012. It provides another software solution (spreadsheet) for runway system capacity estimation, but does not suggest any further improvements in relation to apron capacity. The spreadsheet model is again based on Blumstein's approach.

## 4.2 Apron capacity modeling

Opposite to the case of runway system capacity, not much has been done in the field of macroscopic apron modeling either because its capacity was not considered a serious capacity constraint or the problem was too specific to be generalized. Nevertheless, a few generic apron models can be found in literature. They estimate dynamic apron capacity based on apron layout (i.e. number of stands), use strategy (with respect to aircraft class or airline) and weighted average stand occupancy time of the aircraft mix demanding service.

These models are based on the similar approach applied to runway system capacity estimation, estimating the capacity of a service unit as the reciprocal of the weighted average occupancy time of all users served by the given service unit, as set by Blumstein (1959).

In the remainder of the text, the existing analytical apron capacity estimation models are described, as in Mirkovic (2011b) and Mirkovic and Tosic (2013).

In general, two different models can be found in the literature. The basic one assumes that all aircraft can use all available apron stands. The other assumes restriction on stand use by aircraft class – that aircraft of a certain class can use the stands that are designed for those or any larger aircraft class.

Runway system capacity models estimate saturation capacity, which stands for the average number of movements that can be performed on the runway system in 1h in the presence of continuous demand, while adhering to all the separation requirements imposed by the ATM rules (De Neufville and Odoni, 2003). Similarly, saturation capacity of the apron (hereinafter referred to as "apron capacity") can be defined as the average number of aircraft that can be served at the apron (fixed number of stands) during given period, in the presence of continuous demand (characterized by fleet mix and user mix), while adhering to all constraints on stand use.

When there are no restrictions on the stand use, implying that all aircraft can use all the stands, the capacity of the apron can be expressed as:

$$C = \frac{N_{all}}{\bar{t}} \tag{1}$$

$N_{all}$ – total number of available stands

$\bar{t}$ – weighted average stand occupancy time of all aircraft demanding service

$$\bar{t} = \sum_i p_i \cdot T_i \tag{2}$$

$p_i$ – proportion of aircraft of class *i* in the population of aircraft demanding service

$T_i$ – average stand occupancy time of the aircraft of class *i*

The apron capacity model with no restrictions on stand use (and numerical examples) can be found in relevant literature on airport planning: Horonjeff (1975), Horonjeff and McKelvey (1994), Ashford and Wright (1992), De Neufville and Odoni (2003), Horonjeff et al. (2010), Ashford et al. (2011).

A second model assumes restrictions in stand use, by stand size. It is defined by Horonjeff (1975) and reformulated in later editions (Horonjeff, McKelvey, 1994; Horonjeff, et al., 2010). For restricted stand use, it is necessary to define the group of stands that can accommodate each aircraft class (classification is based on aircraft size). It is assumed that a stand can accommodate the aircraft class they are designed for and all smaller-class aircraft. The apron capacity limited by each group of stands is calculated from the number of stands in the group and weighted average stand occupancy time of aircraft using that group of stands. The minimum of the capacities set by each group of stands is the considered as the apron capacity:

$$C = \min_i (C_i) \tag{3}$$

The capacity limited by the group of stands available for aircraft class *i* ($C_i$) is as follows:

$$C_i = \frac{N_i'}{\bar{t}_i'} \tag{4}$$

$N_i'$ - number of stands that may be used by aircraft of class *i* (stands designed for aircraft class *i* and for aircraft larger than *i*):

$$N_i' = N_i + N_{i+1} + ... + N_n \tag{5}$$

$\bar{t}_i'$ - weighted average stand occupancy time demanded by all aircraft that can use stands from the $i^{th}$ group:

$$\bar{t}_i' = \sum_{k \geq i} p_k \cdot T_k \tag{6}$$

$p_k$ – proportion of aircraft of class *k* in the population of aircraft demanding service

$T_k$ – average stand occupancy time of the aircraft of class *k*

Ashford and Wright (1992) explain the apron capacity model for restricted use (by aircraft class), but under a different assumption. They assume that each stand can be used only for the aircraft they are designed for (small for small, medium for medium, large for large). Obviously, they do not take into account that each stand can also accommodate smaller aircraft classes. So, apron capacity, in their so-called "exclusive use" apron capacity model, is formulated as follows:

$$C = \min_i (C_i) \tag{7}$$

Where apron capacity limited by the group of stands designed for aircraft of class *i* is:

$$C_i = \frac{N_i}{p_i \cdot T_i} \tag{8}$$

$N_i$ - number of stands designed for aircraft class *i* (only)

$p_i$ – proportion of aircraft of class *i* in the population of aircraft demanding service

$T_i$ – average stand occupancy time of the aircraft of class *i*

This apron capacity model for exclusive use is not suitable for apron capacity estimation with restrictions on stand size/aircraft class, since the main assumption does not depict what is actually happening in reality. But, such an approach can be applied for capacity estimation of aprons with exclusive use of stands by different airlines (typical for U.S. airports), or by different users based on other criteria such as required security levels (domestic/international).

When apron consist of the separate areas exclusively used by one user each, one can incorrectly conclude that the total capacity of the apron is the sum of the capacities of these separate areas:

$$C = \sum_i \frac{N_i}{T_i} \tag{9}$$

However, that is not the case. To what extent each apron area is utilized depends on the share of users in demand ($p_i$). The most restricting apron area restricts total apron capacity: $C = \min(C_i)$. At the same time, other areas remain underutilized.

For a quick estimation of apron capacity U.S. FAA developed a graphical method shown in Figure 19 (FAA, 1983). The apron-gate capacity expressed in movements/h is determined as: $G^* \cdot S \cdot N$, where *G** is the hourly gate capacity base, determined from the chart based on the share of non-widebody aircraft gate occupancy and their share in the fleet; *S* is the gate size factor, and is determined from the gate mix and percentage of stands that accommodate widebody aircraft; and *N* is the number of gates.

The most recent research, an update of the Advisory Circular (AC) 150/5060 (FAA, 1983), did not suggest any further improvements in regard to the method or models for assessment of the apron (gate) capacity (TRB, 2012b).

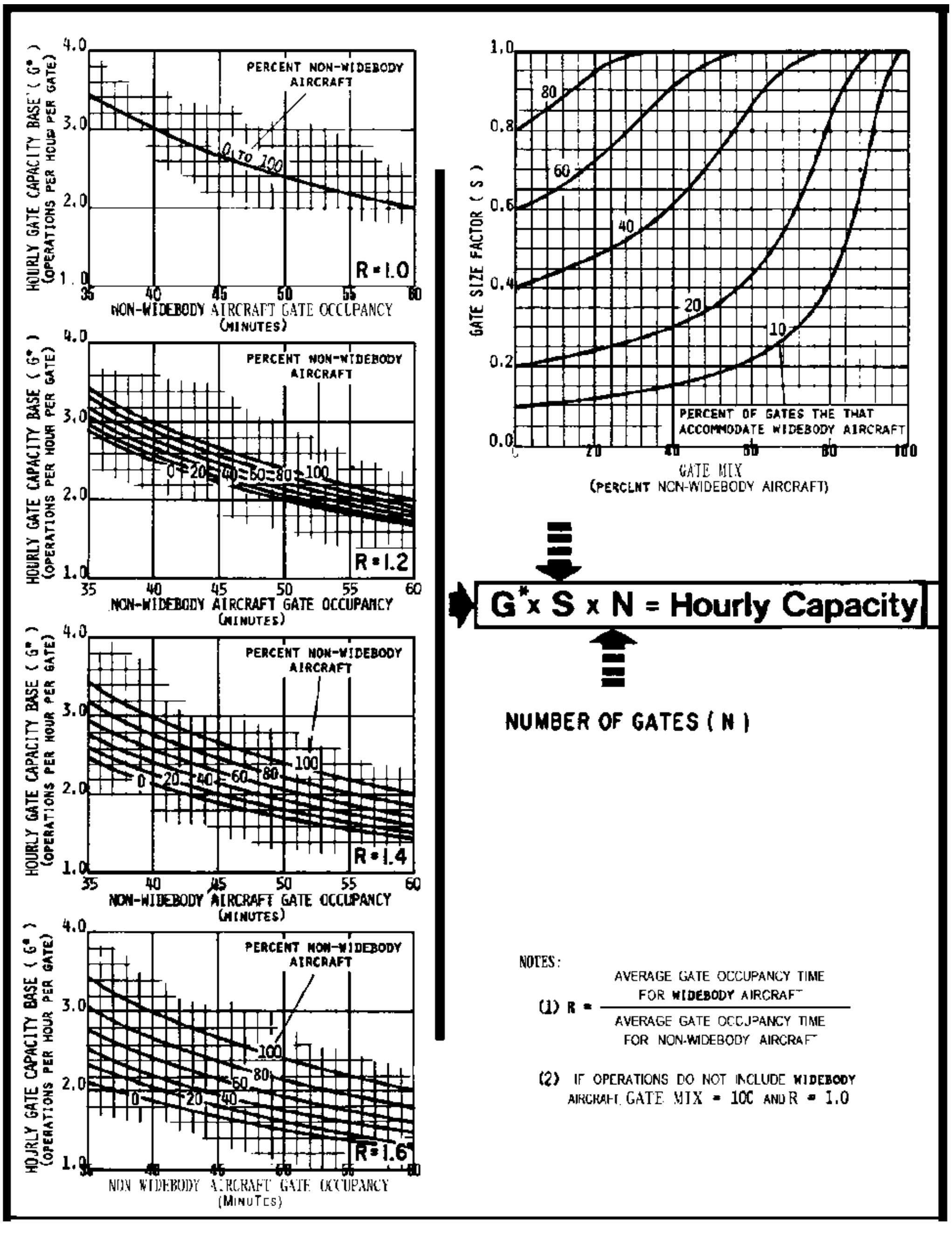


Figure 19. FAA's graphical method for calculating gate capacity

In the area of analytical apron modeling there are several important papers addressing the issue of aircraft gate requirements estimation, which is an issue analogue to apron capacity estimation.

Bandara and Wirasinghe (1988) suggested a stochastic model to estimate the number of gates required to provide a given reliability, based on aircraft arrival rates at gates, the gate occupancy times and the aircraft separation (buffer) times, considering them as random variables. Mean and variance of the number of gates required was obtained using the moment generating function. The design number of gate was chosen to satisfy given reliability. Reliability is defined as the probability that there are sufficient gates to ensure zero delay of aircraft on the apron, during a given time period. The method is applicable both under common and preferential gate use strategies, as well as for estimating the required number of remote stands for overflow situations.

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. He assumed that all flights in the bank have the same behavior. In an extension of this work, Hassounah and Steuart (1993) established a relationship between occupancy of aircraft gates and flights' behaviors, assuming that each flight has a unique behavior relative to its schedule and buffer time. A stochastic model is developed to estimate the demand for gates as a function of time of day, under different assignment strategies (exclusive vs. common) and scheduling practices. They shortly 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.

Wirasinghe and Bandara (1990) suggested a method for determining the optimum number of gate positions to minimize the sum of cost of gates and cost of delays to aircraft. Gate cost is calculated from the number of gates and the marginal capital, maintenance and operating costs of the gate per day that is assumed to be constant. Delay cost is calculated from the average cost of delay per aircraft per hour and the total deterministic delay to aircraft per day caused by the lack of gates. The total deterministic delay is calculated from the maximum arrival rate, the average arrival rate and the time during which the average rate is exceeded. A distinction is made between triangular and parabolic shaped peaks when calculating delay. Cases with one and several non-overlapping peaks during the day were discussed, as well as the modification that uses a known shape of the expected arrival rate curve instead of average values.

This approach was further expanded by de Barros and Wirasinghe (2004) to take into account: the use of common areas that could be shared by different aircraft types, and the effect of interest and demand increase over the lifespan of the terminal to support development in stages ("how much to build and when"). These issues were addressed in light of the introduction of new large aircraft (NLA). Two variations of the space-sharing model were discussed. In the first one, gates for NLA and wide-body (WB) aircraft are allowed to be used by conventional jets (CJ). The second one assumes that CJ are allowed to use NLA/WB gates, and one CJ is allowed between every two WB and/or NLA gates. It was shown that significant savings are achievable with stage construction and carefully planned shared space between different aircraft types.

Flexible design, i.e. use of shared space at airports, is addressed more often from the perspective of the landside. For example, De Neufville and Belin (2002) addressed use of shared space as a strategy to cope with traffic peaking (hourly and daily variations) and uncertainty (daily and long term variations). They focus primarily on shared gate hold-rooms to accept hourly peaking and long-term uncertainty; and shared gates to accept daily uncertainty (stochastic delays). Also, De Neufville (2008) addresses an issue of flexible design of the terminal building to cope with long-term uncertainty related to airport client changes (particularly the entry of low cost carriers at "legacy carriers airports").

Table 5 summarizes the most relevant literature on apron modeling with respect to:

- Input required,
- Output delivered,
- Constraints considered, and
- Impact of wave (bank) system.

Table 5. Summary of the relevant literature on apron modeling

| papers/books | input | output | constraints on a/c type | constraints on airline/ origin-destination | wave(bank)-system |
|---|---|---|---|---|---|
| Steuart (1974) | traffic schedule | expected value and variance of number of aircrfat occupying the gates | not considered | possible application disscussed for exclusive use strategy, not connected to bank-system | considered in detail - effects of bank length and bank separation, not connected to runway performance |
| Bandara and Wirasinghe (1988) | average arrival rate, average gate occupancy time, average separation time | reaquired number of gates to assure zero delay with certain reliability | not considered | preferential use strategy by airlines and type of services considered and applied | not considered |
| Hassounah and Steuart (1993) | traffic schedule | expected value and variance of number of aircrfat occupying the gates | considered and applied without constraints on airline/type of service constraints | exclusive use strategy without constraints on a/c type considered and applied | possible application discussed |
| Wirasinghe and Bandara (1990) | average arrival rate, max arrival rate, arrival rate curves, average gate occupancy time, average separation time | reaquired number of gates based on the optimum arrival rate that minimizes delay+gate cost | not considered | possible application discussed for preferential use strategy | not considered |
| de Barros and Wirasinghe (2004) | service rate, average arrival rate, max arrival rate, average gate occupancy time, average separation time | required number of gates (terminal frontage length) based on the optimum arrival rate that minimizes delay+gate cost | considered in detail (different space usage strategies addressed) without any other constraints (on type of traffic/airline) | not considered | not considered |
| Horonjeff et al. (1975-2010) | number of gates, expected (weighted) gate occupancy time | gate capacity | not considered | exclusive use strategy | not considered |
| Ashford and Wright (1992) | number of gates, (weighted) average gate occupancy time | gate capacity | considered (gates are available for design aircrfat and any smaller aircrfat) without other constraints (on type of traffic/airline) | not considered | not considered |
| FAA (1983) graphical approach | number of gates, gate size factor and hourly gate capacity base | hourly capacity of gates (graphical approach) - questinable results | considered | not considered | not considered |

### 4.3 A way forward

The thesis offers modifications/extensions to apron capacity modeling and, together with that, an overall airside capacity analysis. It considers the following:

- Both aircraft class and user constraints and their impact on apron capacity.
- The impact of wave-system at hub airports on apron capacity. It does not derive it from the detailed traffic schedules, but observes apron capacity sensitivity to different hubbing parameters.
- The functional relationship between the runway system and the apron(s), in order to provide an overall airside capacity picture by connecting existing runway system models to modified apron models.

Furthermore, it observes reserve apron capacity, giving an opportunity to gain additional capacity with available resources reallocation prior to physical expansion. Reserve capacity is observed through the concept of apron capacity flexibility from the airside perspective, accounting primarily for operational users' constraints.

# 5 An approach to analyzing overall airport airside capacity

As a reflection of what occurs in the case of major airports worldwide today, the runway system is considered to be the main capacity constraint. This is why airside capacity is usually expressed through runway system capacity. At the same time, complex taxiway systems and huge apron(s), with a large number of remote stands, usually operate with spared capacity. The literature overview on airside modeling (Chapter 4) confirms that the most mature area is the runway system capacity assessment, together with simulation modeling of the entire airside. The issue of the apron capacity assessment is not often referred to in the literature.

However, the air transport network counts dozens of major airports while, at the same time, there are hundreds or even thousands of small-to-medium airports that suffer from different capacity issues. At these airports, which mainly (but not necessarily) operate with single or two dependant runways, the capacity constraint is often at the terminal complex, until runway system capacity limit is reached[27]. In order to accept traffic increase, the airport needs to rearrange/expand terminal-apron complex, maintaining balanced usage of the runway system, all until the capacity issue switches back to runway system. After (if) another runway is built, again the same task lays before the airport planners, to further develop other elements in accordance with traffic changes.

An approach to analyzing the overall airside capacity of the existing (built) system under given physical and operational constraints and for given demand characteristics, is proposed in Section 5.1. Runway system capacity is assumed as known i.e. possible to obtain through any of existing runway system capacity models. Taxiway system is assumed not to be the capacity issue. The main attention is on the apron capacity modeling. Existing apron capacity estimation models are modified/expanded, as given in Sections 5.2. In Section 5.3 sensitivity of the apron capacity on demand structure is represented using apron capacity envelopes. Section 5.4 elaborates important variables that influence apron capacity estimates.

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[27] A single runway at Gatwick Airport handles between 240,000 and 260,000 annual movements since 2000 (in 2007 it handled 266,550 movements).

As summarized in Chapter 3, although runway system and apron capacity are affected by similar factors, it does not imply that both of those resources reach their maximum throughput under the same conditions, because the nature of processes is different, due to the different roles of the runway system and the apron in the airside system. In order to create an overall airside capacity usage scheme, it is necessary to understand and define functional relationship between the runway system and the aprons.

The presence of different market segments at the airport can influence this functional relationship, due to different usage of the resources. As it is discussed in Chapter 1, the runway system is usually the common resource for all, which is not the case with apron(s), where different market segment may have their own terminal-apron complexes or preferential apron areas. In such case, the airport represents a system at which all clients enter/exist through the same service unit, and are processed at different service units.

The thesis deals only with airports with a dominant passenger market segment. As summarized in Chapter 1, the majority of European airports have only one dominant market segment, of which 85% are passenger dominated. Among all European airports, regardless of the number of dominant market segments, again the majority (72%) serve mainly passenger traffic (Eurocontrol, 2007).

In the case of passenger market segments (traditional, low-cost and/or charter) all three may share the same terminal building, while certain segmentation usually exist on the apron, for example preference of the LCCs and charter airlines to use remote over the contact stands. Additional segmentation is not expected to have any impact on the functional relationship between apron(s) and the runway system, because all aircraft are of the equal priority when using the runway system, unlike the case when different market segments are involved.

At passenger airports runway-apron functional relationship is mainly influenced by the role of the airport in the air transport network (elaborated in Chapter 2). Section 5.5 addresses the difference in capacity utilization of available resources, depending on the nature of the traffic at the airport. Two main airport types, with respect to their role in air transport network, are analyzed: origin-destination airports, serving primarily point-to-point traffic (resulting in rather “uniform” traffic distribution during the day, with more or less pronounced peak periods) and hub airports serving primarily transfer traffic typically concentrated in waves (banks) of flights. Following network evolution the thesis also addresses the co-existence of coordinated and point-to-point flights at a single airport. Different examples are used to show how apron and overall capacity react to changes in: type of traffic served, runway system performance, and apron operational constraints.

The thesis also addresses the issue of reserve/latent apron capacity (Section 5.6). Namely, capacity bottleneck at the apron is not necessarily a consequence of capacity shortage, but it may appear due to a mismatch between demand structure and constraints on available resources allocation. Reserve capacity is discussed through the concept of apron capacity flexibility. It is suggested how to express and interpret apron capacity flexibility. On one hand, apron capacity flexibility is observed as an indicator of ability of the apron to respond on changes in demand structure. At the same time, it is an indicator of latent/reserve capacity that may be “activated” by reallocation of available resources i.e. relaxation of the constraints on stand use.

Having the capacity of both elements and their functional relationship, under given demand characteristics, it is possible to create an overall capacity usage scheme, to identify bottlenecks and underutilized resources within the system. The discussion is included through different examples.

At the end (Section 5.7) a short discussion is given on possible areas of application of the proposed approach in the field of airside capacity planning.

## 5.1 Conceptual model

An approach to analyzing airport airside capacity and how it is utilized with respect to demand characteristic (structure and distribution in time) is given in the flowchart in Figure 20.

The thesis addresses mainly issues related to apron capacity estimation and the impact of different traffic patterns of capacity utilization which are identified as the main gaps in current literature.

However, runway system capacity is needed in order to further discus its connection with apron capacity, but it is assumed in this thesis as known.

An analysis should be based on representative peak periods reflecting the traffic structure of the typical day(s) at the airport. According to peak period discussion in Chapter 2, it is suggested to observe typical 2.5-3.5h period(s) for O/D airports, while for hubs wave length and wave repeat cycle are far more important.

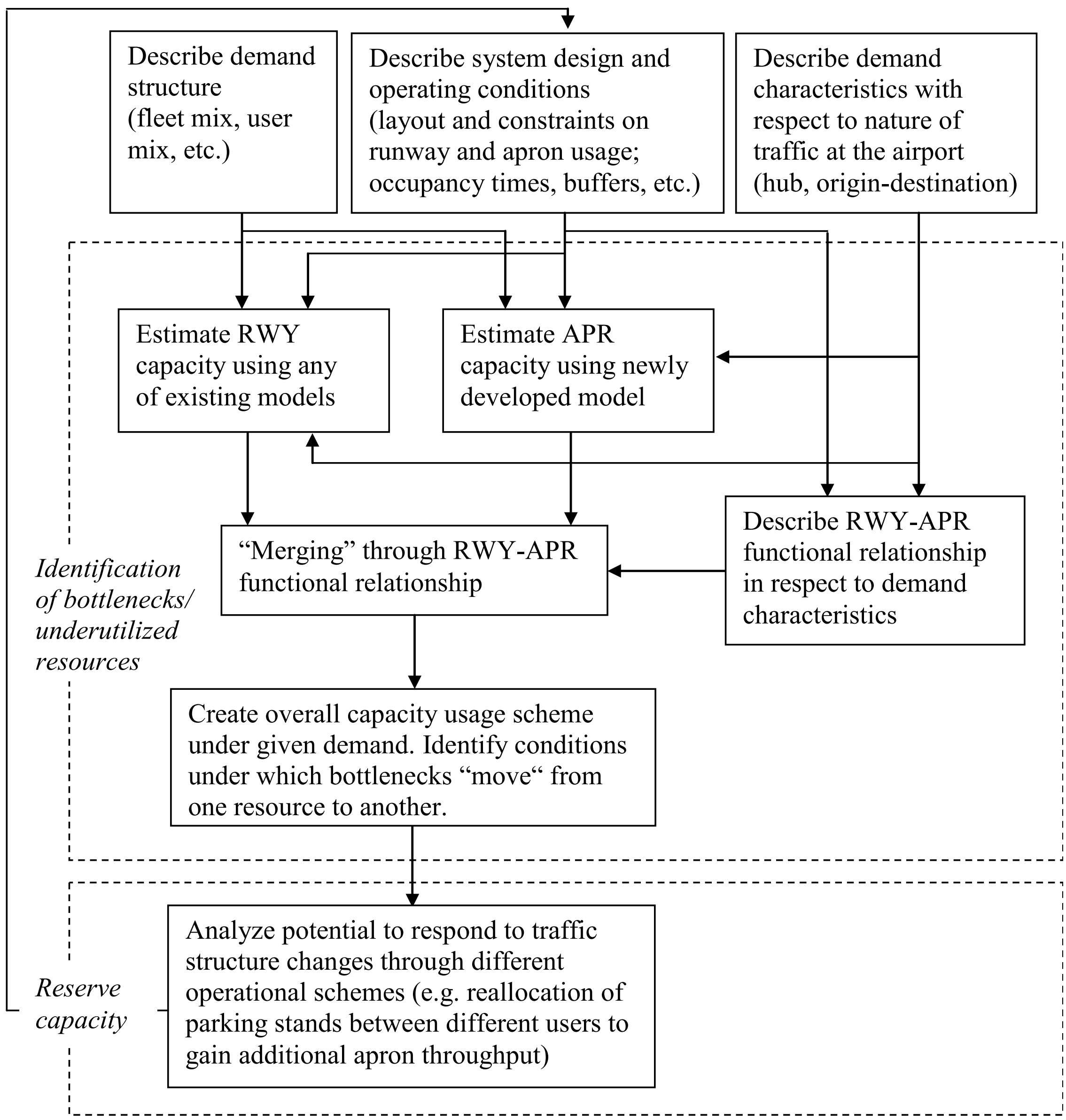


Figure 20. An approach to overall airside capacity analysis

The models for assessing and analyzing apron capacity and overall airside capacity proposed in the thesis are based on the following assumptions:

- The proposed analytical models, representing extension and modification of the existing models, estimate apron saturation capacity. This implies continuous demand for service during the specified period of time.
- The apron capacity models are deterministic, implying that the average values of particular variables are used in estimating capacity.
- The sensitivity of apron capacity to demand structure changes is observed from the perspective of the dominant user (vs. all other users).
- The runway system capacity is known, i.e. estimated through any of the existing runway capacity models. The taxiway system is not considered the potential bottleneck in the airport airside area, and it is not considered when defining the runway-apron functional relationship.
- The focus is on the two types of passenger airports: O/D airports serving mainly point-to-point traffic and hub airports, serving coordinated flights of the base airline, primarily or in combination with additional point-to-point traffic. The presence of other market segments at the airport is not considered.
- Parameters related to and derived from wave-system structure are based on the ideal wave: arrival and departure time windows are of approximately the same length and the sequence of arrivals is the same as the sequence of departures.
- Analysis of the potential for providing additional apron capacity through relaxation of the user constraints does not take into consideration associated costs for implementation of the proposed solutions.

## 5.2 Apron capacity estimation module

Based on the existing models (as given in Section 4.2), an extension is proposed, that combines size and user restrictions, in order to include both physical and operational constraints on aircraft stand usage.

Apron capacity is determined by the minimum of the capacities set by each $ij^{th}$ group of stands, (Mirkovic, 2011b; Mirkovic and Tosic, 2013):

$$C = \min_{ij}\left(C_{ij}\right) = \min_{ij}\left(\frac{N_{ij}'}{\bar{t}_{ij}'}\right) \tag{10}$$

where:

$i$ 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

$N_{ij}'$ - 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 $j$)

$$N_{ij}' = \sum_{k \in K} \sum_{l \in L} N_{kl} \tag{11}$$

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

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

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

$$\bar{t}_{ij}' = \sum_{k \in K} \sum_{l \in L} p_{kl} \cdot T_{kl} \tag{12}$$

The same sets of users ($K$) and aircraft classes ($L$) apply as in expression (11), for $N_{ij}'$

$p_{kl}$ – proportion of aircraft of user *k* and class *l* in the population of aircraft demanding service

$T_{kl}$ – average stand occupancy time of the aircraft of user *k* and class *l*

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

For aircraft classes standard ICAO (International Civil Aviation Organization) categorization may apply (from A to F), or they may be categorized in a different way e.g. small, medium and large.

A user-class criterion depends on the airport itself. Considering only passenger traffic, it may be airlines/alliances (typical U.S. stand usage strategy - exclusive, preferential, joint), and/or type of service with respect to security level required inside the terminal building (general case - domestic/international, or European specific – domestic, Schengen, non-Schengen, international with special requirements).

For example, the airport is operated by base airline, other traditional airlines and low-cost airlines, on domestic and international routes. It results in the following users: base-domestic, base-international, base-mix, other-domestic, other-international, other-mix, LCC-domestic, LCC-international and LCC-mix. Not all of them necessarily account for a significant share in peak period. For example, assuming that other-domestic, other-mix and LCC-mix account for very small shares, it leaves six (out of nine) representative users.

The number of stands that may be used by user class *i* and aircraft class *j* is determined from apron layout and operational constraints defined by:

- Total number of aircraft stands; number of contact stands (i.e. gates) and remote stands;
- Number of stands by aircraft class, assuming that the stand may be used by design aircraft and any smaller aircraft;
- Number of stands by user - it applies particularly to contact stands, although some preferences may exist in practice towards remote stands as well; and

- Policy of aircraft stands use - set of rules that define if the group of stands of a certain user may or may not to be used by other users.

Weighted average stand occupancy time is calculated from average stand occupancy times for different user/aircraft class combination and demand structure. Demand structure considers:

- Share of different aircraft classes, and
- Share of different users.

Numerical example from AC 150/5060 (FAA, 1983) is used to compare results from the analytical model to results from the FAA's graphical method (Mirkovic, 2011b). The results are given in Appendix 10.

For apron(s) with flexible layouts, with respect to aircraft classes, combined with different user constraints (either by airline, or type of service) the calculation can be somewhat tedious. It requires several iterations, as it is explained in Appendix 11.

### 5.3 Apron capacity representation

The common way to illustrate saturation capacity for a given configuration of the runway system and given demand structure is the runway capacity envelope, introduced by Gilbo (1993). He uses the runway capacity envelope to represent a set of capacity values that reflect the operational capability of the airport under certain conditions. An example is given in Figure 21, for a single runway.

Runway capacity envelope consists of four typical points, representing different arrival/departure shares. Point 1 represents the capacity of arrivals-only. Point 2 represents so-called departure-free capacity and considers additional departures that can be performed without any changes in arrivals separation. Point 3 represents capacity under a 50/50% arrivals/departures share, and Point 4 is the departures-only capacity.

The thesis suggests possible shape(s) of the apron capacity envelope to illustrate the ability of a certain apron configuration to accept different demand structures with respect to dominant users, rather than using a single number instead (Mirkovic, 2011b; Mirkovic and Tosic, 2013).

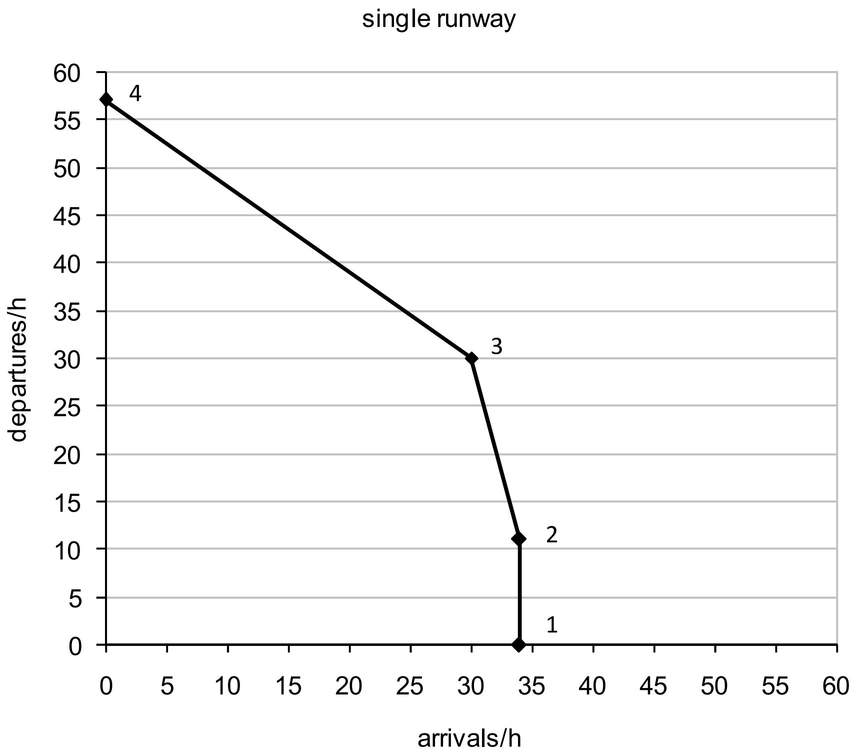


Figure 21. Example of the runway capacity envelope for a single runway

A runway capacity envelope gives the saturation capacity for one runway system configuration, for a given demand structure, but for different shares of arrivals and departures. Runway system capacity is expressed in operations per hour, but smaller time units are also used (usually 15min). If we consider that arrivals and departures are the main "customers" of the runway system as a resource, conversely, the apron capacity envelope should represent the saturation capacity of a certain apron configuration and given demand structure (fleet mix, share of different aircraft classes) for different shares of its users (airlines, origin/destination combination, traffic type, etc.). Apron capacity is expressed in aircraft per hour. Depending on the traffic pattern, different time units might be more suitable than one hour, e.g. the length of the arrival wave at hub airports, as discussed earlier. In Figure 22 the apron capacity envelope for *Example 1* is given.

<u>Example 1</u>: An apron has 11 stands, of which 5 stands are available only for domestic rotations[28] (both origin of flight and destination after turnaround are domestic) and 6 stands are available for all rotations (domestic, international and mixed). Average stand occupancy time for domestic rotations is 45min, and for other than domestic rotations (domestic-international, international-international) it is 55min.

If we assume demand of 50% domestic flights and 50% other than domestic flights, apron capacity is 13.1 aircraft/h[29]. Apron capacity changes with user structure changes in demand, as shown in Figure 22.

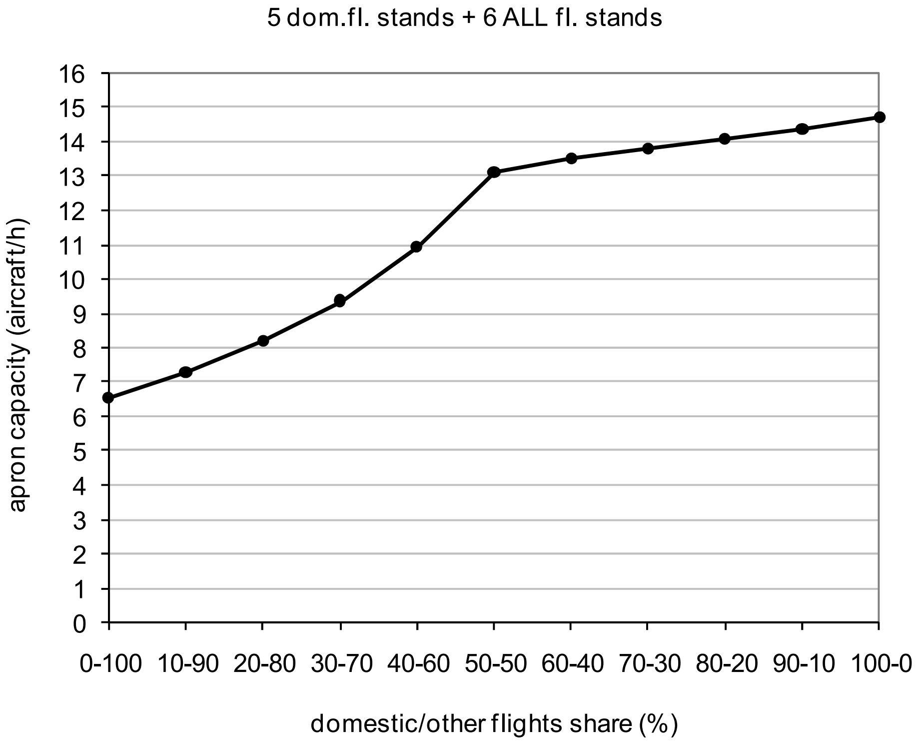


Figure 22. Apron capacity envelope in Example 1

Together with apron configuration changes, the shape of the apron capacity envelope also changes. Figures 23 and 24 represent a set of apron capacity envelopes for different apron configurations. Number of stands available for domestic flights and number of stands for all flights is varied (the total number of stands remains the same).

[28] A rotation refers to a combination of the aircraft origin and its destination after its turn-around.

[29] $C = \min(C_1, C_2) = \min\left(\frac{5+6}{0.5\cdot 45 + 0.5\cdot 55}\cdot 60, \frac{6}{0.5\cdot 55}\cdot 60\right) = \min(13.2, 13.1) = 13.1 aircraft / h$

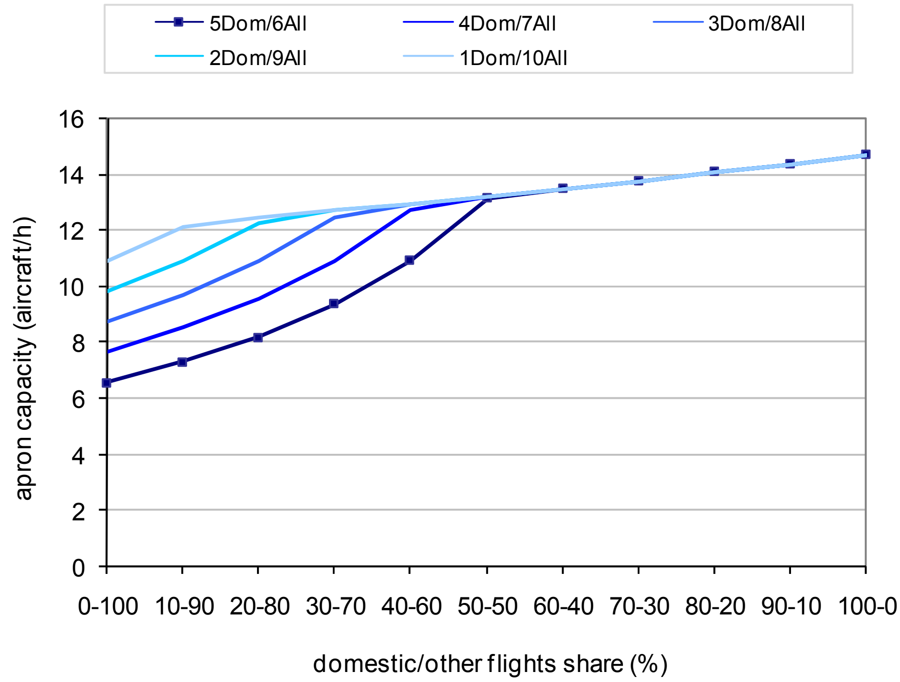


Figure 23. Set of apron capacity envelopes illustrating an increase in number of mixed-use stands in Example 1

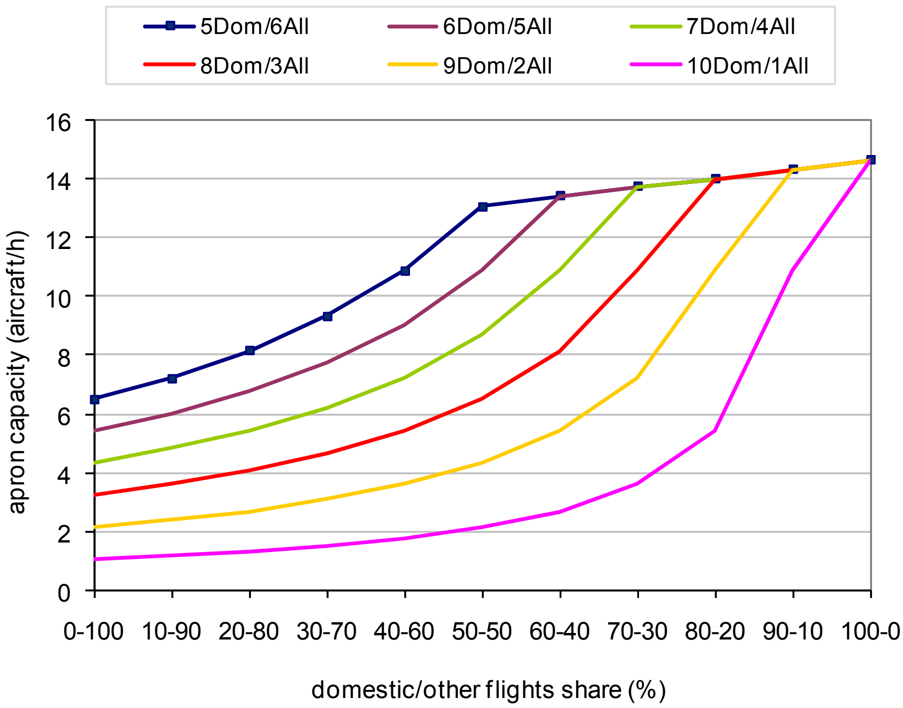


Figure 24. Set of apron capacity envelopes illustrating an increase in number of exclusive-use stands in Example 1

Figure 23 shows that, as the number of stands for all flights increases, the apron becomes less sensitive to user mix in total demand. In extreme case of a configuration with one stand for domestic flights and 10 stands for all flights, the capacity ranges from 10.9 to 14.7 aircraft/h. As the number of "exclusive" stands for domestic flights increases, the apron becomes more sensitive to the share of different users in total demand, as it is shown in Figure 24. In the opposite extreme case, assuming a configuration with 10 stands for domestic flights and only one stand for all flights, the capacity of the apron ranges between (only) 1.1 aircraft/h and 14.7 aircraft/h.

This is a simple example to show an apron's ability to accept different demand structures, and how it changes with apron configuration changes. In this example, demand structure is given as the share of domestic/other flights. Depending on the policy of stand usage at the apron it can be expressed with respect to other users, such as airlines/alliances.

The indicator of the sensitivity of a certain apron configuration to demand structure changes with respect to users will be referred to, hereinafter, as apron capacity flexibility. With an increase in the number of exclusive use stands, apron capacity flexibility decreases. Higher flexibility goes with apron configurations with fewer constraints on stand usage.

"The knowledge of the sensitivity of a physical facility component to a variation in demand can lead to better decisions and an understanding of the flexibility in any facility design" (Horonjeff *et al.,* 2010).

Saleh et al. (2009) thoroughly discuss the concept of flexibility in different disciplines (among others engineering design). They argue that "both robustness and flexibility of a design refer to the ability of a system to handle change", but "what is changing" and "how is change achieved" differs. They discuss views of different authors on robustness and flexibility in design, and accept the following as the most appropriate:

- Robustness of a design "is the property of a system that allows it to satisfy a fixed set of requirements, despite changes in the environment or within the system". It "implies de-sensitizing the system's performance or quality characteristics to changes in the system environment, or within the system".

- Flexibility of a design "implies an ability of the design to be changed in order to track requirement changes".

Authors consider flexibility and robustness to be separate characteristics of a design.

Robustness of the apron may be used to describe its "ability to handle change" when speaking of e.g. apron design with respect to minimum safe separation (taxiway to object, aircraft on stand to other aircraft and/or object, etc.), or apron surface strength. In order to describe the ability of the apron to accept changes in demand structure in terms of capacity, the term flexibility is more appropriate. In this case, "apron" design is defined by set of operational rules, which allow greater or fewer possibilities to change in order to respond to demand changes.

Flexible use of the same area by different aircraft sizes was addressed by De Barros and Wirasinghe (2004). They propose an analytical methodology to determine the number of contact stands (gates) required to accommodate a mix of aircraft classes, which takes into account the concept of space sharing between different aircraft classes. They determine shared space based on the requirements for gates by each aircraft class in peak periods and idle gate positions during secondary peaks of a typical day. The space to be shared should be carefully planned so that the apron remains able to respond successfully to variations in demand (volume and structure) during a typical day. With space sharing, the total area required to serve the demand is reduced, as it becomes more flexible with respect to class of aircraft. In addition to aircraft class, the paper also discusses operational issues, imposed by type of flights/passengers, which needs to be resolved within the terminal, so as to enable full implementation of space sharing.

If particular operational constraints (different types of users, aircraft class) are combined, there are many possible scenarios that could be analyzed. However, not all of them are within the scope of airport planner's interest. For the purpose of comparison between different scenarios, a set of selected segments of the apron capacity envelopes can be observed.

Example 2: An airport has an apron of 11 stands, of which 5 stands are exclusively used by the base airline and 6 stands are for all other airlines. At the base airline apron area, 3 stands are designed for aircraft class 1, and 2 stands for aircraft class 2. The apron area for other airlines consists of 1 stand for aircraft class 1, 2 stands for aircraft class 2 and 3 stands for aircraft class 3.

The share of flights (by airline and aircraft class) and average occupancy times are given in Table 6. The share of the base airline is 40% and the share of other airlines is 60%. 70% of base airline flights are operated by aircraft class 1 and 30% by aircraft class 2. 15% of the flights of other airlines are operated with aircraft class 1, 50% by aircraft class 2 and 35% by aircraft class 3.

Table 6. Demand structure and average stand occupancy times in Example 2

| number of stands | user | aircraft class | share in demand (%) | average stand occupancy time (min) |
|---|---|---|---|---|
| 3 | base airline | 1 | 28 | 30 |
| 2 | | 2 | 12 | 45 |
| 1 | other airlines | 1 | 9 | 30 |
| 2 | | 2 | 30 | 45 |
| 3 | | 3 | 21 | 70 |

Let us assume that an increase in base airline flights is predicted for the future, as well as a change in fleet mix. Three expected demand scenarios are: 50/50, 60/40 and 70/30 shares of base/other airlines in traffic. Fleet mix by user is given in Table 7.

Table 7. Current and future demand structure with respect to fleet mix and users in Example 2

| user | aircraft class | current demand structure (%) | future demand structure (%) |
|---|---|---|---|
| base airline | 1 | 70 | 55 |
| | 2 | 30 | 45 |
| other airlines | 1 | 15 | 20 |
| | 2 | 50 | 45 |
| | 3 | 35 | 35 |

Three possible Scenarios are considered as a response to the future change in demand. Scenario 1 assumes changes in layout at the base airline apron area. One small stand for aircraft class 1 is widened to accept aircraft class 2, resulting in 2 small and 3 mid-sized stands. Scenario 2 assumes changes in operational constraints. The layout is the same as in the current state, but all stands in apron area for other airlines are available for the base airline. Scenario 3 includes both changes in layout (the same as in Scenario 1) and in operational constraints (as in Scenario 2).

Apron capacity envelopes (not complete, but relevant segments) for the basic and three proposed scenarios are given in Figure 25.

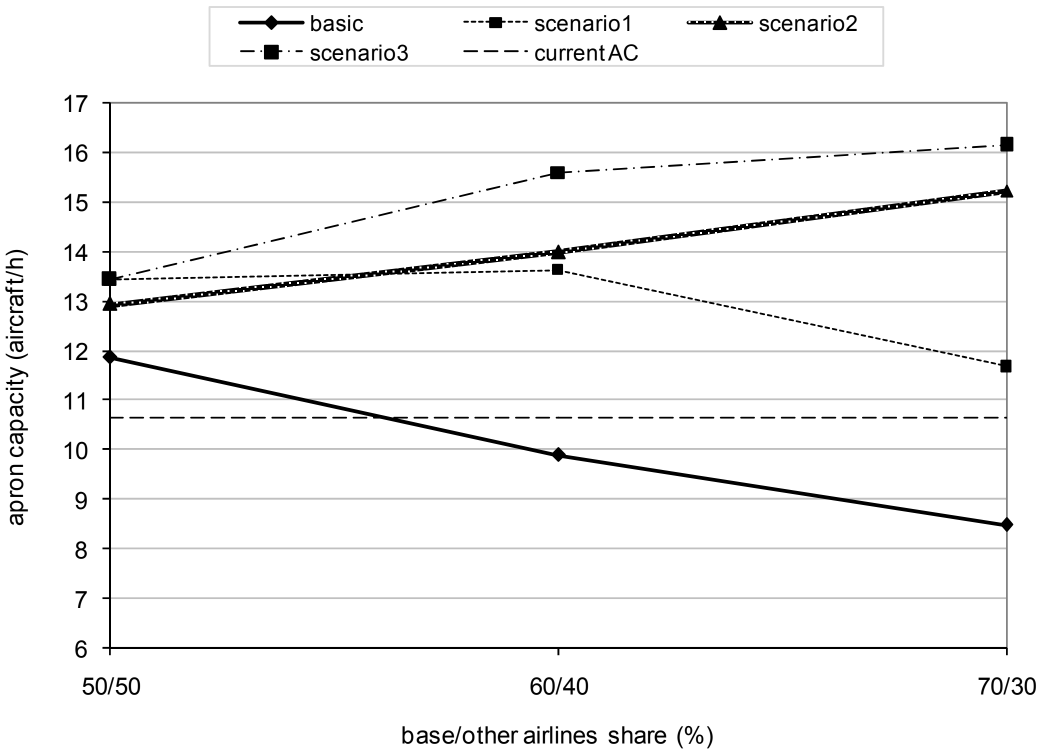


Figure 25. Relevant segments of apron capacity envelopes for scenarios analyzed in Example 2

The solid line in Figure 25 shows how the existing apron (basic scenario) reacts to changes in demand. For the 50/50% share it will provide somewhat higher capacity (by 11%) than with the current demand structure (under which apron area for base airline is underutilized). With a further increase of the base airline share, apron capacity falls below the current capacity level (dashed horizontal line in Figure 25), and continues decreasing with an increase in the base airline share. Changes in apron capacity (in %) relative to the current capacity level (10.6 aircraft/h) are given in Table 8 (Column 2 for the Basic Scenario).

In all three base/other airlines share cases, Scenario 1 provides higher apron capacity than the current level and the Basic Scenario, for given demand structures (Column 3 in Table 8). Although better than the Basic Scenario, Scenario 1 responds well on an increase in base airline share up to certain level, after which a mismatch between the share of stands by the users and share of users in demand appears, and apron capacity starts to decrease.

Table 8. Apron capacity changes (in %) relative to the current apron capacity level (10.6 aircraft/h) in Example 2

| base/other airline share | Basic scenario | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| 50/50 | 11 | 26 | 21 | 26 |
| 60/40 | -7 | 28 | 31 | 46 |
| 70/30 | -20 | 10 | 43 | 52 |

In Scenario 2 the apron capacity is similar to Scenario 1 for the 50/50 and 60/40 mixes of base/other airlines. With a more significant increase in base airline flights (70/30 mix), Scenario 2 is much better than Scenario 1 due to more flexibile use of available apron stands. For the case of 70/30 mix, Scenario 2 provides capacity which is for 43% higher than current capacity (Column 4 in Table 8), against the 10% increase which is gained in Scenario 1.

As expected, the most significant improvement can be achieved in Scenario 3, which considers both changes in layout (the same as in Scenario 1) and operational constraints (as in Scenario 2). Scenario 3 provides a capacity increase from 26% to 52% (Column 5 in Table 8) depending on the mix of aircraft/flights of the base and other airlines.

## 5.4 Utilization factor and stand occupancy times

The calculations as given above assume that all stands are fully utilized (i.e. 100% of time). In order to get more realistic estimate of apron capacity, calculated values can be corrected by introducing the stand utilization factor. It represents the amount of time the stands are occupied with respect to total time available (Horonjeff, 1975; Bandara and Wirasinghe, 1988; Hassounah and Steuart, 1993; De Neufville and Odoni (2003).

In general, it is assumed that, for each group of stands, the following applies: the time supplied by the stands has to be greater or equal to the time demanded for the same stands. For the $i^{th}$ group of stands it follows (Horonjeff and McKelvey, 1994):

$$\mu_i' N_i' \geq \overline{t_i}' C_i \qquad (13)$$

In expression (13):

$\mu_i'$ represents the percentage of time in an hour that the stands from the $i^{th}$ group can be used by all aircraft that are allowed to use stands from the $i^{th}$ group

$N_i'$ - number of stands in the $i^{th}$ group of stands

$\bar{t}_i'$ - weighted average stand occupancy time demanded by all aircraft allowed to use the $i^{th}$ group of stands

$C_i$ - apron capacity limited by the $i^{th}$ group of stands

Consequently, apron capacity corrected for utilization factor is: $C = \min(C_i)$ (expression 3) where restriction set by the $i^{th}$ group of stands is:

$$C_i = \frac{N_i'}{\bar{t}_i'} \cdot \mu_i' \tag{14}$$

Up to date experience has shown that the utilization factor typically ranges from 0.6 to 0.8 (Ashford *et al*., 2011). It becomes more complicated when it has to be expressed for different groups of stands (by user/size), where one stand can belong to more than one group.

Another approach to avoid overestimating of apron capacity takes into account that the time during which a stand is blocked by one aircraft and cannot be used by any other, consists not only of the turnaround time at the stand, but also includes the separation time between two consecutive aircraft using the same stand.

Bandara and Wirasinghe (1988) define separation time as 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. Defined like this, separation time depends on the apron and terminal layouts and it is independent of flight schedules. On the other hand, the utilization factor, determined empirically, is a function of number of stands and existing schedule at the airport where it is estimated. Because of that, Bandara and Wirasinghe (1988) considered separation time to be more convenient correction than utilization factor.

De Neufville and Odoni (2003) define so-called stand blocking time as the sum of stand occupancy time (SOT), positioning time and buffer time. In their approach SOT stands for scheduled turnaround time. It depends on the size of the aircraft, flight distance, airline, and model (low-cost, traditional, general aviation, etc.). It can range from 20min (for small regional aircraft) to 4h (for wide-body intercontinental flights). According to authors, positioning time can range from 2min to 10min depending on whether the aircraft does power in /power out or it is pushed-back. In order to absorb possible disturbances in the flight schedule they argue it is desirable by airports (and airlines) to provide the buffer time between two consecutive users of the same stand. It can range from several minutes to an hour, depending on the local circumstances, such as: typical delays, policy of stand-use, stand type (contact or remote), apron configuration, etc.

For a certain user, as is the case for low-cost airlines, one can make a good guess of average turnaround times. Their business model is such that it insists on short turnaround times (25min to 30min), operating primarily point-to-point services with uniform fleet on short-to-medium haul routes, without being dependant on any connecting flights, at least not intentionally. On the other hand, traditional airlines, operating both hub-and-spoke and point-to-point concept, with variety of aircraft classes and wide range of routes, may have turnaround times from 20min to several hours (TRB, 1987; de Neufville and Odoni, 2002).

The analysis of turnaround times and important factors that affect them (e.g. manufacturers' requirements[30], scheduling, hubbing, increasing aircraft size, etc.) is elaborated by Caves (1994). However, it is based on empirical analysis using data that is too old to be considered relevant today. For example it involves old Munich Airport – Riem and effects of hubbing during the 1990s, which have significantly evolved in the meantime. Average turnaround times showed tendency to decrease when the hubbing role of an airport increases. That is exactly the opposite if we assume temporal

[30]They are usually based on assumptions, such as: simultaneous forward and aft galley servicing even for small aircraft, fueling simultaneously with passenger embarking and disembarking, etc., which present turnaround times as being shorter than it is possible to achieve under real operating conditions.

concentration of traffic in waves, which may increase only "ground" times, aiming to connect with all flights within the wave. In his lecture notes Dennis (2005), on a simple example, argues that the average turnaround time increases together with the increase in the number of aircraft per wave.

Different information on apron capacity is provided when utilization factor and separation times are employed as a correction As discussed above, using separation times provides information on available capacity of the given apron layout regardless of the flight schedule. On the other hand, the utilization factor is entirely a reflection of demand requirements, and it provides information to what extent available capacity is utilized under given demand.

When using separation time and/or the utilization factor, one should be cautious, in order not to include the same correction twice in the calculation which would result in underestimating the capacity of the apron. For example, if the utilization factor is expressed considering separation time and/or buffer time between two occupancies of the same apron area, then the same should not be added again to the stand occupancy time.

In this thesis apron capacity estimation is based on the stand occupancy times that account for:

- The turnaround time for different users/aircraft classes and separation time between two consecutive occupancies of the same apron area (for O/D airports);
- The time required for facilitating transfers between connecting flights, and/or the time between consecutive waves of the same airline/alliance (at hub airports).

Stand occupancy time reflects the time during which a stand is reserved/blocked for a particular user regardless whether the aircraft (physically) occupies it during entire time.

It is desirable to select representative user/aircraft class categories carefully, in order to catch the variety of turnaround times typical for given airport.

Separation time considers both the time that has to be provided between two consecutive occupancies of the same group of stands, due to apron layout, and, if it applies to the airport, additional buffer time for absorbing regular disturbances in traffic schedules. Certain buffer times have been already included by airlines in their planned turnaround times.

At hub airports, the stand occupancy time for aircraft concentrated in waves of flights has to account for the time required to enable for the efficient transfers between flights and/or the time between two consecutive waves. Apron utilized capacity can be derived by applying both to the hub case serving only connecting flights, aiming to present to what extent theoretical capacity may be exploited depending on the specific demand for service (airline concentrate its fights in waves). In general, the period during which a stand is blocked by connecting flights, preventing the same resources to be used by other potential users, depends on the strategy of apron usage applied at the airport.

The influence of waves of flights at hub airports on stand occupancy/blocking times and consequently apron capacity is addressed in details in the reminder of this chapter.

## 5.5 Runway-apron functional relationship[31] under different traffic patterns

Services provided to aircraft on the runway system and in the apron(s) (i.e. aircraft contact and remote stands) are different in nature. The runway system is entry/exit point to/from the 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. Interaction of arrival and departure flows exists at both elements. Different arrivals and departures interact at these two service units, due to difference in service times and the transitional (taxi) times between them.

Analytical models express apron capacity in aircraft/h, while the runway system capacity is expressed in operations/h.

The roughest calculation is to multiply aircraft/h by two, 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.

[31] The physical runway-apron relationship related to taxi times and their impact on exchange of arrivals and departures between apron and runway is not considered in this thesis.

De Neufville and Odoni (2003) take into consideration largest fraction of arrivals in the traffic mix during a certain time interval. For example, if we have 65% of arrivals and 35% of departures and an apron capacity of 11 aircraft/h, that will correspond to 16.9 operations/h.

However, this calculation is still not sufficient to capture the real connection between apron and the runway system capacities, since this relation can be rather complex. It generally depends on factors such as: dominant market segments (e.g. scheduled, charter, low-cost, general aviation), type of airport with respect to traffic pattern (primarily hub and O/D, but also seasonality, etc.), airside elements design (taxiway system and apron taxiway/taxilane system), etc.

In this thesis the emphasis is on the difference between traffic patterns at O/D and hub airports i.e. between traffic distribution ("uniform", concentrated in waves or combination of the two). In the general case (O/D airports) capacities provided by the apron and the runway system can be calculated independently and compared to each other to identify the bottleneck in the system. This is not the case for hub airports that serve coordinated flights[32] concentrated in waves (solely, or in combination with other point-to-point flights[33]). The apron capacity depends on the capacity provided by the runway system. These two elements should be coupled with each other.

### 5.5.1 Origin-destination airports

The matter discussed above, related to transformation of arrivals/h to operations/h or vice versa, given a share of arrivals and departures in representative peak period, can apply to O/D airports. Consequently, provided the capacities of the runway system and apron(s) for typical peak periods, it is simple to identify which of the resources is the bottleneck, and to what extent the other resource is utilized.

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[32] The term "coordinated" aircraft/flight/traffic hereinafter refers to aircrfat carrying primarily transfer passengers. Coordinated aircraft are concentrated in waves, aimed at providing efficient transfers between flights.

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

<u>*Example 3*</u>*:* Let us observe a single-runway airport with 22 contact stands (of which 12 for aircraft class 2, and 10 for aircraft class 3) and 8 remote stands (of which 5 for aircraft class 1, and 3 for aircraft class 2).

Minimum ATC separation requirements between two consecutive arriving aircraft on approach are given in Table 9 (in Nm). Aircraft approach speeds are 110kts for class 1, 130kts for class 2, and 150kts for class 3. Runway occupancy time is 40sec for all aircraft. Critical separation is imposed by the separation requirements in the air, implying that the runway occupancy time is shorter than the required separation time between any pair of the arriving aircraft.

Minimum ATC separation requirements between two consecutive departing aircraft are given in Table 10 (in seconds).

Table 9. Minimum ATC separation rules between arriving aircraft on approach in Example 3

| $d_{ij}$ (Nm) | | class *j* 1 | 2 | 3 |
|---|---|---|---|---|
| class *i* | 1 | 3 | 3 | 3 |
| | 2 | 4 | 3 | 3 |
| | 3 | 5 | 4 | 4 |

Table 10. Minimum ATC separation rules between departing aircraft in Example 3

| $q_{ij}$ (s) | | class *j* 1 | 2 | 3 |
|---|---|---|---|---|
| class *i* | 1 | 45 | 45 | 45 |
| | 2 | 60 | 60 | 60 |
| | 3 | 120 | 90 | 90 |

In addition, separation of 2Nm has to be provided between departing aircraft and arriving aircraft on approach. The length of the final approach path is assumed to be 5Nm.

All stands are available to all users with respect to airline/type of service i.e. there are no user constraints on stand usage. Turnaround times are 30min for class 1, 45min for class 2, and 60min for class 3 aircraft. Separation time between any two consecutive stand occupancies is assumed to be 5min.

Aircraft fleet mix is: 20% class 1, 60% class 2 and 20% class 3 aircraft.

Apron configuration (contact stands + remote stands), demand structure, and turnaround times and separation times are summarized in Table 11.

Table 11. Apron configuration, demand structure, turnaround times and separation times in Example 3

| number of stands | aircraft class | share in demand (%) | average turnaround time (min) | separation time (min) |
|---|---|---|---|---|
| 0+5 | 1 | 20 | 30 | 5 |
| 12+3 | 2 | 60 | 45 | 5 |
| 10+0 | 3 | 20 | 60 | 5 |

Based on the given inputs, single runway capacity envelope is derived and shown in Figure 26.

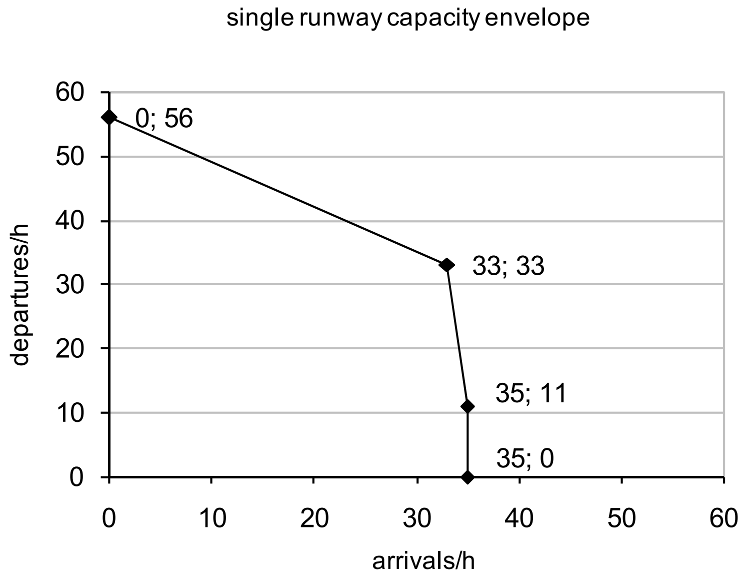


Figure 26. Runway capacity envelope in Example 3

Capacity of the runway is: 35 arrivals/h (plus additional 11 departures/h), 56 departures/h and 66 operations/h in mix mode.

Apron capacity is estimated as follows:

$$C = \min_i (C_i) = \min_i \left( \frac{N_i'}{\bar{t}_i'} \right)$$

$$C = \min(C_1, C_{2,}, C_3) = \min\left(\frac{0+12+10+5+3+0}{0.2\cdot 35+0.6\cdot 50+0.2\cdot 65}\cdot 60, \frac{12+10+3+0}{0.6\cdot 50+0.2\cdot 65}\cdot 60, \frac{10+0}{0.2\cdot 65}\cdot 60\right)$$

$$C = C_2 = 34.9 \quad aircraft/h$$

Translated into operations/h, it makes 70 operations/h, assuming a 50/50% share of arrivals and departures in peak period.

Capacity provided by contact stands only, i.e. gate capacity is:

$$C = \min_i(C_i) = \min_i\left(\frac{N_i'}{\bar{t}_i'}\right)$$

$$C = \min(C_1, C_{2,}, C_3) = \min\left(\frac{0+12+10}{0.2\cdot 35+0.6\cdot 50+0.2\cdot 65}\cdot 60, \frac{12+10}{0.6\cdot 50+0.2\cdot 65}\cdot 60, \frac{10}{0.2\cdot 65}\cdot 60\right)$$

$$C = C_1 = 26.4 \quad aircraft/h$$

It makes 53 operations/h, assuming a 50/50% share of arrivals and departures in peak period.

If all available stands are used, capacities provided by apron and runway are similar. The bottleneck is on the runway, which provides 93% utilization of apron capacity.

If only contact stands are used (e.g. remote stands are in the maintenance area), then the bottleneck is the apron. Runway (mixed mode) capacity is engaged up to 81%, assuming 50/50% share of arrivals and departures in peak period[34].

### 5.5.2 Hub airports – only coordinated flights

At hub airports relation between apron and the runway system is more complex than at O/D airports. In order to show such a relation, let us observe an ideal example of the hub airport where base airline/alliance operates exclusively waves of incoming and outgoing flights. The main parameters describing traffic pattern at hub airport i.e. wave-system structure, are shown in Figure 27.

[34] The utilization level is simple to calculate for other shares of arrivals and departures, depending on their mix in peak periods.

In this case, aircraft arrive during arrival time window ($ARR_{tw}$), allow for at least minimum connecting time (MCT) for transfers between flights and then depart during departure time window ($DEP_{tw}$). This is considered a wave.

The wave length (WL) is determined as:

$$WL = ARR_{tw} + MCT + DEP_{tw} \tag{15}$$

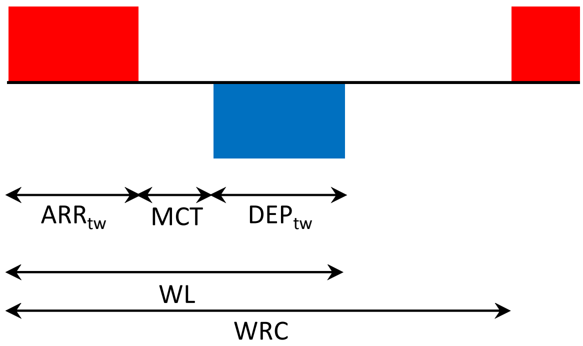


Figure 27. Parameters describing wave-system structure in the case of split waves (WRC≥WL)

The wave length depends on the runway system performance, because it has direct impact on the lengths of the arrival and departure time windows.

When discussing ideal wave of flights, the departure time window ($DEP_{tw}$) is approximated to be of the same length as arrival time window ($ARR_{tw}$), (Dennis, 1994; Burghouwt and de Wit, 2005; Burghouwt, 2007). This approximation is also adopted in the thesis. It makes wave length as:

$$WL = 2 \cdot ARR_{tw} + MCT \tag{16}$$

Dependence of the wave length on changes in the number of aircraft per wave and MCT is shown in Figure 28. Runway capacity is assumed to be 30 arrivals or departures per hour (implying 2 minutes separation time).

Wave length should satisfy the given level of service defined through the maximum acceptable connecting time (MaxCT) i.e. WL≤MaxCT. This means that the maximum number of aircraft per wave is limited either by apron static capacity or by MaxCT, whichever is more constraining.

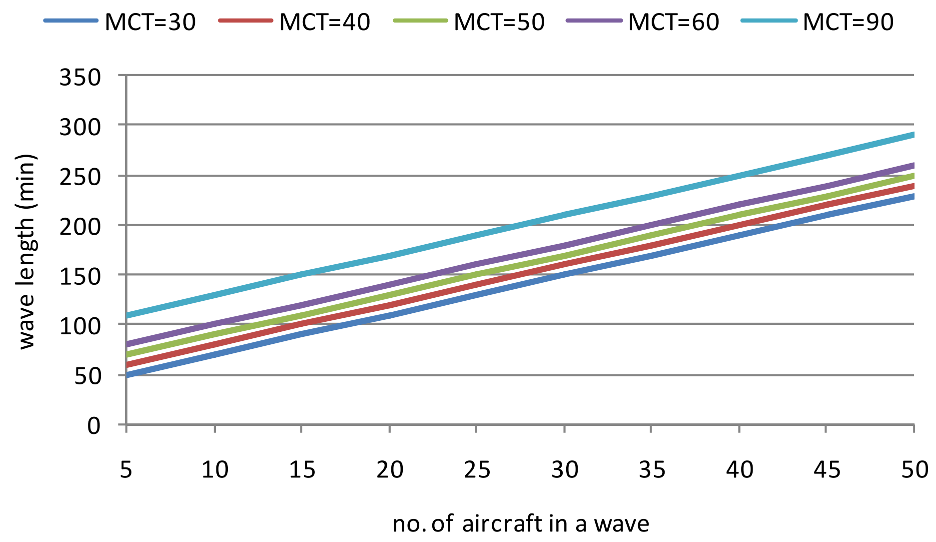


Figure 28. Dependence of the wave length on the number of aircraft per wave and MCT, assuming runway capacity of 30 arrivals/h

The static capacity of an apron is the maximum simultaneous number of aircraft that can be accommodated at the aircraft stands on the apron. This capacity depends both on the apron configuration and demand structure. Assuming that single (home base) airline or alliance participates in the wave[35], the static apron capacity[36] is determined as follows:

$$N_{a/c} = \min_{ij}(N_{ij}) = \min_{ij}\left(\frac{N_{ij}'}{s_{ij}'}\right) \quad (17)$$

where:

$N_{ij}$ - maximum simultaneous number of aircraft at the apron, limited by the group of stands available for user *i* and aircraft class *j*

$N_{ij}'$ - 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*), see expression (11)

[35] In this case, users can be defined with respect to type of service related to the level of security required inside the terminal building.

[36] It is derived from the condition that the number of stands supplied has to be larger or equal to the number of stands demanded: $N_{ij}' \geq s_{ij}' \cdot N_{ij}$, analogue to expression (13) for deriving dynamic capacity.

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

$$s_{ij}' = \sum_{k \in K} \sum_{l \in L} p_{kl} \tag{18}$$

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

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

$p_{kl}$ – proportion of aircraft of user *k* and class *l* in the population of aircraft demanding service

If the level of service is the limiting factor, it follows that:

$$WL = MaxCT \tag{19}$$

$$MaxCT = 2 \cdot ARR_{tw} + MCT \tag{20}$$

$$MaxCT - MCT = 2 \cdot ARR_{tw} = 2 \cdot N_{los} \cdot \overline{t_A} \tag{21}$$

$$\Rightarrow N_{los} = \frac{MaxCT - MCT}{2 \cdot \overline{t_A}} \tag{22}$$

where:

$\bar{t}_A$ - weighted average separation time of all arriving aircraft on the runway[37].

Dependence of $N_{los}$ on changes in MaxCT and MCT is shown in Figure 29. Runway capacity is again assumed to be 30 arrivals or departures per hour (implying 2 minutes separation time).

---

[37] In the general case, expression (22) would be: $N_{los} = \frac{MaxCT - MCT}{\overline{t_A} + \overline{t_D}}$, where: $\bar{t}_D$ - is weighted average separation time between all departing aircraft on the runway.

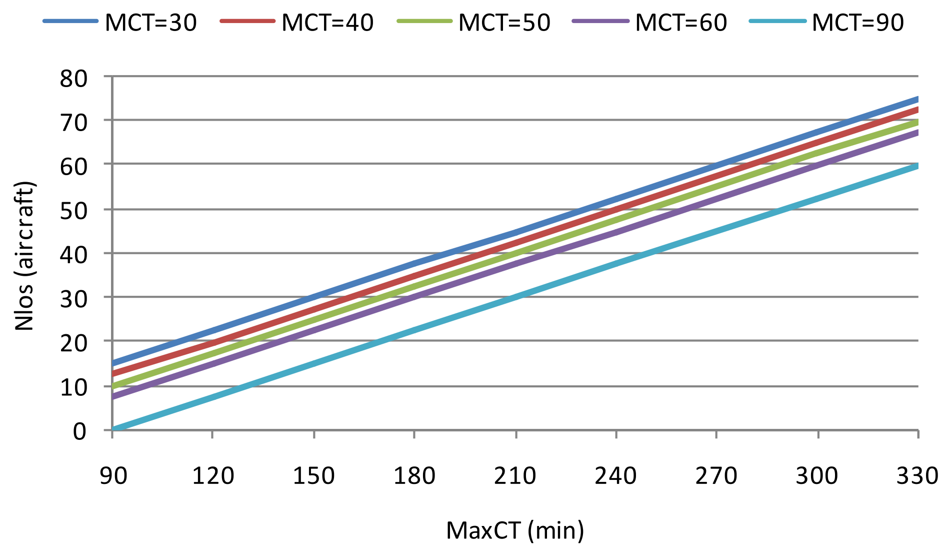


Figure 29. Dependance of $N_{los}$ on MaxCT and MCT, assuming runway capacity of 30 arrivals/h

Maximum number of aircraft that can be scheduled within a wave is:

$$N = \min\left(N_{a/c}, N_{los}\right) \tag{23}$$

Depending on which one is more constraining, the maximum number of aircraft is a function of runway performance (if it is limited by $N_{los}$) or this effect is omitted (if static apron capacity is more critical).

Assuming that arrival and departure waves are of the same length and the sequence of arrivals is the same as the sequence of departures, the average turnaround time (TAT) of the aircraft connected in the wave can be estimated as it follows:

$$TAT = ARR_{tw} + MCT = N \cdot \overline{t_A} + MCT \tag{24}$$

The parameter that describes the demand pattern is the wave repeat cycle (WRC). It is the time interval between the same points of the two consecutive waves.

Figure 27 has shown the case with split waves (WRC≥WL). Otherwise, if WRC<WL, waves partially overlap (departure time window with arrival time window of the next wave) as it is given in Figure 30.

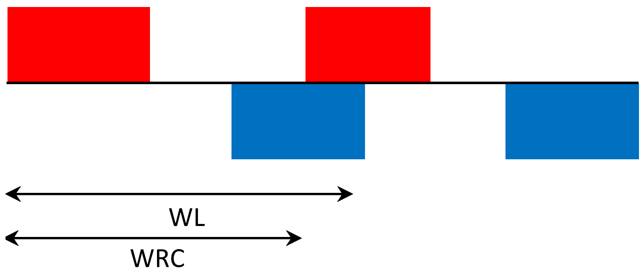


Figure 30. Parameters describing wave-system structure in the case of overlapping waves, WRC<WL

The theoretical capacity assumes exchange of aircraft i.e. new aircraft arrive as soon as the previous aircraft release stands. When an airline concentrates its flights in waves, the theoretical capacity is reached in the case with complete overlapping between the departure time window and the following arrival time window, as shown in Figure 31, i.e. $WRC = SOT$ .

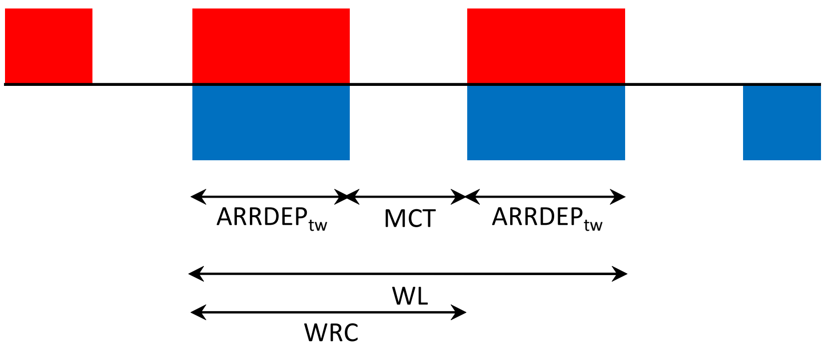


Figure 31. Parameters describing wave-system structure in the case with entirely overlapped waves, WRC=SOT

"Providing" exchange of arrivals and departures on the runway requires[38] the following:

$$ARR_{tw} = DEP_{tw} = ARRDEP_{tw} = N \cdot \overline{t_A^p} \tag{25}$$

where:

$\overline{t_A^p}$ - weighted average separation time of all arriving aircraft on the runway allowing one departure to be performed between any two consecutive arrivals

[38] At airports with parallel runways, one of which is for arrival and one is for departure, $ARR_{tw}$ is equal to $N \cdot \overline{t_A}$ .

Assuming an exchange of aircraft on the runway and apron, maximum number of aircraft per wave limited by the level of service is:

$$MaxCT = 2 \cdot ARRDEP_{tw} + MCT \tag{26}$$

$$MaxCT - MCT = 2 \cdot ARRDEP_{tw} = 2 \cdot N_{los} \cdot \overline{t_A^p} \tag{27}$$

$$\Rightarrow N_{los} = \frac{MaxCT - MCT}{2 \cdot \overline{t_A^p}} \tag{28}$$

With the number of aircraft per wave N (calculated from expression 23), the average stand occupancy time can be calculated as it follows:

$$SOT = TAT + ST = ARRDEP_{tw} + MCT + ST = N \cdot \overline{t_A^p} + MCT + ST \tag{29}$$

Consequently, the theoretical apron capacity for serving coordinated flights is[39]:

$$C_T = \frac{N}{SOT} \tag{30}$$

Theoretical apron capacity to serve waves of flights is exploited only to a certain extent. If no other flights are scheduled until the next wave, WRC can be observed as certain form of stand blocking time. This means that the utilized capacity (due to demand requirement) cannot be more than:

$$C_U = \frac{N}{WRC} \tag{31}$$

Utilization of theoretical capacity by the given demand is:

$$U = \frac{C_U}{C_T} \% \tag{32}$$

---

[39] In the case in which the number of aircraft per wave (N) is limited by the static apron capacity ($N_{a/c}$), expression (30) could be derived also from the general apron capacity estimation model (Section 5.1), because static capacity already takes into account shares in demand, and SOTs for all users are equal. The same does not apply when $N_{los}$ imposes the constraint on the number of aircraft per wave.

In the case with non-overlapping waves WRC≥WL the airline effectively uses runway capacity during $ARR_{tw}$ and $DEP_{tw}$, while during the MCT period and WRC-WL period it remains idle.

In the case of completely overlapping waves, periods when the runway is effectively used in mix mode ($ARRDEP_{tw}$) alternate with idle MCT periods.

The entire discussion, as given above, refers to wave of flights having all flights connected to each other (e.g. continental connections). In the case of mixed intercontinental (IC) and continental (C) connections, the calculation of $N_{los}$ and TAT for different groups of flights (with respect to type of service) is given in Appendix 12.

<u>*Example 3a*</u>*:* Let us observe the same airport as in Example 3, i.e. single-runway airport with 22 contact stands (of which 12 for aircraft class 2, and 10 for aircraft class 3) and 8 remote stands (of which 5 for aircraft class 1, and 3 for aircraft class 2). The base airline operates waves of flights with WRC of 180min. It uses only contact stands to provide a MCT of 30min. Remote stands are used only for aircraft overnights. MaxCT is 150min. Traffic structure is 20% aircraft class 1, 60% aircraft class 2, and 20% aircraft class 3 (as it is in Example 3).

Static apron capacity is determined as it follows:

$$N_{a/c} = \min_i \left( \frac{N_i'}{s_i'} \right)$$

$$N_{a/c} = \min\left(N_{1,} N_{2,} N_3\right) = \min\left( \frac{0+12+10}{0.2+0.6+0.2}, \frac{12+10}{0.6+0.2}, \frac{10}{0.2} \right)$$

$$N_{a/c} = N_1 = 22 \quad aircraft$$

In the case of split waves, the maximum number of aircraft that can be scheduled in a wave, to satisfy the level of service, would be:

$$N_{los} = \frac{MaxCT - MCT}{2 \cdot \overline{t_A}} = \frac{150-30}{2 \cdot 1.69} = 35 \quad aircraft$$

As a reference for theoretical capacity, complete overlapping has to be considered, implying:

$$N_{los} = \frac{MaxCT - MCT}{2 \cdot \overline{t_A^p}} = \frac{150 - 30}{2 \cdot 1.84} = 32 \quad aircraft$$

In both cases apron static capacity appears to be more critical.

$$N = \min\left(N_{a/c}, N_{los}\right) = 22 \quad aircraft$$

Stand occupancy time is determined as:

$$SOT = N \cdot \overline{t_p} + MCT + ST = 22 \cdot 1.84 + 30 + 5 = 75.5 \min$$

Consequently, the theoretical apron capacity is determined as:

$$C = \frac{N}{SOT} = 17.5 \quad aircraft / h$$

The utilized capacity with respect to demand requirements i.e. wave-system structure, is:

$$C_U = \frac{N}{WRC} = 7.3 \quad aircraft / h$$

It implies that the base airline uses 42% of theoretical apron capacity:

$$U = \frac{C_U}{C_T} = \frac{SOT}{WRC} = 0.42$$

Figure 32 shows the theoretical and utilized apron capacity for different wave-system structures i.e. WRCs. All inputs are the same as in Example 3a, only WRC varies from 300min to SOT. It can be seen that theoretical capacity does not change, because SOT remains the same, regardless of WRC. As WRC decreases, utilized capacity increases, until it reaches the theoretical capacity, when WRC becomes equal to SOT.

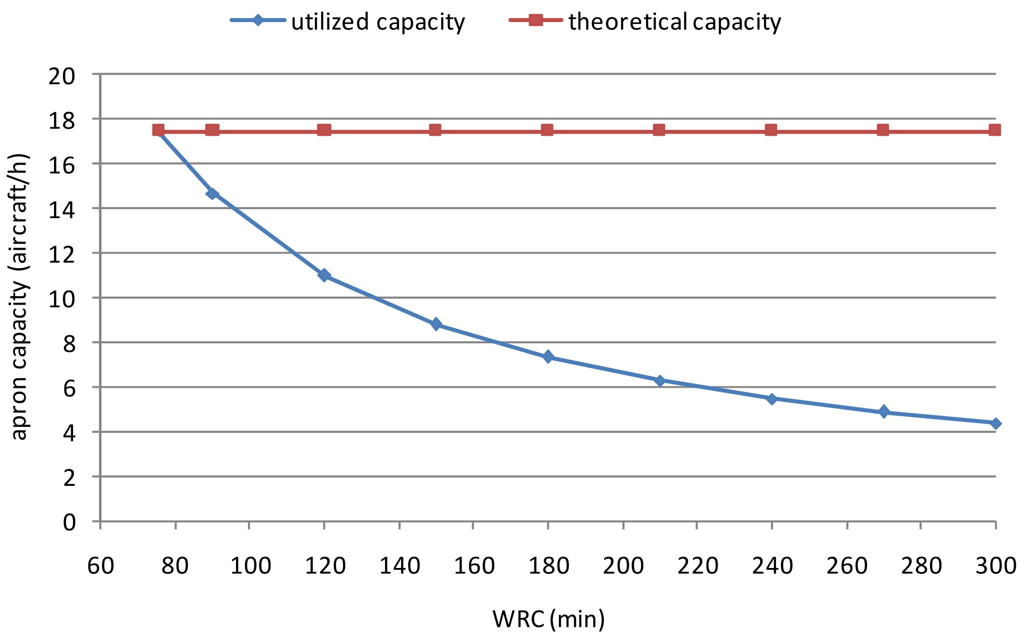


Figure 32. Theoretical vs. utilized capacity for different WRCs in Example 3a

Figure 33 shows how maximum number of aircraft per wave changes with MaxCT[40]. Under the conditions observed in Example 3a, MaxCT below 110min would become constraint for the maximum number of aircraft per wave.

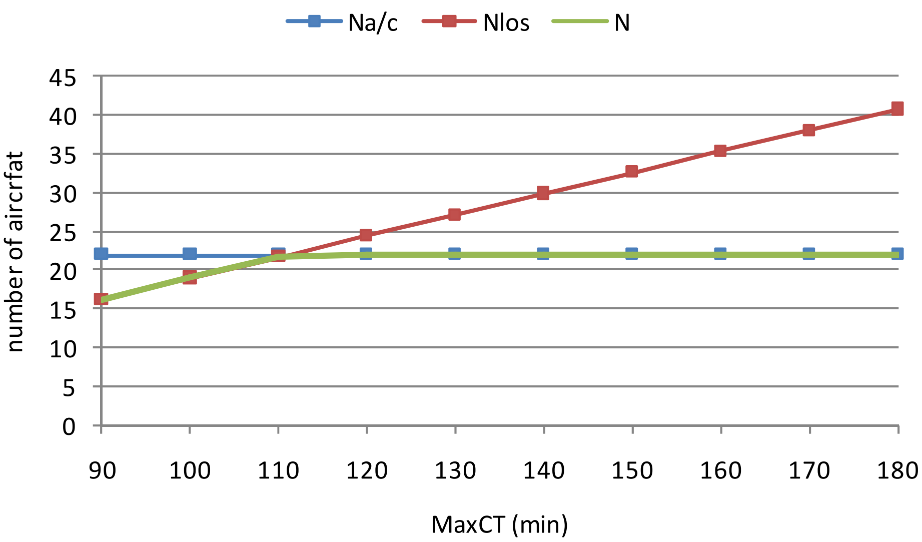


Figure 33. Maximum number of aircraft per wave for different MaxCTs in Example 3a

[40] $N_{los}$ is calculated using $\overline{t_A^p}$ .

In the case of split waves, 22 aircraft are served during the period of wave length:

$$WL = 2 \cdot ARR_{tw} + MCT = 104.6\min$$

The runway is effectively used for arrivals during 37min, followed by idle period of 30min, before it is used by departures during another 37min.

The remaining period until the next wave (WRC-WL) of 75.4min remains idle.

Literature review showed that only Steuart (1974) and Hassounah and Stuart (1993) addressed the issue of impact of wave (bank) operations on requirements for contact stands (gate) positions. They suggested how to calculate the expected number of aircraft occupying gate positions at time *t* from a given schedule, accounting for random deviations from the schedule. Steuart (1974) observed the scheduling alternatives to decrease (increase) the number of aircraft in the bank, while decreasing (increasing) the time interval between the banks (i.e. WRC), under constant arrival rate. He analyzed the changes in the expected number of aircraft at gates for short time intervals, from 0min (random schedule) to 60min, which are more of a theoretical approach than reflection of the real scheduling practice.

Hassounah and Steuart (1993) briefly discussed an impact of the time interval between the banks on gate requirements on numerical example, given a fixed number of aircraft per wave and fixed stand occupancy time. They analyzed more realistic time intervals, from 60min to 150min. They showed, as the spacing between the two banks decreases, the required number of gates starts to increase, reaching its maximum when the departure of the flights of the first bank and the arrival of the flights of the second bank coincide. Authors did not observe influence of the number of coordinated aircraft in the bank on average stand occupancy time, nor the influence of the runway system performance on apron capacity.

In addition, let us also consider the case when all 30 stands (contact + remote) can be engaged for coordinated flights, solely for the purpose of comparison to O/D airport. In this case, the maximum number of aircraft per wave is:

$$N = \min\left(N_{a/c}, N_{los}\right) = 30 \quad aircraft$$

The level of service becomes a greater constraint than static capacity only when MaxCT≤140min (see Figure 34).

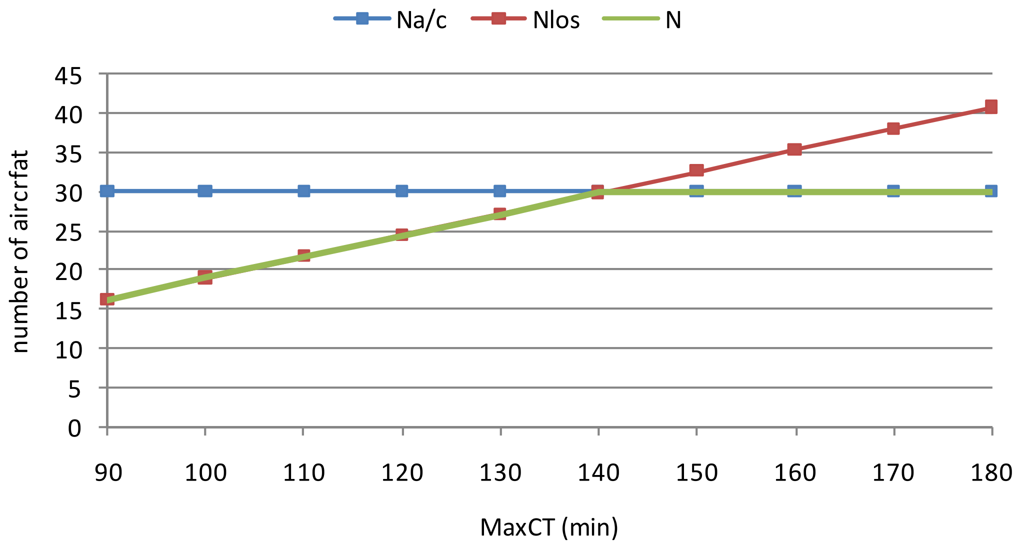


Figure 34. Maximum number of aircraft per wave for different MaxCTs in Example 3a (contact and remote stands)

In this case, stand occupancy time changes. It is:

$$SOT = 90.2\min$$

Consequently, theoretical and utilized capacities are:

$C_T = 19.9 \quad aircraft / h$ and

$C_U = 10 \quad aircraft / h$, respectively.

Figure 35 shows the capacity of an apron with 22 contact and 8 remotes stands for O/D airport case (Example 3) and pure hub airport serving only coordinated flights (Example 3a). The dark blue bar represents the capacity of contact stands, while the light blue bar represents additional capacity if remote stands are also engaged.

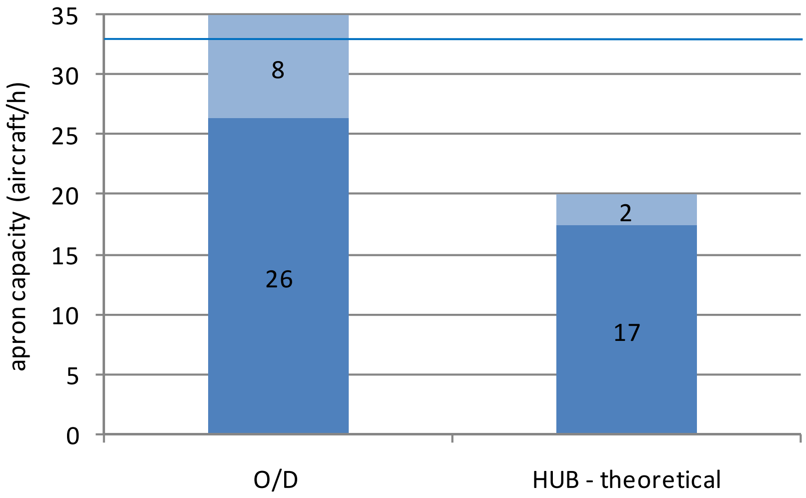


Figure 35. Apron capacities for O/D and hub airports (Examples 3 and 3a)

The capacity of the same apron serving the same fleet mix is as much as 50% higher in the case of O/D airport in comparison to hub. If all stands are taken into consideration[41] this difference increases to 65%. The reason lies in the significant difference in weighted stand occupancy times. Theoretical capacity for hub airport is used as a reference for comparison, because the utilized capacity is a reflection of demand pattern (WRC=180min), not the system's ability to handle it.

The blue line represents the arrival capacity provided by the runway operating in mix mode. As discussed in Example 3, it is lower than apron capacity when all stands are used, but exploited to 83% when only contact stands are considered. In the case of hub airport there is not much sense to compare runway and apron capacities. In order to provide greater number and better quality of connections, the runway is exploited to 100% in the periods of ARR and DEP time windows while the rest of time it remains idle.

[41] The percentage is expressed relative to runway capacity in this case, because it does not allow more than 33 arrivals/h in mixed mode, which is less of the apron potential to serve 35 aircraft/h.

### 5.5.3 Hub airports – mix of coordinated and point-to-point flights

If static apron capacity is greater than the number of aircraft per wave constrained by MaxCT, it could theoretically happen that: $WRC<ARR_{tw}+MCT$. However, it is not reasonable for this to happen in practice. In such circumstances, base airline can rather decide to expand the waves (increase the number of aircraft in a wave), decreasing the level of service to some extent. The other possibility is that the remaining apron capacity is used by other airlines operating point-to-point flights (in strong O/D markets), i.e. not participating in the wave-system.

Additional point-to-point flights are even more reasonable to expect in off-wave periods, which begin when connected aircraft, after exchanging passengers, start to leave the apron, and last until the next arrival wave.

In the case of airports with mixed coordinated and point-to-point traffic, in addition to airline and/or type of service/security level, different users ("customers") have to be defined also with respect to the nature of traffic. It is because different stand occupancy times apply to flights/aircraft coordinated flights and to point-to-point flights. The period of analysis should be the wave repeat cycle.

Apron capacity is determined as the minimum of the capacities set by the group of stands for different types of traffic, implying the following:

$$C = \min(C_{I,} C_{II}) \tag{33}$$

where:

$C_I$ - apron capacity limited by the group of stands available for coordinated flights

$C_{II}$- apron capacity limited by the group of stands available for other point-to-point (non-coordinated) flights

Let us assume that out of *n* users, $i \in [1, n]$, the first *g* users belong to group of coordinated flights, $q \in [1, g]$, and the rest *(n-g)* belong to group point-to-point flights, $r \in [g+1, n]$.

For the group of stands available for coordinated traffic, apron capacity ($C_I$) is calculated using expression (31), having a maximum number of stands per wave determined according to expression (23) (based on expressions (17) and (28)). These expressions have to be corrected for the share of coordinated traffic in total demand ($s_I$), during period observed (WRC), as given below:

$$C_I = \frac{C_U}{s_I} = \frac{N}{WRC \cdot s_I} \tag{34}$$

where:

$$s_I = \sum_{q=1}^{g} \sum_{j=1}^{m} p_{qj} \tag{35}$$

*q* designates the user that belongs to the group of coordinated flights, $q \in [1, g]$

*j* designates the aircraft class, $j \in [1, m]$, where *1* stands for the smallest aircraft class, and *m* for the largest aircraft class

The maximum number of aircraft per wave is determined using expression (23), as follows:

$$N = \min(N_{a/c}, N_{los})$$

where the maximum number of aircraft constrained by the level of service is determined using expression (28):

$$N_{los} = \frac{MaxCT - MCT}{2 \cdot \overline{t_A^p}}$$

while the static apron capacity is determined using the modified expression (17), as follows:

$$N_{a/c} = \min_{qj}\left( \frac{N_{qj}'}{s_{qj}'} \cdot s_I \right) \tag{36}$$

$$N_{qj}' = \sum_{o \in O} \sum_{l \in L} N_{ol} \text{ }^{42} \tag{37}$$

$$s_{qj}' = \sum_{o \in O} \sum_{l \in L} p_{ol} \tag{38}$$

$O = \{o|\ \ o \in [1, g]$ and user-class $o$ allow its stands to be used by user-class $q\}, O \subseteq [1, g]$

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

For the group of stands available for point-to-point traffic, apron capacity ($C_{II}$) is calculated using expression (10). Only those sub-groups that are related to users $r$, $r \in [g+1, n]$ are considered. Corresponding shares, with respect to total demand during the observed period, are taken into account. The following is implied:

$$C = \min_{rj}\left(C_{rj}\right) = \min_{rj}\left( \frac{N_{rj}'}{\bar{t}_{rj}'} \right) \tag{39}$$

where:

$r$ designates the user that belongs to the group of other (non-coordinated) flights, $r \in [g+1, n]$

$j$ designates the aircraft class, $j \in [1, m]$, where *1* stands for the smallest aircraft class, and $m$ for the largest aircraft class

[42] If remote stands for other users can also be used by coordinated flights it becomes: $N_{qj}' = \sum_{k \in K} \sum_{l \in L} N_{kl}$ ; $K = \{k|\ \ k \in [1, n]$ and user-class $k$ allows its stands to be used by user-class $q\}$. This is applicable only for preferential use case.

The number of stands for each sub-group of stands and corresponding weighted average stand occupancy times are determined as in the basic case, using expressions (11) and (12), as follows:

$$N_{rj}' = \sum_{k \in K} \sum_{l \in L} N_{kl}$$

$$\bar{t}_{rj}' = \sum_{k \in K} \sum_{l \in L} p_{kl} \cdot T_{kl}$$

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

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

Let us observe the case where in addition to coordinated flights, the same or other airlines operate also other point-to-point flights (low-costs, regionals, charters, etc.). They can use either remote stands only (exclusive use case), or they are also allowed to use contact stands during off-wave periods (preferential use case).

<u>*Example 3b*</u>: Apron configuration and runway parameters are the same as in Example 3: single-runway airport with 22 contact stands (of which 12 for aircraft class 2, and 10 for aircraft class 3) and 8 remote stands (of which 5 for aircraft class 1, and 3 for aircraft class 2). Hubbing parameters are the same as in Example 3a: WRC is 180min; MCT is 30min and MaxCT is 150min.

During the WRC period demand structure is 40% ($s_I$) coordinated flights (of which 20% aircraft class 1, 60% aircraft class 2, and 20% aircraft 3) and 60% other flights (of which 60% aircraft class 1, and 40% aircraft class 2 aircraft). Table 12 summarizes information on apron configuration, demand structure during the WRC period, average turnaround times and separation time.

Table 12. Apron configuration, demand structure, turnaround times and separation times in Example 3b

| number of stands | traffic type | aircraft class | share in demand (%) | average turnaround time (min) | separation time (min) |
|---|---|---|---|---|---|
| 0 | coordinated | 1 | 8 | 70,5 | 5 |
| 12 | | 2 | 24 | 70,5 | 5 |
| 10 | | 3 | 8 | 70,5 | 5 |
| 5 | other | 1 | 36 | 30 | 5 |
| 3 | | 2 | 24 | 45 | 5 |

Two cases are analyzed:

1. Exclusive use case: contact stands are exclusively used by coordinated flights; remote stands are available for other flights; and
2. Preferential use case: contact stands are also available for other (point-to-point) flights when they are not used by coordinated flights.

*Case 1 – exclusive use*

For the exclusive use case contact stands are blocked for use by other users, implying that no one else, besides coordinated flights can use them during the WRC period. Other aircraft can exchange only on remote stands after being turned-around and separation from other aircraft is provided. Overall apron capacity is determined as the minimum of the capacity limited by the group of stands for coordinated flights i.e. contact stands ($C_I$) and the capacity limited by the group of stands for other flights i.e. remote stands ($C_{II}$), under the given demand structure. It follows[43]:

$$C_I = \frac{C_U}{s_I} = \frac{N/WRC}{0.4} = \frac{7.3}{0.4}$$

$$C_I = 18.3 \quad aircraft/h$$

$$C_{II} = \min(C_{II1}, C_{II2})$$

$$C_{II} = \min\left(\frac{5+3}{0.36 \cdot 35 + 0.24 \cdot 50} \cdot 60, \frac{3}{0.24 \cdot 50} \cdot 60\right) = \min(19.5, 15)$$

[43] $C_U$ is calculates as in Example 3, expression (31). N is derived from expression (23), where $N_{a/c}$ from (17) and $N_{los}$ from (28); $s_I$ is the share of coordinated flights (0.4 in this example).

$$C_{II} = 15 \quad aircraft/h$$

$$C = \min(C_I, C_{II}) = 15 \quad aircraft/h$$

Apron capacity in the exclusive use case is 15 aircraft/h and is limited by the group of stands for other flights.

*Case 2 – preferential use*

In the preferential use case contact stands are used by coordinated flights, but when they leave the stands (after $ARR_{tw}$+MCT+ST), until the next wave (WRC), they can be used by other aircraft, in addition to remote stands. Overall apron capacity is the minimum of the capacity limited by the group of stands for coordinated flights ($C_I$) and the capacity limited by the group of stands for other flights ($C_{II}$), under the given demand structure. Capacity $C_I$ is calculated in the same way as in Case 1, since the next wave of coordinated flights does not arrive before WRC. Capacity $C_{II}$ takes into account that contact stands are released after the period: $ARR_{tw}$+MCT+ST. It follows:

$$C_I = \frac{C_U}{0.4} = \frac{7.3}{0.4}$$

$$C_I = 18.3 \quad aircraft/h$$

$$C_{II} = \min(C_{II1}, C_{II2})$$

$$C_{II} = \min\left( \frac{0 + 12 + 10 + 5 + 3}{(0.08 + 0.24 + 0.08) \cdot 75.5 + 0.36 \cdot 35 + 0.24 \cdot 50} \cdot 60, \frac{12 + 10 + 3}{(0.24 + 0.08) \cdot 75.5 + 0.24 \cdot 50} \cdot 60 \right)$$

$$C_{II} = \min(32.8, 42.5)$$

$$C_{II} = 32.8 \quad aircraft/h$$

$$C = \min(C_I, C_{II}) = 18.3 \quad aircraft/h$$

Apron capacity in the preferential use case is 18.3 aircraft/h and is limited by the group of stands for coordinated flights.

In the exclusive use scenario contact stands are utilized only to 42% (as shown in Example 3a) by the coordinated flights. By allowing them to be used by point-to-point flights between consecutive waves in the preferential use scenario, it results in a 22% higher capacity.

Example 4 is used to show apron capacity changes in the preferential and exclusive use cases, with different shares of coordinated flights and other flights during the WRC period.

*Example 4*: The same airport is observed as in Example 3: single-runway airport with 22 contact stands (of which 12 for aircraft class 2, and 10 for aircraft class 3) and 8 remote stands (of which 5 for aircraft class 1, and 3 for aircraft class 2). Hubbing parameters are the same as in Example 3a: WRC is 180min; MCT is 30min and MaxCT is 150min. The average turnaround time for other, non-coordinated aircraft, operating point-to-point flights is 40min. Runway capacity is the same as in Example 3.

During the WRC period the demand structure, in terms of share coordinated flights vs. other flights, is varied from 0/100 % to 100/0 %, as shown in Figure 36. All the other physical and operational system parameters are assumed as in Example 3b.

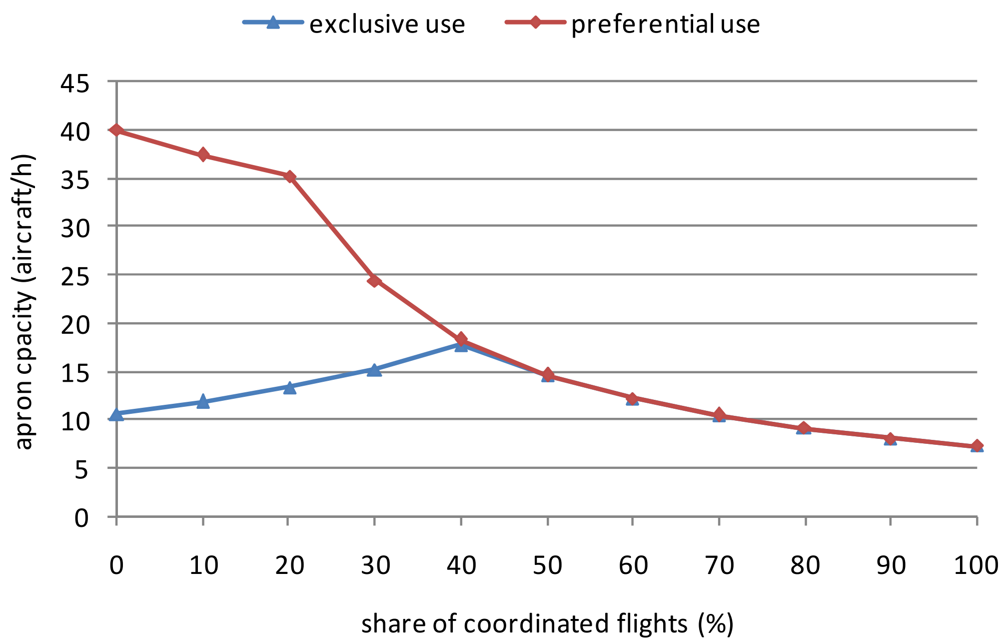


Figure 36. Apron capacity sensitivity to share of coordinated and other flights under exclusive and preferential use cases in Example 4

It can be seen that once the constraint moves from the contact stands area, designated for coordinated flights, to the group of stands available for other flights, preferential use case provides higher capacity figures than exclusive use case.

In Figure 37 the same relation is shown, only expressed in the number of coordinated and other aircraft that can be served during the period of 3h (WRC). The corresponding values are summarized in Table 13.

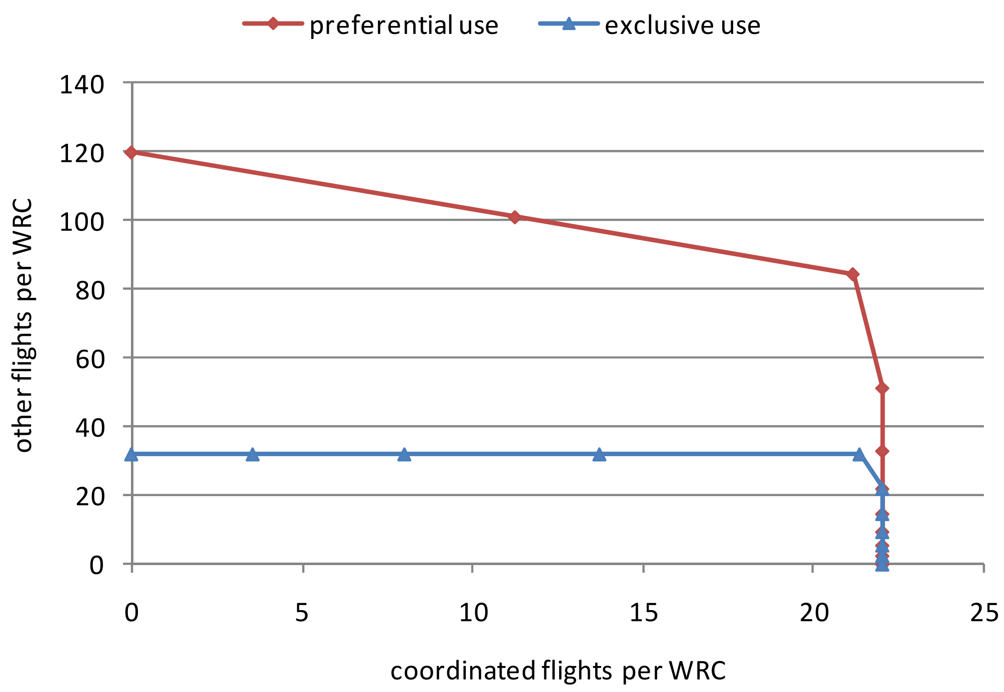


Figure 37. Relationship between number of coordinated and other aircraft handled on the apron, during the WRC, for different demand structures, under exclusive and preferential use cases in Example 4

It can be seen that the number of coordinated flights per wave does not exceed the limit of 22 aircraft (set by contact stands static capacity). The number of other flights that can be served during WRC varies depending on their share in demand and the policy of contact stand use.

In his work Steuart (1974) addressed the impact of different scheduling practices on gate requirements, including wave operations and the difference between exclusive and common use gate strategies. However, he observed these two independently one of the other.

Table 13. Estimated number of coordinated and other aircraft handled on the apron, during the WRC, for different demand structures, under exclusive and preferential use cases in Example 4

| coordinated/ other flights share | exclusive use | | preferential use | |
|---|---|---|---|---|
| | coordinated | other | coordinated | other |
| 0/100 | 0 | 32 | 0 | 120 |
| 10/90 | 4 | 32 | 11 | 101 |
| 20/80 | 8 | 32 | 21 | 85 |
| 30/70 | 14 | 32 | 22 | 51 |
| 40/60 | 21 | 32 | 22 | 33 |
| 50/50 | 22 | 22 | 22 | 22 |
| 60/40 | 22 | 15 | 22 | 15 |
| 70/30 | 22 | 9 | 22 | 9 |
| 80/20 | 22 | 6 | 22 | 6 |
| 90/10 | 22 | 2 | 22 | 2 |
| 100/0 | 22 | 0 | 22 | 0 |

Figure 38 summarizes apron capacities for pure hub (Example 3a) and for hub with additional point-to-point traffic (Example 3b).

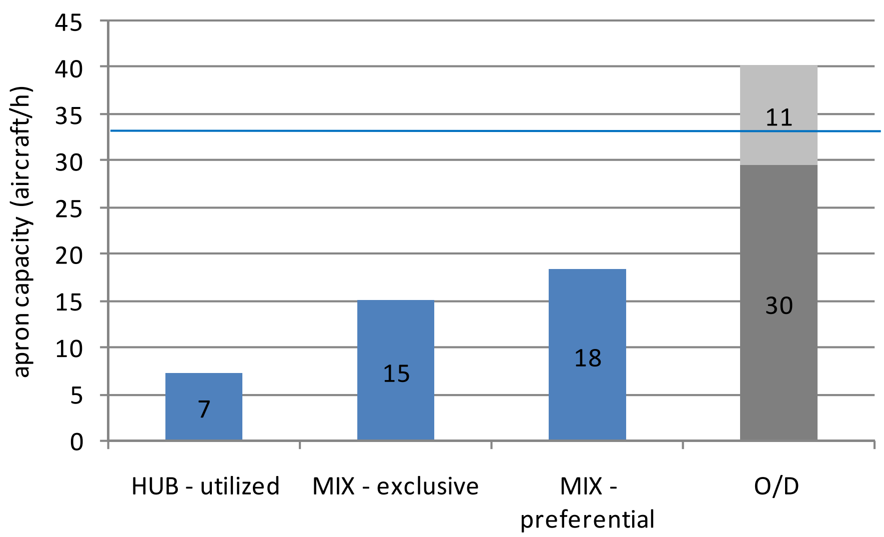


Figure 38. Apron capacities for different airport types (Examples 3a and 3b and modified Example 3)

The aim is to show apron capacity changes at hub airports when additional point-to-point traffic is allowed to use only remote stands (exclusive use), and contact stands in addition, during off-wave periods (preferential use). Furthermore, the O/D airport case is given as a reflection of the capacity if only point-to-point traffic is served at all stands.

For the case of pure hub, the comparison reference is the contact stand utilized capacity (with respect to WRC), because coordinated flights also use only contact stands in the exclusive/preferential use cases. The same fleet mix as used for the pure hub (Example 3a) is used for coordinated flights in exclusive/preferential cases (Example 3b).

In order to make the O/D case comparable to hub (mainly preferential) case, the overall fleet mix at exclusive/preferential case (Example 3b) is also applied for the O/D case. Table 14 summarizes the demand structure for different cases compared in Figure 38.

In this particular case (40/60 share of coordinated/point-to-point flights) apron capacity is two times higher (7.3 vs. 15 aircraft/h) when only (eight) remote stands are engaged for point-to-point traffic (exclusive use) and as much as 2.5 times higher (7.3 vs. 18.3 aircraft/h) when point-to-point traffic can also use (22) contact stands during off-wave periods, in addition to remote stands (preferential use).

Table 14. Demand structure for pure hub (Example 3a), for hub with additional point-to-point traffic (Example 3b) and for O/D airport (modified Example 3)

| flight type | aircraft class | HUB pure | HUB exclusive/ preferential | O/D |
|---|---|---|---|---|
| coordinated | 1 | 0,2 | 0,08 | 0 |
| | 2 | 0,6 | 0,24 | 0 |
| | 3 | 0,2 | 0,08 | 0 |
| other | 1 | 0 | 0,36 | 0,44 |
| | 2 | 0 | 0,24 | 0,48 |
| | 3 | 0 | 0 | 0,08 |

With only point-to-point traffic served (O/D case), runway capacity becomes the constraining factor. It is 78% higher than apron capacity in the preferential use case. There is no sense comparing O/D to the exclusive use case, since contact stands are not used in the same regime.

### 5.5.4 The impact of runway system performance on apron capacity

As discussed earlier, the runway system capacity does not have any impact on apron capacity for O/D airports. Apron and the runway system capacities are calculated separately, based on the variables that each of them depends on. The one that allows a lower capacity imposes the constraint on the overall airside capacity.

At hub airports apron and the runway system capacities cannot be observed separately. Capacity of apron to handle coordinated flights is affected by runway system performance characteristics.

Maximum number of aircraft within the wave may depend on apron configuration and demand structure (static apron capacity), or it may be a function of runway system performance (through maximum acceptable connecting time). If the number of aircraft per wave is limited by the level of service, i.e. not by static apron capacity, this would make apron capacities (both theoretical and utilized) dependant on the runway system performance.

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

- Theoretical apron capacity still depends on the runway system performance because SOT is a function of weighted average separation times on the runway;
- Utilized apron capacity does not depend on runway performance, since being derived from WRC, which is a characteristic of the demand itself, not a reflection of runway performance.

<u>*Example 5*</u> assumes different minimum separation rules between arriving and departing aircraft on the runway compared to Example 3. The minimum separation between all aircraft classes on approach is 5Nm, and minimum separation between all departing aircraft is 120sec. The apron has the same structure as in Example 3, which is: 22 contact stands (of which 12 for aircraft class 2, and 10 for aircraft class 3) and 8 remote stands (of which 5 for aircraft class 1, and 3 for aircraft class 2). Hubbing parameters are the same as in Example 3a: WRC is 180min; MCT is 30min and MaxCT is 150min.

The demand structure is the same as given in Table 14 (modified O/D example is used as comparable to hub with mixed coordinated and point-to-point flights).

In this case, runway capacity drops to 25 arrivals/h, 50 operations/h (alternating arrivals and departures), and 30 departures/h. The impact of runway performance on apron capacities is shown in Figure 39.

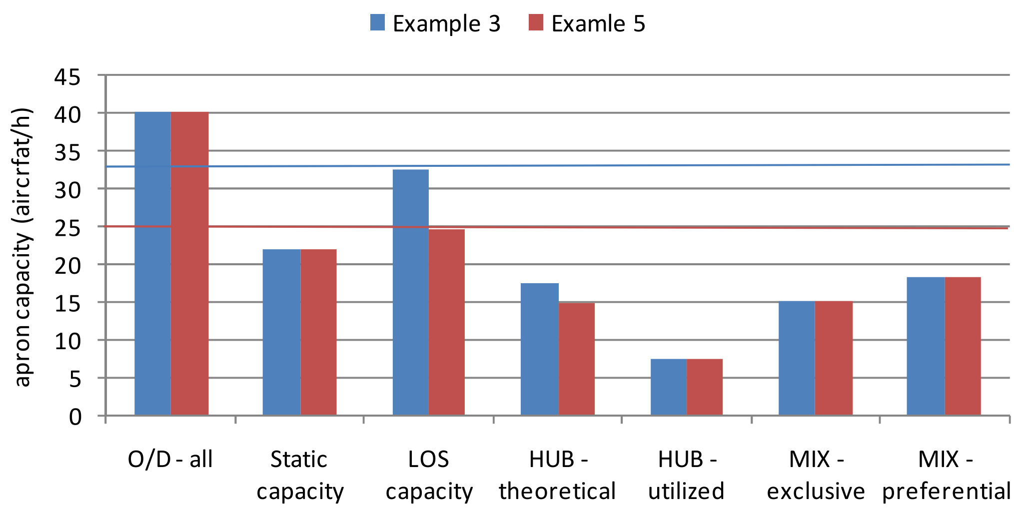


Figure 39. Apron capacity sensitivity to runway system performance, comparison between Example 3 and Example 5

The blue and red lines represent runway capacity (arrivals/h) in mix mode, for Example 3 and Example 5, respectively. In both examples airside capacity is limited by runway capacity for the O/D case and by apron capacity for hub cases.

In the O/D case apron capacity remains the same regardless of runway capacit, only the mismatch between the two is higher in Example 5 (40 vs. 25 arrivals/h) than in Example 3 (40 vs. 33 arrivals/h).

At hub cases, the influence of runway capacity on apron capacity is not clearly visible in all of them. This is due to fact that only some variables that determine apron capacity are functions of runway performance, as discussed earlier.

The maximum number of aircraft scheduled in a wave of flights, limited by the maximum acceptable connecting time (LOS capacity i.e. $N_{los}$), decreases from 32 to 24 aircraft per wave[44]. In both cases it is still higher than static apron capacity ($N_{a/c}$=22 aircraft), which means that in this case static apron capacity dictates the maximum number of coordinated aircraft in a wave.

Due to this, utilized capacity is not influenced by changes in runway performance, being derived from static capacity and WRC, which reflects demand characteristics. The theoretical capacity of the hub to handle coordinated flights decreases, due to the increase in $ARR_{tw}$, and SOT.

The impact of runway performance on apron capacity at airports with mixed coordinated and point-to-point flights exists, but it may be hidden, like it is in the case shown in Figure 39. It results from the more significant influence of other variables that affect apron capacity. In the exclusive use case, apron capacity is limited (to 15 aircraft/h) by the capacity of group of stands for other flights/aircraft class 2. In the preferential use case, capacity (of 18.3 aircraft/h) is constrained by the (utilized) capacity of the group of stand for coordinated flights (i.e. contact stands). The effect of runway parameters on apron capacity is not visible, because in these examples the constraining group of stands is not sensitive to them.

The additional example is given in Appendix 13. It assumes 6Nm separation between all aircraft classes on approach. In this case, $N_{los}$ becomes more constraining than static capacity. The influence of runway performance on apron capacity is also visible in the pure-hub and preferential use case.

## 5.6 Reserve apron capacity

Forsyth (2007) explores the main problems that changing demand poses to airports and how they cope with changes in the level and pattern of demand. He emphasizes aviation trends in Europe and their implications on airports. Five main aspects are observed: demand growth in the short run and in the long run; impact of new business models (particularly LCCs) and new aircraft types (A380 and B787) on the demand/capacity

[44] $N_{los}$ is calculated with $\overline{t}_A^p$ which is more constraining than when calculated using $\overline{t}_A$ .

balance; as well as improving airport efficiency and reducing costs in a competitive environment.

In order to cope with demand growth in the short run (when expansion of the airport airside elements is not an option), airport has to ensure that the existing capacity is utilized more efficiently. Two mechanisms applicable for avoiding congestion on the short run, under growing demand and unchanged infrastructure: slot allocation and congestion pricing (Forsyth, 2007). However, in the long run, airport needs to expand it capacity in accordance to projected demand growth (too little investment leads to congestion or suppressed demand; while too much investment leads to expensive use).

Airport capacity expansion is usually connected to huge infrastructural investments, primarily building new runway and/or terminal complex (terminal building and apron(s)). In order to meet demand volume and structure changes between these significant capacity jumps, airport capacity may be increased in smaller steps mainly through expansion and/or modification of existing elements, but only to a certain extent.

When it comes to runway system capacity scarcity, there is not much that can be done before building a new runway. Runway extension and widening enable larger aircraft to land and take-off, and may indirectly increase the overall airport throughput in terms of volume of accommodated passengers, while the runway system capacity may even decrease due to increase in separation rules. In the case of small airports, the runway system capacity may be increased with some structural changes to the taxiway system (such as introduction of high speed exits and parallel taxiways). Additional gain may be achieved through technological improvements i.e. better navigational equipment (category upgrade) to increase runway system utilization, and/or different tools for supporting managing (sequencing) the runway operations. Also, some operational measures may result in higher runway system capacity e.g. intersection take-off, staggered and/or steeper approach at parallel runways, etc.

On the other hand, before terminal complex reaches its capacity limit (usually expressed in the number of passengers that may be served through the terminal building on an annual basis), it can be modified and extended in smaller steps, as a response to demand characteristics changes. It is in a way a more "live" and adaptable airport element than the runway system. To increase terminal complex capacity, the airport may:

- In the terminal building: expand the terminal building (corridors, waiting rooms, etc.), engage additional equipment or introduce new technologies to improve passenger processing (check-in, baggage claim, security, waiting rooms, etc.), install additional air bridges, etc.;
- In the apron area: invest in fixed installations to improve efficiency of aircraft turnaround, rearrange the apron area to accept different aircraft classes and/or different users (with respect to different criteria), expand the apron area with additional stands and/or parallel taxiways, etc.

One of the above mentioned modifications related to apron area relate to the concept of reserve capacity (Mirkovic, 2011b and Mirkovic and Tosic, 2013). This thesis analyses apron potential to gain additional capacity (prior to physical expansion) through appropriate reallocation of available resources, mainly by changing i.e. relaxing existing operational constraints.

Representation of apron capacity as given in Section 5.3 allows the comparison of the effects resulting from the changes on the supply side in order to meet expected demand changes. However, this type of envelope does not provide information about the extent to which the apron is already utilized by the traffic it serves. If the runway capacity envelope is presented using a scatter diagram (having dominant users on the x and y axes), this information becomes available.

In Figure 40 the apron capacity envelope for *Example 1* is given. It assumes: 5 stands for domestic and 6 stands for all flights; average stand occupancy times of 45min for domestic and 55min for other rotations. The number of aircraft flying on domestic rotation are given on the x-axis and the number of aircraft other than domestic rotations (purely international and mixed domestic-international) on the y-axis.

The shares: 100/0, 80/20, 60/40, 50/50, 40/60, 20/80 and 0/100 of domestic/other rotations in total traffic are used to create the envelope. It shows expected, as the number of other rotations increases, the capacity decreases since the domestic stands are not available for other rotations. This apron configuration appears better adjusted to traffic with a greater share of domestic flights, as they can use all the stands at the apron.

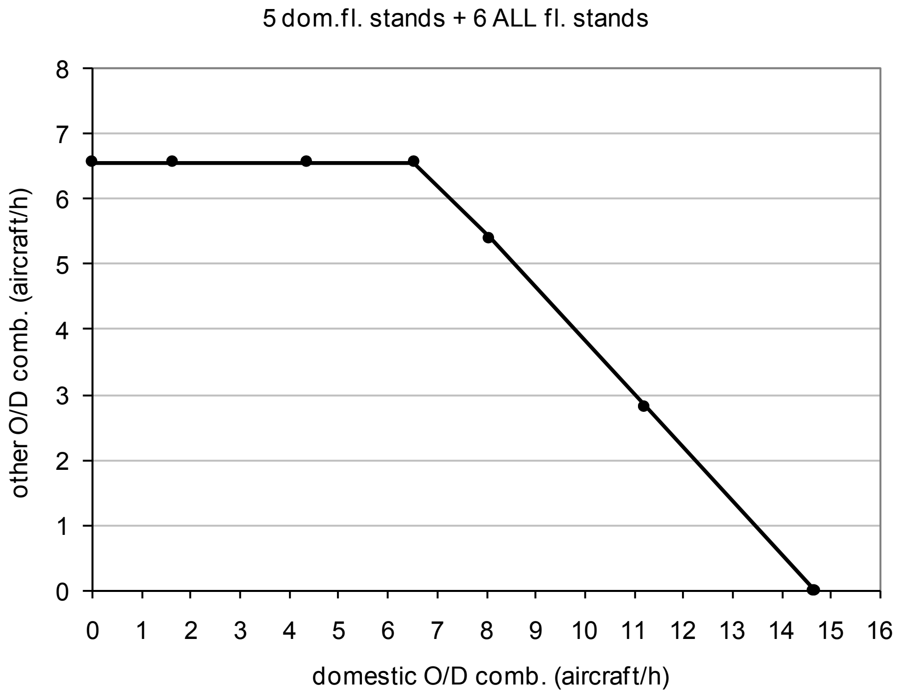


Figure 40. Apron capacity envelope for Example 1, scatter diagram

Figure 41 depicts apron capacity envelope for apron at which groups of stands are strictly divided between the users, like in *Example 2a* (5 stands for the base airline and 6 stands for all other airlines, assuming average stand occupancy times of 45min for the base airline and 55min for other airlines). The same shares as in the previous case are used (100/0, 80/20, 60/40, 50/50, 40/60, 20/80 and 0/100) to create apron capacity envelope. Only, in this case, these are shares of the base airline and other airlines in total traffic.

Depending on the operational constraints applied, each apron configuration has the ability to respond to demand structure changes with respect to users, which is its apron capacity flexibility. But, it also has some reserve/latent capacity that may be activated by changing/relaxing user constraints. How much an apron can gain through relaxation of the constraints depends on the level of flexibility that is already built in with existing operational rules. Generally, fewer constraints (more shared resources) lead to higher flexibility, which implies that a constraint-free apron configuration is absolutely flexible.

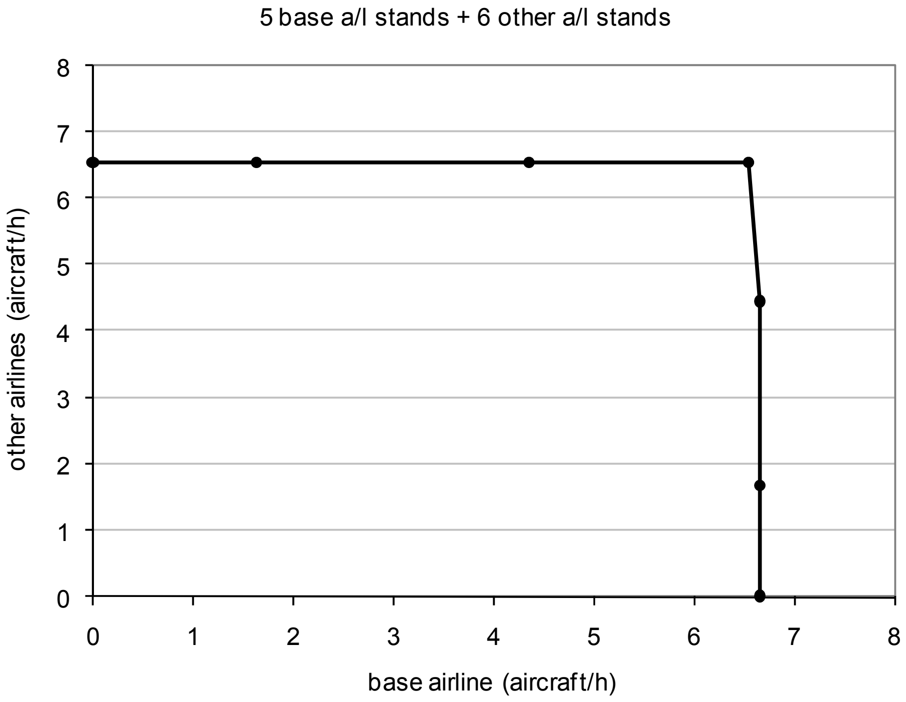


Figure 41. Apron capacity envelope for Example 2a, scatter diagram

Apron capacity flexibility of a certain apron configuration can be expressed as the ratio of the capacity provided by current apron (given configuration and operational constraints) and theoretical capacity allowed by an absolutely flexible apron with no user constraints.

For the two examples given above we have apron capacity envelopes of the constraint-free apron depicted in Figures 42 and 43, with a dashed line, while the solid lines are capacity envelopes of the current configurations.

By using the two envelopes (of the current and constraints-free apron configurations), flexibility of the current configuration can be expressed as the ratio of the surfaces under these envelopes. For the first case, apron capacity flexibility is 0.8 and in the second case it is 0.5. An absolutely flexible apron has a flexibility equal to 1.0.

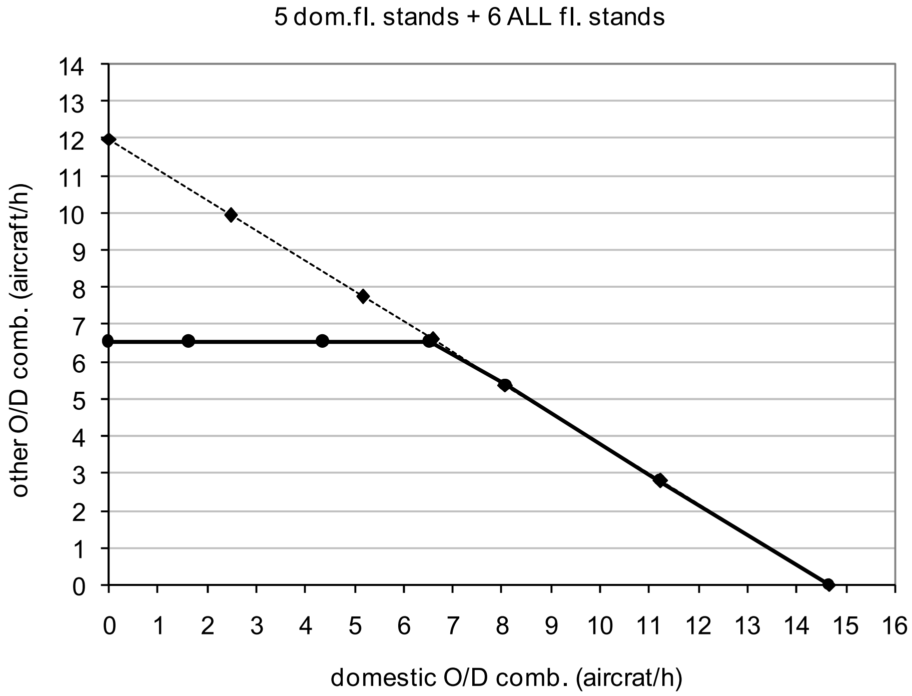


Figure 42. Apron capacity envelopes for a constraint-free apron and current configuration in Example 1

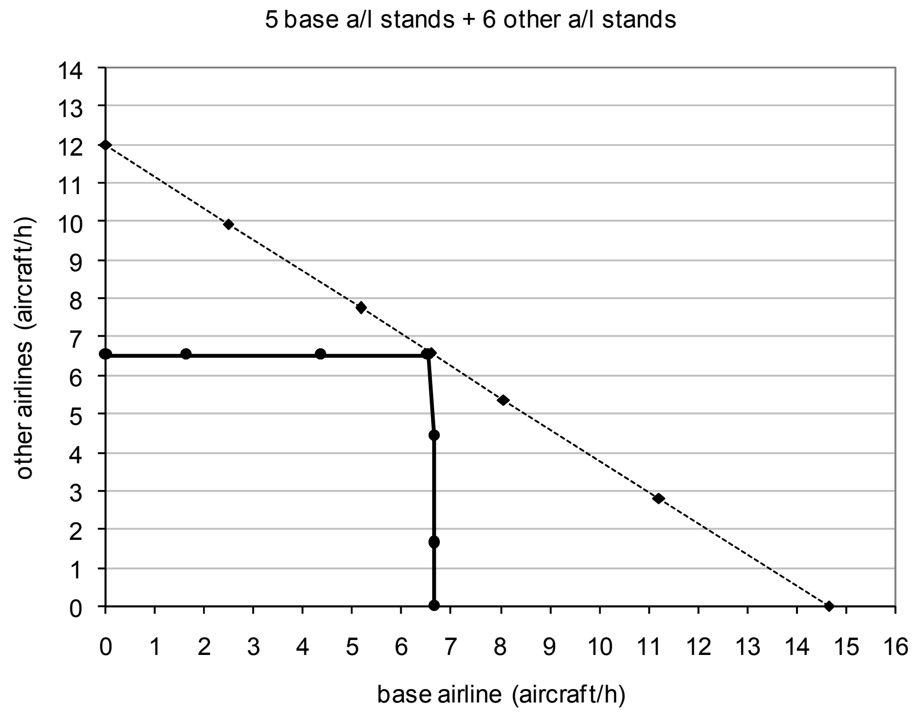


Figure 43. Apron capacity envelopes for a constraint-free apron and current configuration in Example 2a

Expressed this way, apron capacity flexibility can serve as a measure of the opportunity of a current apron configuration to gain more capacity by reallocation of stands between dominant users. It indicates to what extent the available physical resources (offered by a constraint-free configuration) are utilized, or, in other words, to what extent capacity reserves have already been exhausted. The more flexible the apron configuration is (i.e. closer to 1.0), the more able it is to accept changes in traffic structure. However, if congestion appears on the apron, a higher flexibility at the same time signifies a lower ability to accept for additional traffic through adequate resources reallocation. This means that, if an absolutely flexible apron is confronted with congestion, the only solution would be expansion of the capacity. Less flexible aprons are more sensitive to changes in traffic structure, but allow more possibility to meet (temporary or long term) changes in traffic volume and structure with relaxation of constraints, than do highly flexible aprons.

This information can be used for planning purposes, when deciding how to manage resources to meet changes in demand, prior to physical expansion. It provides information on how close to the upper limit of the capacity it is, as well as how much can be done to gain additional capacity through reassignment, before expansion.

Both Figure 42 and Figure 43 illustrate passenger apron capacity flexibility, as an indicator of its ability to cope with changes in user's structure changes to which it is exposed during day, week or season. In other words, it can serve as a measure of the passenger apron's potential to meet changes in traffic structure by users, expected on the medium- to long-term horizon, with adequate reallocation of available resources.

Furthermore, if the entire apron area (not only passenger aprons) is taken into consideration, then the potential of the apron in accommodating changes in passenger traffic, of an irregular and temporary character, can also be discussed. These changes may be due to the occurrence of certain events, either planned in advance (medium-term, e.g. congresses, sports competitions, etc.), or unexpected (short-term, due to e.g. meteorological conditions). In such situations the overflow in passenger traffic can be accommodated by underutilized apron areas for non-passenger users, such as cargo or general aviation.

## 5.7 Possible areas of application

"Dealing with an uncertain future, planners, managers and designers need to recognize the wide range of situations that may occur, examine the implications of these scenarios, and develop strategies that enable them to seize opportunities and protect them from risk" (TRB, 1987). In this case macroscopic models have their advantage, enabling fast analysis of various scenarios requiring less detailed input data (but still enough to provide good estimates). The output from macroscopic models is not meant to be directly used for final decision-making, but rather for selection of the best candidate scenarios that will be further analyzed through high-level-of-detail simulation tools.

The approach to airport airside modeling, aimed at airside capacity assessment and analysis, proposed in the thesis, is suitable for analysis of small-to-medium airports with the capacity constraint mainly at the terminal complex. It can also apply for a quick scan of the reserve capacity at airports exposed to frequent and significant changes of their dominant airlines/other users. Practice shows that the reasons for this can be various.

For example, after Switzerland entered the Schengen zone, Zurich Airport (Switzerland) had to transform the concept of its terminal-apron complex from exclusively international to the Schengen/non-Schengen concept. The transitional and final concepts are shown in Appendix 15. During the transitional (reconstruction) period remote stands had to be intensively used. For such purpose, new Busgates were built in order to enable higher utilization of the available remote stand, which are now used for overflow of traffic from contact stands.

Also, numerous airports experience changes in their uses structure, imposed by the constant growth of low-cost market segment.

Another example is Belgrade Airport (Serbia) which recently changed its main customer, when Etihad signed the contract of strategic partnership with (former) Jat Airways (now Air Serbia), in August 2013. With new entrant in the market and favorable location from the perspective of west-east connections, there is a certain potential for the airport to change its role in the air transport network, from O/D into a regional hub.

Some recent tendencies in airside modeling, for the purpose of supporting strategic (as well as tactical) airport planning, are directed toward the integration of existing macroscopic (and microscopic) models covering a wide range of issues, such as capacity, noise, emissions, cost-benefit analysis, 3rd party risk, etc. which are important for decision-makers to balance between. Improvement of each of the components can contribute to the entire decision-making process.

Regarding the airside capacity analysis, a group of authors (Zografos and Madas, 2007) propose MACAD (for strategic) and TAAM, SIMMOD or RAMSPlus (for tactical planning). Another group of authors (Wijnen et. Al., 2008; and Kwakkel et al., 2009) apply the usual approach – the runway system is taken as the constraining factor and the FAA Airfield Capacity Model is used for airside capacity modeling. An approach described in the thesis offers the possibility to include apron capacity into consideration when needed.

# 6 Conclusion

The introductory chapters of the thesis summarized important factors that affect runway system, apron and overall airside capacity.

Chapter 1 discussed airports element usage with respect to different criteria: market segments, physical constraints and operational constraints, together with their impact on the capacity of the entire airside system. Additionally, Chapter 2 elaborated different airport categorizations with respect to traffic parameters, giving a special emphasis on airport types with respect to their role in the network.

Chapter 3 summarized the definitions of airport airside capacity and factors that affect it. A particular attention was given to the characteristics of hub airports, such as: temporal concentration, ideal wave, wave-system structure and evolutionary phases as important factors that affect runway-apron functional relationship and consequently the overall airside capacity. The reminder of this chapter also discussed the issue of peak period: traditional approaches and some of the latest research results.

Chapter 4 gave a broad overview of the models for airside capacity modeling. It showed that the most mature areas are the runway system and entire airfield capacity modeling. Detailed state-of-the-art in the field of apron capacity modeling followed, being the main research area of this thesis.

In Chapter 5 an approach to analyzing the capacity of the existing (built) system under given physical and operational constraints, for given demand characteristics, is proposed. The approach considers linking of the (existing) runway system capacity model with the (extended) apron capacity model, through the runway-apron functional relationship (observed and defined in the thesis for different airport types: origin-destination and hub).

For such a purpose, modification of the existing analytical models was proposed, by including both constraints on aircraft classes and users, considering later different traffic types as well. It was followed by apron capacity representation, using newly suggested apron capacity envelopes. They provide information about capacity sensitivity of a certain apron configuration in dependence of the demand structure with respect to the dominant users. Furthermore, utilization factor, separation time and turnaround time, being significant variables that influence estimated capacity figures, were discussed.

Different numerical examples were used to show sensitivity of apron and consequently overall airside capacity to changes in: type of traffic, the runway system performance, and apron operational constraints.

Two airport types, with respect to the role of the airport in the air transport network, were analyzed: origin-destination airports (serving mainly point-to-point traffic, resulting in traffic being distributed rather “uniformly” during the day, with more or less pronounced peak periods), and hub airports (serving primarily airline/alliance coordinated flights, resulting in traffic being concentrated in waves of flights). The thesis also addressed the co-existence of point-to-point and coordinated flights at a single airport.

It was shown that the common approach to overall airside capacity can be applied at origin-destination airports: the runway system and apron may be observed independently of each other, deriving a conclusion on overall airside capacity by comparing the two of them.

On the other hand, capacities of the runway system and apron at hub airports have to be observed linked to each other. It was shown that the maximum number of aircraft within the wave depends either on apron configuration and demand structure (static apron capacity), or it is limited by the given level of service (defined over maximum acceptable connecting time). The latter is a function of the runway system performance. It was also shown that turnaround times for aircraft concentrated in waves depend on the runway system performance.

Consequently, an approach to estimating apron capacity at hub airport was offered. In addition to apron configuration and demand structure, it also takes into consideration wave-system structure parameters and the runway system performance.

The difference between apron capacity for origin-destination airports and hub airports that serves only coordinated flights was analyzed. It was shown that the same infrastructure provides higher throughput for point-to-point traffic (O/D airports) than for coordinated traffic (hub airport), having the same demand structure. That is a consequence of longer turnaround times for aircraft concentrated in waves, resulting from at least minimum connecting time required between all connections.

Further on, the difference between the theoretical apron capacity hub airport can offer for coordinated flights (assuming continuous exchange of departures and arrivals of the successive wave) and utilized apron capacity under specific wave-system structure which base airline/alliance operates from the hub (defined by wave repeat cycle) was analyzed.

The idle periods between the waves were seen as a spare capacity that can be "offered" to other users (if they appear) without jeopardizing the wave-system structure. Due to this, utilization of apron capacity at hub airports was analyzed, assuming that point-to-point traffic is allowed to use idle stands. Two scenarios were observed: preferential use (when contact stands are available for point-to-point flights between consecutive waves) and exclusive use (when contact stands are used only by coordinated flights). Capacity changes for both scenarios were shown for the full range of coordinated/point-to-point flights shares (100-0 to 0-100 %). As expected, the results showed higher utilization with the preferential use scenario, than in the case when contact stands are exclusively used by coordinated flights.

Further on, the conditions under which apron capacity is sensitive to the runway system performance were analyzed. Results showed that a lower runway system performance may result in a lower maximum number of aircraft per wave, and consequently a lower apron and overall airside capacity. However, under certain conditions, the effects of the runway system performance on apron capacity may be concealed, for example when apron static capacity is more constraining than level-of-service capacity.

The thesis also observed reserve/latent apron capacity, being considered as a potential for accepting additional demand prior to physical expansion. It was suggested to express apron capacity flexibility relative to apron capacity of the absolutely flexible apron (with no operational constraints on stand usage). On one hand, apron capacity flexibility is used as an indicator of the ability of the apron to respond to changes in demand structure. At the same time, it is considered as an indicator of latent/reserve capacity that may be “activated” by reallocation of available resources i.e. relaxation of the constraints on stand use.

At the end a short discussion was given on possible areas of application of the proposed approach in the field of airport airside capacity analysis.

An apron capacity estimation tool was developed as a supplementary material to the thesis. The general user instructions on how to use it for O/D and hub airports is provided in Appendix 14.

Research results of this thesis can be further developed in different directions. The main avenues for expansions/modification of the models offered in the thesis for airport apron and overall airside capacity analysis are indicated in the list of assumptions that the models are based on, summarized in Section 5.1. Of all the ones listed, the two can be considered of higher importance.

One is introduction of stand occupancy times as random variables to obtain estimates of mean and standard deviation of apron capacity. Similar approach as in Bandara and Wirasinghe (1988) can be applied.

The other is evaluation of the scenarios for gaining additional capacity through operational constraints relaxation, based on the cost of their implementation. Associated costs depend on the type of transformation proposed (terminal building reconstruction, implementation of the new technologies in passenger processes, reallocation of the stands between traditional airlines and LCCs, relaxation of stand use policy from exclusive to preferential or to partially/entirely joint use, etc.). The best scenario(s) are those that provides capacity/demand match at acceptable costs.

The models offered in the thesis can also be further adapted for airside capacity analysis of passenger airports with specific operational requirements (e.g. de-icing process is done at the aircraft stand), or other types of airports with respect to demand characteristics (e.g. seasonal airports, airports with mixed passenger/non-passenger market segments, etc.).

# 7 List of abbreviations

| | |
|---|---|
| AC | Advisory Circular |
| ACATS | Airport Capacity Analysis Through Simulation |
| ACRP | Airport Cooperative Research Program |
| AIP | Aeronautical Information Publication |
| AMAN | Arrival Manager |
| $ARR_{tw}$ | ARRival time window |
| ATC | Air Traffic Control |
| ATM | Air Transport Management |
| BAA | British Airports Authority |
| CALM | Computer-assisted Approach and Landing Management |
| CJ | Conventional Jet Aircraft |
| CLOU | Co-operative Local resOUrce planner |
| CUMA | Civil Use of Military Aerodromes |
| $DEP_{tw}$ | DEParture time window |
| DFS | Deutsche Flugsicherung |
| DMAN | Departure Manager |
| EC | European Commission |
| EU | European Union |
| EUR | Continental flights |
| FAA | Federal Aviation Administration |
| HERMES | Heuristic Runway Movement Event Simulation |
| IATA | International Air Transport Association |
| ICA | Intercontinental flights |
| ICAO | International Civil Aviation Organization |
| ICT | Intermediate Connecting Time |
| JFK | John F. Kennedy International Airport |
| LCC | Low-Cost Carrier |
| LEONARDO | Linking Existing on Ground, Arrival and Departure Operations |
| LOS | Level Of Service |
| MACAD | Mantea Airfield Capacity and Delay |

| | |
|---|---|
| MAP | Military Airport Programme |
| MARS | Multi Aircraft Ramp System Concept |
| MaxCT | Maximum Connecting Time |
| MCT | Minimum Connecting Time |
| MLS | Microwave Landing System |
| MUC | Munich International Airport |
| NLA | New Large Aircraft |
| OAG | Official Airline Guide |
| O/D | Origin-Destination |
| RAMS | Reorganized ATC Mathematical Simulator |
| SEAP | Steeper Approach Procedure |
| SGAP | Staggered Approach Procedure |
| SMAN | Surface Manager |
| SFO | San Francisco International Airport |
| SIMMOD | Airport and Airspace Simulation Model |
| SOT | Stand Occupancy Time |
| TAAM | Total Airspace and Airport Modeler |
| TAM | Total Airport Manager |
| TAT | TurnAround Time |
| TMAN | Turnaround Manager |
| TRB | Transportation Research Board |
| WB | Wide Body aircraft |
| WL | Wave Length |
| WRC | Wave Repeat Cycle |
| WNX | Weighted indirect connection number |
| ZRH | Zurich International Airport |

# 8 List of variables and parameters

| | |
|---|---|
| $ARR_{tw}$ | arrival time window - the time period during which aircraft (concentrated in a wave) arrive |
| $ARRDEP_{tw}$ | time window for alternating arrivals and departures |
| C | apron capacity – saturation apron capacity |
| $C_i$ | apron capacity limited by the $i^{th}$ group of stands (designated for user *i*, or for aircraft class *i*) |
| $C_{ij}$ | apron capacity limited by the group of stands available for user *i* and aircraft class *j* |
| $C_I$ | apron capacity limited by the group of stands available for coordinated flights |
| $C_{II}$ | apron capacity limited by the group of stands available for point-to-point flights |
| $C_T$ | theoretical apron capacity – saturation apron capacity at hub airport serving only coordinated flights (assumes completely overlapped waves) |
| $C_U$ | utilized apron capacity at hub airport serving only coordinated flights, accounting for demand requirement (defined by the wave repeat cycle) |
| $DEP_{tw}$ | departure time window – the time period during which aircraft (concentrated in a wave) depart, after being served, including transfers between flights |
| MCT | minimum connecting time – minimum time period to facilitate transfers between two connections |

| | |
|---|---|
| $MCT^C$ | minimum time period to facilitate transfers between continental connections |
| $MCT^{IC}$ | minimum time period to facilitate transfers involving intercontinental connections |
| MaxCT | maximum acceptable connecting time as a measure of level of service |
| $MaxCT^C$ | maximum acceptable connecting time between continental connections |
| $MaxCT^{IC}$ | maximum acceptable connecting time involving intercontinental connections |
| $\mu_i$ | utilization factor of the $i^{th}$ group of stands (designated for user *i*, or for aircraft class *i*) |
| $N_{all}$ | total number of available stands |
| $N_i$ | number of stands designed for aircraft class *i* (only) |
| $N_i$' | number of stands in the $i^{th}$ group of stands (stands allowed to be used by user *i*, or stands designed for aircraft class *i* and for aircraft larger than *i*) |
| $N_{ij}$' | number of aircraft 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*) |
| N | maximum number of aircraft in a wave |
| $N_{a/c}$ | static apron capacity – maximum simultaneous number of aircraft at the apron, accounting for apron configuration and demand structure |
| $N_{ij}$ | maximum simultaneous number of aircraft at the apron limited by the group of stands available for user i and aircraft class *j* |

| | |
|---|---|
| $N_{los}$ | maximum number of aircraft that may be scheduled within a wave to satisfy given level of service (defined by maximum acceptable connecting time - MaxCT) |
| $N_{los}^{C}$ | maximum number of continental aircraft that may be scheduled within a wave to satisfy given level of service (defined by maximum acceptable connecting time - $MaxCT^{C}$) |
| $N_{los}^{IC}$ | maximum number of intercontinental aircraft that may be scheduled within a wave to satisfy given level of service (defined by maximum acceptable connecting times – $MaxCT^{C}$ and $MaxCT^{IC}$) |
| $p_i$ | proportion of aircraft of user/class *i* in the population of aircraft demanding service |
| $p_{ij}$ | proportion of aircraft of user *i* and class *j* in the population of aircraft demanding service |
| $s_I$ | share of coordinated traffic in total demand |
| $s_{ij}'$ | cumulative share user/aircraft class combination allowed to use the $ij^{th}$ group of stands |
| SOT | average stand occupancy time as a sum of average turnaround time (TAT) and average separation time (ST) |
| $SOT^{C}$ | average stand occupancy time for continental flights |
| $SOT^{C}$ | average stand occupancy time for intercontinental flights |
| ST | separation time between two consecutive aircraft stand occupancies, accounting for positioning time and apron taxiway/taxilane system leading to/from aircraft stands |
| TAT | average turnaround time |

| | |
|---|---|
| $TAT^{C}$ | average turnaround time for continental flights |
| $TAT^{IC}$ | average turnaround time for intercontinental flights |
| $\bar{t}$ | weighted average stand occupancy time of all aircraft demanding service |
| $\bar{t}_i'$ | weighted average stand occupancy time of all aircraft allowed to use the $i^{th}$ group of stands |
| $\bar{t}_{ij}'$ | weighted average stand occupancy time of all user/aircraft class combination allowed to use the $ij^{th}$ group of stands |
| $T_i$ | average stand occupancy time of the aircraft of user *i* or class *i* |
| $T_{ij}$ | average stand occupancy time of the aircraft of user *i* and class *j* |
| $\bar{t}_A$ | weighted average separation time of all landing aircraft on the runway<br>$\bar{t}_A = \sum_{i,j} p_{ij} \cdot t_{ij}$<br>$t_{ij}$- minimum separation time between aircraft *i* and *j* (separation time on approach between aircraft *i* and *j* , or runway occupancy time of aircraft *i,* whichever is greater)<br>$p_{ij}$ - probability of (*i,j*) pair appearance $p_{ij} = p_i \cdot p_j$ |
| $\bar{t}_D$ | weighted average separation time between all departing aircraft on the runway<br>$\bar{t}_D = \sum_{i,j} p_{ij} \cdot t'_{ij}$<br>$t'_{ij}$ - minimum separation time between aircraft *i* and *j* on take-off |

| | |
|---|---|
| $\bar{t}_A^p$ | weighted average separation time of all landing aircraft on the runway allowing one departure to be performed between any two consecutive arrivals<br><br>$\bar{t}_p = \sum_{i,j} p_{ij} \cdot t_{ij}^p$<br><br>$t_{ij}^p$ - minimum separation time between aircraft *i* and *j* on approach that allows releasing one departure between them |
| U | utilization of the theoretical capacity at pure hub airports with respect to demand requirements |
| WL | wave length - the total length of a wave of flights including arrival time window ($ARR_{tw}$), minimum connecting time (MCT) and departure time window ($DEP_{tw}$) |
| WRC | wave repeat cycle – the time period between the same points of the consecutive waves, e.g. beginning of the arrival time window |

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# 11 Appendices

## Appendix 1 – European air transport networks

### European hub-and-spoke networks

Hubs airports may be classified according to size of the origin-destination market, the stage-length of the indirect connections offered, and the geographical specialization of the hubs.

Based on the size (measured through its indirect connectivity[45]), the main European hub airports, as from the traffic data from 2003, are: Frankfurt, Paris CDG, London Heathrow and Amsterdam (Burghouwt, 2007). "Together the four hubs accounted for 57 per cent all indirect connections generated by the airline stations with more than 10 indirect connections per day". They were followed by: Madrid, Munich, Zurich, Copenhagen, Vienna, Rome Fuimicino, Barcelona and Milan Malpensa. Ten years later the situation is quite similar, only the ranking may have changed (which also depends on the specific measure of hubbing performance[46]) and some airports have lost their hubbing role after the bankruptcy of the base airline or its decision to withdraw (e.g. Milan Malpensa and Barcelona). This is a proof that airport hubbing role is highly dependent on airline strategy.

Redondi et al. (2010) rank the top-20 world airports in number of (viable[47]) connections (as from September, 2009). Among them are six European airports: Frankfurt, Paris Charles de Gaulle, Munich, London Heathrow, Amsterdam Schiphol and Madrid.

Based on the stage-length of the indirect connections, a hub may be hinterland, directional (hourglass) or regional.

Hinterland hubs connect long-haul and international routes to short-haul routes. Hinterland hubs may be further classified based on the geographical specialization. In Europe some hubs are specialized for intra-European connections, so called Eurohubs,

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[45] Some measures of indirect connectivity are addressed in Chapter 3.

[46] Addressed in Section 3.3.3.

[47] It is between flights of the same airline/alliance; time between incoming and outgoing flight is between 1h and 3h, and the detour necessary to complete the trip is not more than 20% longer than the direct distance between origin and destination.

while some other are specialized for one subgroup of routes mainly driven by social, economic and historical relations with the area considered, e.g. Madrid to Latin America. Hourglass hubs connect long-haul routes located in opposite directions. They are mainly unidirectional (east-west, or north-south), but with excellent geographical position enabling them even to be multi-directional hub. Regional hubs connect short-haul routes.

As a result from traffic analysis for year 2003, eight principal geographical sub-markets are identified at the main European hub airports (Burghouwt, 2007):

1. Intra-European Union (EU) connections
2. Connections between EU and other European destinations
3. EU-intercontinental connections (five different regions are recognized[48])
4. Connections between non-European sub-markets

In addition four categories among European hubs are recognized, (Burghouwt, 2007)[49]:

1. Global all-around hubs serving long-haul to long-haul hub traffic (directional hubbing), short-haul to long-haul (hinterland hubbing) and short-haul to short-haul (regional hubbing), e.g. Frankfurt, London Heathrow, Amsterdam, Paris Charles de Gaulle;

2. Specialized hinterland hubs serving a specific segments of the hinterland hubmarket between the EU and extra-EU destinations, e.g. Munich, Lisbon, Paris Orly, Madrid;

3. Regional hubs (Eurohubs and mini-hubs) serving short-haul to short-haul connections between intra-EU destinations (more than 65% intra-EU). From a geographical perspective, these connections can be EU-wide (Euro-hub) or truly regional (mini-hubs), e.g. Oslo, Rome Fiumicino, Helsinki, Manchester; Lyon;

4. Directional or hourglass hubs serving the long-haul to long-haul market (extra-EU to extra-EU).

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[48] North America, Latin America, Asia and the Pacific, Africa and Middle East

[49] Examples are updated.

**European low-cost carriers' networks**

LCCs have established their point-to-point networks mainly between secondary and regional airports that were previously underutilized or even abandoned. In addition, they included traditional airport where adequate potential is foreseen. Constant growth of the Low-cost market is achieved by:

- Attracting new air travels, by taking over passengers from other non-competitive modes of transport, mainly on domestic routes,
- Inducing higher frequency of flying of current air passengers, but also to some extent taking over shares of traditional airlines passengers – by operating from nearby secondary airports with lower fares, or from main airports with weak home base carriers, and
- Taking over to large extent passengers from charter airlines – by operating from seasonal airports.

Some main common characteristics of low-cost networks are summarized by (Dobruszkes, 2006). For example on European market LCCs operate on short and middle-haul routes, spreading mainly over the Western Europe. Over the past years, they are also strengthening west-east connections (Dobruszkes, 2009). Looking for niches, LCCs established their services primarily at airports not operated by national carriers, being at the same time poorly connected to the rest of the country or region by other modes of transport (primarily rail services).

LCCs do not necessarily operate out of capital cities. In large countries there is a need for connecting the province with the capital city. On the other hand, some capital cities (e.g. in Central and Eastern Europe) may be poorly connected to Western Europe, due to being served by a weak national airline. In such case LCCs can complement the routes.

Relatively large low-cost networks have been developed from/to countries where charter flying was already successful (mainly north-south connections). LCCs do not systematically concentrate their demand, having the airports be regular entrance and exit points to/from the network, as opposed to being predominantly transfer/connecting points.

Considering the location of low cost airport, as well as volume and share, there are five types of airports serving the LCCs (Dobruszkes, 2006):

1. Medium or large traditional airports, e.g. Athens, Dublin, London Gatwick, Nice and Budapest;

2. Secondary urban airports of large cities, e.g. Rome Ciampino, London Stansted, London Luton and Milan Bergamo;

3. Regional airports in the wider vicinity of large cities, e.g. Hahn, Gerona and Liverpool;

4. Remotely located regional airports (used by airlines to access tourist areas),

5. Traditional airports of tourist zones, e.g. Malaga, Alicante, Faro, Palma de Mallorca and Porto.

**Changes/evolution of the European network**

The constantly growing LCCs market is based on successful competiveness with other markets and continuous opening of new opportunities. LCCs had significant influence on air transport networks evolution in the past, and they will most likely continue to have similar influence it in the future. It became evident that they did not intend to stick "only" to point-to-point networks they set up and strengthened over the time, but 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).

One of the examples of LCCs entrance into primary airports resulted from their readiness to take advantage of opportunities and take over (fully or to certain share) former hub airports after they suffered "de-hubbing". After an airport is abandoned as the home base by a traditional airline (due to bankruptcy, or decision to withdraw due to network restructuring/downsizing), some former hubs were recovered by LCCs that established their services at these airports. Redondi, et al. (2010; 2012) analyzed different examples of de-hubbing of the world airports (37 examples[50]) and their recovery scenarios (re-hubbed; recovered as: alliance-dominated, LCC dominated, unallied-dominated, or combination of these three, the so-called Battleground). The authors did not find any case of airport being re-hubbed by another carrier. Among other investigated scenarios for recovery of the former hubs, on average they did not show any trend towards recovery if they did not consider significant LCC entrance (LCC dominated or battleground lead by LCC)[51]. The only (European) exception is London Gatwick, which recovered without dominant presence of LCC. It may seem, however, that authors favor the impact of LCC in this paper. They did not identify any re-hubbed airports among European de-hubbed cases, while at the same time, in some other recent (even earlier date) analysis of European hubs (e.g. Deutche Bank Research, 2006; Malighetti et al., 2008; Malighetti, et al., 2009) Zurich and, in some cases, Brussels are categorized as hub airports.

Another example of LCC impact on network evolution relies on their readiness to widen their market in the direction of connecting traffic. LCCs try to enter primary airports to a greater extent (both hubs and non-hub airports of large cities), and they start to use the naturally created potential for developing indirect connections at their own strong basis, offering wider coverage to their passengers. For example (Malighetti et al., 2008) Skyeurope[52] introduced a link between Kosice and Bratislava aiming to offer additional connections. It does not coordinate its flights, but it gives certain "assurance" for interconnection. It reimburses the ticket or provides a seat on the next flight. The largest European low-cost airport, Stansted, offers so called "create your own connection" service to take advantage of potential for (not coordinated) indirect connections (Malighetti et al., 2008). LCC's "self-help" hubbing becomes possible at almost no extra cost for the airline. Wide network coverage, high frequencies and low fares, are motivating enough for customers to take advantage of random connections, even if LCCs do not foster this behavior (Franke 2004). Ryanair has announced plans to shift

[50] Major de-hubbing cases in Europe: Gatwick, Brussels, Zurich, Basel, Clermont-Ferrand, Barcelona and Milan Malpensa (source: Redondi et al., 2010).
[51] European examples are: Birmingham (FlyBe), Basel-Mulhouse (Easyjet Switzerland), East Midlands Nottingham (bmibaby), Glasgow (easyJet) and Milan Malpensa (easyJet).
[52] At that time it was leading LCC in the Eastern Europe. It suffered bankruptcy in 2009.

their activities to major airports (excluding only three busiest, Frankfurt, London Heathrow and Paris Charles de Gaulle, from its plans), (De Wit and Zuidberg, 2012).

Castillo-Manzano et al. (2012) analyzed and discussed network changes in Spain's market with large presence of LCCs at hubs. At first they confirm the "common belief" that LCCs do not have any negative effect on traditional airlines in the domestic market, because they attract new air passengers who might have changed from other modes of transport. In the international market, they recognized three different effects – two supplementary (external and internal) and one complementary. On intra-European routes it was identified that with the increase in low-cost flights from regional and secondary airports, the number of flights operated by traditional airlines from main hub airports to the same destination had fallen to a similar extent (external supplementary effect). When operating the same routes (mainly intra-European, but also small number of non-European routes) from both secondary airports and hubs, it is evident that LCCs provide tough competition to traditional airlines (internal supplementary effect). On the other hand, the often-neglected complementary effect is identified at hub airports for long-haul routes. Low-cost traffic between the hubs and other national airports boosts international traffic with Europe (non-European destinations), and to a lesser extent with the rest of the world. Therefore, low-cost national flights act as feeders to traditional airlines for their long routes, reinforcing the role of the hub in the airport system to an even greater extent. It is not a usual practice but there are some examples of formalized agreements on collaboration, e.g. between Vueling and Iberia for feeding long haul flights in Madrid. The presence of LCCs at hub airports have an additional advantage for low-cost passengers, offering them a wider variety of connections.

De Wit and Zuidberg (2012) list other codeshare agreements between LCCs and home based carriers at major hubs: WestJet and Air France-KLM; JetBlue and Lufthansa and Jetstar Airways and American Airlines. They even see further development towards LCCs starting their own hub operations, as Vueling recently did at Barcelona.

The intensive and constant breakthroughs of LCCs into the market may be construed as something that will be a serious threat to the hub-and-spoke concept of full-service carriers, if they do not respond adequately to the changing environment (thoroughly discussed by Franke 2004).

The present situation shows many positive effects of LCCs, while some negative ones may also be foreseen. Recovery of hubs after being abandoned by their home-base airline is certainly a positive outcome. Increased presence of LCCs at hub airports is also primarily positive. On one hand, LCCs provide additional passengers for traditional airlines on long-haul routes. On the other hand, they may offer a wider range of connections to their own passengers (who are willing to wait longer). From the airport's perspective LCCs increase capacity utilization by operating primarily in off-peak periods.

Some (at the moment isolated) examples show that LCCs are attempting to set up their own hub operation e.g. Vueling, as mentioned above. The other is Ryanair's attempted to take over Air Lingus in order to set up connections between European LCC routes and long-haul to North America, through its Dublin hub (de Wit and Zuidberg, 2012). Another example (by same authors) to prove increased pressure by LCCs on the long-haul market is Japanese Skymark Airlines as the first airline to order the A380.

On the other hand, full-service carriers are protecting their long-haul markets by merging and operating multi-hub systems. The current state of the European network for long-haul routes: Air France-KLM operate from Paris CDG, Amsterdam and to a very small extent from Lisbon; Iberia-British Airways from London Heathrow, Madrid, Barcelona and to a small extent from London Gatwick; and Lufthansa Group (as the largest) from various airports: Frankfurt, Munich, Vienna, Zurich, Brussels, and to very small extent from Dusseldorf, Rome Fiumicino and Milan Malpensa (Burghouwt, 2013).

The hubbing itself does not seem to be endangered, as it is indispensable (at least) for long-haul routes. Kraus and Koch (2006) argue that "the concept of consolidating traffic at major airports will remain the dominant approach in the foreseeable future". Those who operate might change. To survive in the competitive environment, both LCCs and full-service carriers will most probably need to introduce certain changes to their original business models (Franke, 2004).

**Appendix 2 – Airport categorizations accounting for hubbing**

Deutsche Bank Research (2006):

1. *Mega-hubs*, through which the big, financially strong scheduled carriers and the strategic alliances organize their business. Given their large catchment area they are also attractive for point-to-point traffic (especially London and Paris), but are too expensive for many LCCs.
   European examples: London-Heathrow, Paris Charles de Gaulle, Frankfurt am Main and, to a lesser extent, Amsterdam and Madrid.

2. *Secondary hubs*, which have an attractive catchment are function both as feeder airports for mega-hubs as well as for small partners of a strategic alliance or else have a hub function for certain regions. They are not overly large size in comparison with mega-hubs. These airports can be affected by the consolidation in air transport if smaller airlines using the airport as a hub are taken over by larger ones. At the same time, though, the free capacities are linked with opportunities to win new customers (scheduled, low-cost and charter carriers).
   European examples: Barcelona, Copenhagen, Lisbon, Manchester, Milan, Munich, Oslo, Rome, Stockholm, Vienna and Zurich.

3. *Secondary airports*, which basically have an attractive catchment area, are important for feeding traffic into the big hubs and offer a certain number of direct scheduled connections, although intercontinental flights are the exception here. In principle, they are attractive also for the LCCs. The airports have no (or merely a rudimentary) hub function.
   European examples: Berlin-Tegel, Bilbao, Birmingham, Cologne, Dusseldorf, Geneva, Hamburg, Lyon, Nice, Turin and Valencia.

Buyck, C. (2008) (cited in: EC, 2008):

1. *Intercontinental or Primary Hub.* Airport with at least one based network carrier offering connecting opportunities. The airport offers numerous long-haul

destinations (at least 20), which are not necessary all operated by the home carrier.

Examples include London Heathrow, Beijing Capital, Chicago O'Hare, Dubai International and Mexico City.

2. *Secondary Hub.* Airport with at least one based network carrier offering connecting opportunities. The airport offers several intercontinental routes and/or numerous medium-haul routes.

   Examples include Denver, Istanbul, Brussels, Dublin and Amman.

3. *Regional platform.* Airport that is not a hub and thus traffic is mainly point-to-point. The airport traffic is focused on short/medium-haul routes.

   Examples include Barcelona, Cancun and Fukuoka.

4. *LCC base.* Airport with at least one based LCC. International hubs and regional platforms all can be an LCC base as well.

Burghouwt, G. (2007):

1. *1st tier airports* - are the primary home bases of carriers that operate on a global or continental scale. The home carrier may or may not (due to saturation) operate a wave-system structure at such an airport.

2. *2nd tier airports* - are somewhat smaller airports in terms of the indirect connections generated compared with the 1st tier airports. These airports are the home bases of at least one home carrier that operates a specialized hinterland, a European, or directional hub/traffic node. A wave-system structure may or may not be present here.

3. *3rd tier airports* - Most of them are the home base of at least one airline operating a European traffic node or hub. Apart from a few exceptions, no wave-system structure can be found at these airports. They are used as secondary or tertiary nodes in networks of large airlines and as primary nodes in the networks of smaller airlines.

4. *4th tier airports* - home based airlines offer only very few indirect connections. Most of them are used as secondary or tertiary nodes in airline networks. No wave-system structure is present.

5. *5th tier airports* - are the smallest airports in the airport hierarchy and do not offer any significant amount of indirect connections. They do not have an intermediate function in the aviation network, but are the terminal destinations for virtually every air passenger. For a hub-and-spoke airline, such airports may function as spokes in the route network. 5th tier airports cover a wide range of airports.

However, this categorization is based on weighted indirect connection number (WNX) derived based on traffic statistics from the year 1999. It does not reflect current state which is confirmation of constantly evolving air-transport networks.

Malighetti et al. (2009) clustered European airports in eight clusters, as follows:

1. *Worldwide hubs* (8 airports) - Airports served by worldwide alliances. They have similar dimensional characteristics, especially in terms of density and intensity. They have a high percentage of overseas destinations and can offer a wide range of opportunities for interconnectivity.
   Examples: London Heathrow, Paris Charles de Gaulle, Amsterdam, Frankfurt, Rome Fiumicino.

2. *Hubs* (16 airports) - Airports are mainly former flag carrier hubs and secondary medium or large-size hub airports. These airports tend to favor European routes (on average 75% of the routes are within Europe) and are served by a variety of LCCs.
   Examples: Athens, Vienna, Zurich, Brussels, Stockholm Gatwick, Orly, Milan Malpensa, London Stansted.

3. *Secondary gates* (11 airports) – Airports of medium-size dimensions and offer a limited number of overseas destinations (less than 30% of the routes offered), with a visible concentration of traffic distribution over a limited number of

destinations. Their role as intermediate connections further confirms their main function as gates for local areas.
Examples: Lisbon, Glasgow, Venice, Warsaw and Marseille.

4. *Airports* with 3-5 million passengers per year (33 airports). They have a high concentration of LCCs (covering 75% of the seats offered, on average). The main destinations are generally non-domestic and European (only 15% of the destinations are domestic, against an average of European destinations higher than 90%).
   Examples: Bergamo Orio al Serio, Ciampino and Pisa.

5. *No low-cost gates* (46 airports). The term "gate" here refers to the European rather than overseas market. This cluster seems to be less homogeneous than all the previous clusters. Destinations here are almost always European. LCCs play a minor role and routes are mainly domestic and intended to connect secondary airports within the country. Some airports may be connecting points between hub and secondary airports, as can be seen from the average of the limited % index (up to 63%) and from the existence of a number of heavily flown routes along with less demanded flights (the index of distribution of the routes is higher here than in any other cluster).
   Examples: Milano Linate, Palermo and Valencia.

6. *Regional airports* (44 airports). This cluster is made of smaller, mainly regional airports. As is the case with the previous cluster, it is not very compact.

7. *Airports for LCCs mainly* (71 airport). This cluster consists of airports dimensionally similar to cluster 6, but mainly featuring a large presence of LCCs, determining a wide offer of European rather than domestic destinations.

8. *Local airports* (238 airports). This is the largest cluster and is made up of local airports. Their offer is often limited to a restricted number of routes, only rarely more than 4 or 5, generally touching domestic destinations; LCCs are seldom found to operate here and are absent in more than 75% of the airports listed in this category.

Airport categorization by Munich Airport (cited in: Oettl and Boeck, 2012):

| Airport type | Examples | Characteristics |
|---|---|---|
| International Hubs | FRA, LHR | Transfer hub for intercontinental traffic;<br>Global service area;<br>Major node for alliances;<br>More than 40 million pax per year (2008). |
| Secondary Hubs | MUC, VIE | Hub with mainly traffic within Europe;<br>Service area mainly concentrated to Europe, partially global possible;<br>Secondary node for alliances;<br>more than 15 million pax per year. |
| International O/D | TXL, GVA | Traffic mainly within Europe;<br>Regional service area;<br>Few long-range destinations;<br>More than 5 million pax per year. |
| Regional O/D | SZG, TRD | Feeding traffic to hubs, several direct destinations and/or low-cost destinations;<br>Local service area;<br>Less than 5 million pax per year. |
| Secondary O/D | HHN, OLB | Signifficant low-cost traffic;<br>Produst differentiation against other airports;<br>Local to regional service area. |

## Appendix 3 – European seasonal airports

Typical European seasonal airports representatives (source: Eurocontrol, 2007) are listed in Table A3-1.

Table A3-1. European seasonal airports in 2006

| | ICAO code | Country | Median Depart. | Airport size (Thousand Annual DEPs) | Peak date (2006) | Week day | Max Dep./ Med Dep. | Peak Description |
|---|---|---|---|---|---|---|---|---|
| Ioannis/ Kapodistrais | LGKR | Greece | 11 | 5 – 10 | Aug.26 | Sat | 8.4 | W&S* |
| Burgas | LBBG | Bulgaria | 9.5 | 5 – 10 | Jul.25 & Aug.8 | Tue | 7.9 | W&S |
| Split | LDSP | Croatia | 15 | 5 – 10 | Jul.22 & Aug.12 | Sat | 6.3 | W&S |
| Kos | LGKO | Greece | 11 | 5 – 10 | Aug.2 | Wed | 6.2 | W&S |
| Mugla-Dalaman | LTBS | Turkey | 17 | 5 – 10 | Aug.28 | Mon | 6.2 | W&S |
| Milas/Bodrum | LTFE | Turkey | 16 | 5 – 10 | Aug.14 | Mon | 6.0 | W&S |
| Varna | LBWN | Bulgaria | 11 | 5 – 10 | Jul.21 & Aug.11 | Fri | 5.8 | W&S |
| Cannes Mandelieu | LFMD | France | 17 | 5 – 10 | May.29 | Mon | 4.5 | Spec. event |
| Dubrovnik | LDDU | Croatia | 16 | 5 – 10 | Jun.25 | Sun | 4.2 | W&S |
| Tempelhof-Berlin | EDDI | Germany | 43 | 10 – 20 | Jul.10 | Mon | 6.8 | Spec. event |
| Olbia Vosta Smeralda | LIEO | Italy | 26 | 10 – 20 | Jul.23 | Sun | 5.2 | W&S |
| Diagoras | LGRP | Greece | 30 | 10 – 20 | Jul.16 | Sun | 4.8 | W&S |
| Mahon/ Menorca | LEMH | Spain | 31 | 10 – 20 | Aug.4 | Fri | 3.5 | W&S |
| Innsbruck | LOWI | Austria | 26 | 10 – 20 | Feb.25 | Sat | 3.1 | W&W ** |
| Salzburg | LOWS | Austria | 43 | 10 – 20 | Feb.18 | Sat | 3.0 | W&W |
| Madeira | LPMA | Portugal | 25 | 10 – 20 | Jan.2 | Mon | 2.9 | Spec. event |
| Ibiza | LEIB | Spain | 49 | 20 – 50 | Aug.20 | Sun | 4.4 | W&S |
| Schoenefeld-Berlin | EDDB | Germany | 79 | 20 – 50 | Jul.10 | Mon | 3.0 | Spec. event |
| Nikos/ Kazantzakis | LGIR | Greece | 54 | 20 – 50 | Aug.4 | Fri | 2.8 | W&S |
| Paris le Bourget | LFPB | France | 85 | 20 – 50 | May.18 | Thu | 2.7 | Spec. event |
| Antalya | LTAI | Turkey | 119 | 20 – 50 | Aug.5 | Sat | 2.5 | W&S |
| Arrecife Lanzarote | GCRR | Spain | 59 | 20 – 50 | Oct.26 | Thu | 2.2 | Weekly seasonality |
| Palma de Mallorca | LEPA | Spain | 258 | 50 – 100 | Aug. 5 | Sat | 2.0 | W&S |
| Nice | LFMN | France | 187 | 50 – 100 | May. 29 | Mon | 1.7 | Spec. event |
| Manchester | EGCC | UK | 306 | 100 – 200 | Aug. 25 | Fri | 1.3 | W&S |

* W&S – Weekly and summer seasonality

** W&W – Weakly seasonality, stronger in winter

The share of the monthly number of departures in the number of annual departures is given in Figure A3-1, for seven seasonal AENA airports (Mirkovic et al. 2013).

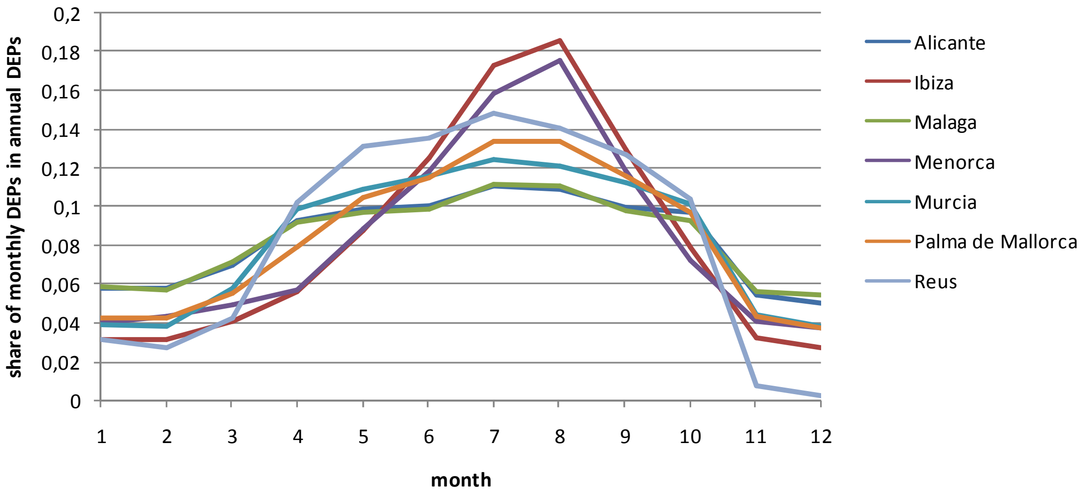



Figure A3-1 - Monthly share in total number of departures in 2011 compiled from AENA Estadisticas (Mirkovic et al. 2013)

These airports fall into different size categories: Palma de Mallorca and Malaga – 10 to 25 million passengers; Alicante and Ibiza – 5 to 10 million passengers; Menorca, Murcia and Reus – 1 to 5 million passengers. There is a clear difference between high season (usually from the 4$^{th}$/5$^{th}$ to the 9$^{th}$/10$^{th}$ month of the year) and off-season traffic. Depending on the airport, the difference is smaller (Alicante and Malaga) or larger (Palma de Mallorca, Murcia and Reus), or even extremely pronounced in some cases (Ibiza and Menorca).

**Appendix 4 – Minimum connecting times – examples at the world's airports**

| AMS - Amsterdam Schiphol | ATL - Hartsfield-Jackson |
|---|---|
| Domestic to Domestic - 25 minutes<br>Domestic to International/Europe - 50 minutes<br>Domestic to Europe - 40 minutes<br>International to Domestic - 50 minutes<br>Europe to Domestic - 40 minutes<br>International to International - 50 minutes<br>Within Europe - 40 minutes | Domestic to Domestic - 55 minutes<br>Domestic to International - 1 hour<br>International to Domestic - 1 hour 30 minutes<br>International to International - 1 hour 30 minutes |
| **BKK - Bangkok International** | **BCN - El Prat** |
| Domestic to Domestic - 30 minutes<br>Domestic to International - 2 hours<br>International to Domestic - 2 hours<br>International to International - 1 hour 15 minutes | Domestic to Domestic - 30 minutes<br>Domestic to International - 45 minutes<br>International to Domestic - 45 minutes<br>International to International - 45 minutes |
| **BOS - Logan International** | **ORD – Chicago O'Hare International** |
| Domestic to Domestic - 40 minutes<br>Domestic to International - 1 hour<br>International to Domestic - 1 hour 30 minutes<br>International to International - 1 hour 15 minutes | Domestic to Domestic - 50 minutes<br>Domestic to International - 1 hour 15 minutes<br>International to Domestic - 1 hour 30 minutes<br>International to International - 1 hour 30 minutes |
| **CPH - Copenhagen** | **DFW - Dallas/Ft Worth International** |
| Domestic to Domestic - 30 minutes<br>Domestic to International - 45 minutes<br>International to Domestic - 45 minutes<br>International to International - 45 minutes | Domestic to Domestic - 50 minutes<br>Domestic to International - 50 minutes<br>Domestic to Canada - 50 minutes<br>International to Domestic - 1 hour 10 minutes<br>Canada to Domestic - 50 minutes<br>International to International - 1 hour 10 minutes |

Source: Airtravel about (2013)

Munich Airport (2013): within T2 - 30 minutes

Vienna Airport (2013): for Star Alliance flights - 25 minutes

Timisoara Airport (Carpatair, 2013): Carpatair flights - 20 minutes

**Appendix 5 – Indirect connectivity indices**

Dennis (1994) calculated connectivity ratio, as the ratio between the total number of viable connections offered at the airline hub during a typical airline operational day (15 hours) and approximate number of viable connections that would be expected in the case of a random timetable. A viable connection is considered the one that fulfills criteria of MCT of 45min and MaxCT of 90min. If scheduling is not better than random overall, the ratio is 1.

Danesi (2006) proposed a weighted connectivity ratio, by combining Dennis' (1994) and Burghouwt and de Wit's (2005) approaches. He introduced intermediate connecting time (ICT), which is between MCT and MaxCT. For all possible arrival-departure connections at an airline hub during the day, temporal and spatial weights are assigned. In temporal connectivity matrix weight 1 is assigned to all connections with transfer time between MCT and ICT, weight 0.5 if transfer time is between ICT and MaxCT, and weight 0 if transfer time is longer than MaxCT. Similarly, in space connectivity matrix weights (0, 0.5 and 1) are assigned to all connections based on the de-routing index (ration between great circle distance of the direct route and great circle distance of the indirect route). Multiplying temporal and spatial connectivity matrices gives a weighted connectivity matrix. Summarizing all values from the weighted connectivity matrix gives a weighted number of viable connections offered by the airline hub during a typical airline operational day. The approximate number of viable connections in the case of purely random timetable is calculated somewhat differently, as they include ICT in addition to MCT and MaxCT. Their ratio finally yields the weighted connectivity ratio.

Malighetti et al. (2008) suggested an approach to estimate the potential for indirect connectivity and analyzed how much of it was already used by the main global alliances: One World, SkyTeam and Star. An approach is based on the connectivity index (calculated as the average of the minimum paths between a certain airport and all other airports in the network). In order to take in account centrality of the airport, "betweenness" (the number of minimal paths within the entire network to pass through a certain airport) and "essential betweenness" (the number of unavoidable minimal paths passing through a certain airport) are determined. In addition, the average minimum travel times, based on flight time and waiting time (fewest possible connections), is determined, assuming a minimum connecting time of 60min and no constraints on maximum connecting time (it is reasonable considering they investigate potential).

The extent potential indirect connectivity is used by the alliances, based on the average number of fastest paths passing through each of 20 best connected airports (all connections, two-step connections, as well as connections fulfilling the condition of connecting time between 1h and 3h are considered) was analyzed. Authors stressed that possible indirect connectivity is only partially exploited by alliances (2/3 remain unexploited).

**Appendix 6 – Evolution of wave-system in 1990s: Example of Munich Airport**

Burghouwt (2007) applied a theoretical approach to identify presence of wave-system structures at European hub airports. Hypothetical ideal wave is identified based on minimum connecting time of 40min and maximum acceptable connecting time of 90min. The wave center (C) moves forward in steps of six minutes and the number of flights within arrival (C-45, C-20) and departure (C+20, C+45) windows for the specific wave center are counted respectively. An actual wave centre (C) is identified when the maxima of the waves for arriving and departing flights (almost completely) coincide.

An example illustrating wave-structure evolution during the 1990s is shown in Figure A6-1. The number of waves the airline operates and the number of aircraft per wave are clearly visible.

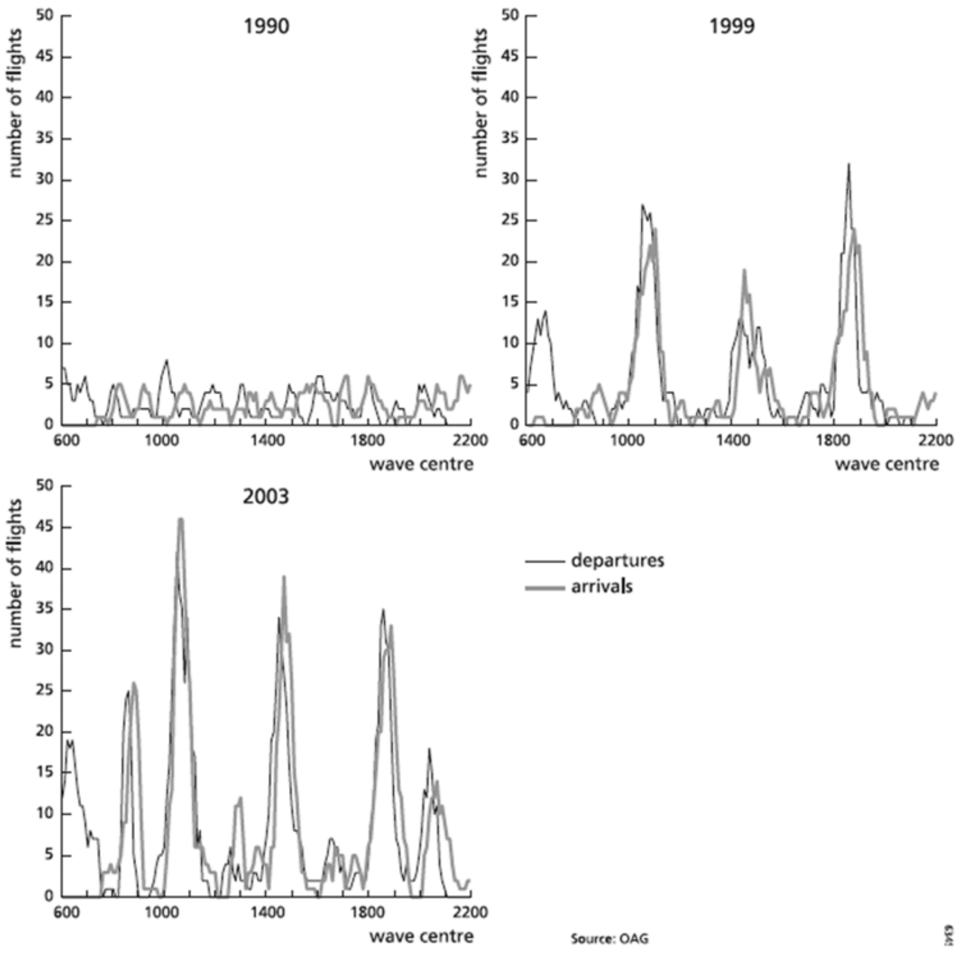



Figure A6-1. Wave-structure evolution at Munich Airport, Germany (Burghouwt , 2007)

However, with this approach, information about the exchange between the arrival time window and the departure time window is somehow lost. They appear as overlapped, which is not the case. Traffic patterns at (Lufthansa's) Terminal 2 at Munich Airport, for summer 2000 and 2005 are given in Figures A6-2 and A6-3, respectively (source: Munich Airport[53]).

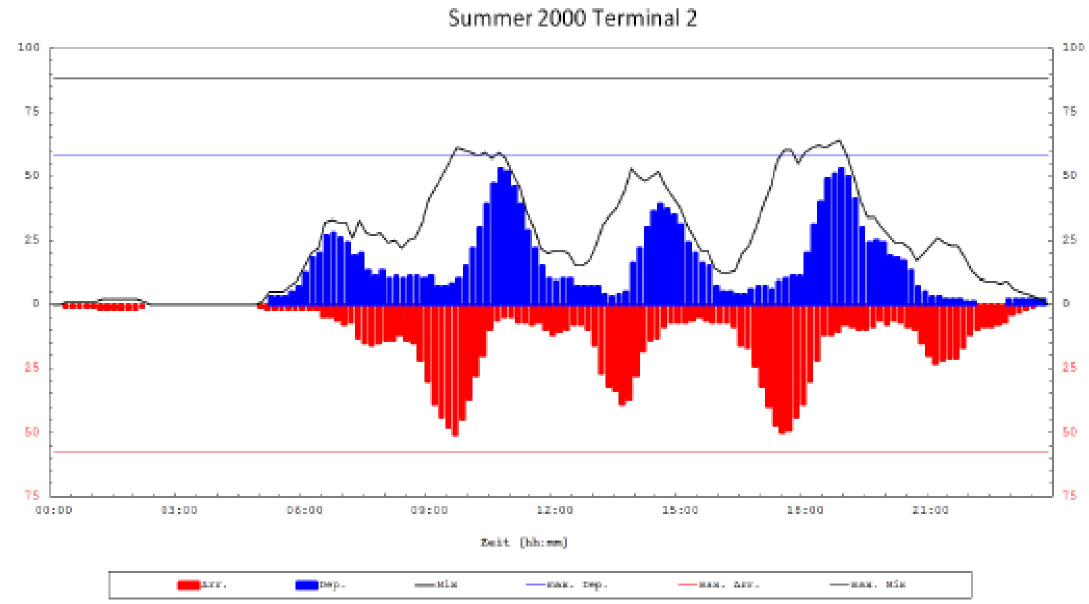



Figure A6-2. Lufthansa's wave-system structure at Munich Airport Terminal 2, summer 2000 (source: Munich Airport)

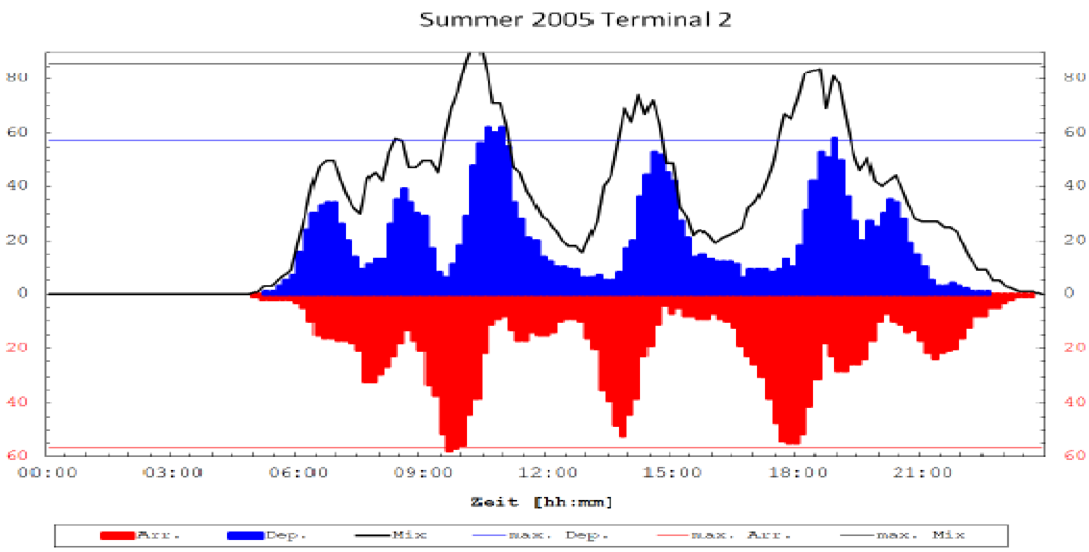



Figure A6-3. Lufthansa's wave-system structure at Munich Airport Terminal 2, summer 2005 (source: Munich Airport)

[53] Provided through the courtesy of Michael Hoehenberger, Head of Operational Planning at MUC

**Appendix 7 – Selected definitions of peak hour and design day**

Selected definitions of Peak Hour (de Neufville and Odoni, 2002; Ashford et al, 2013):

- Standard busy rate - the 30th busiest hour of the year; also 20th or 40th busiest hour of the year,
- Typical peak hour (passengers) - the peak hour of the average day of the peak month of the year; also the peak hour of the average day of the two peak months of the year,
- The peak hour of the 95th percentile busy day of the year, i.e. the peak hour of, roughly, the 18th busiest day of the year; also the peak hour of the 7th or 15th busiest day of the year,
- Busy-hour rate - the “5 percent busy hour,” i.e., an hour selected so that all the hours of the year that are busier handle a cumulative total of 5 percent of annual traffic,
- The peak hour of the 2nd busiest day during the average week in a peak month,
- Peak profile hour or average daily peak – largest hourly volume in the average peak day of the peak month,
- Busiest timetable hour – calculated from average load factor and existing/projected timetable (for small airports with limited data bases).

The U.S. FAA uses peak hour of the average day of the peak month of the year. The ICAO recommends the peak hour of the average day of the two peak months of the year (de Neufville and Odoni, 2002). In the United Kingdom (U.K. BAA – British Airports Authority) before busy-hour rate was introduced, standard busy rate (mainly) and peak profile hour (in some cases) were used. Aeroports de Paris use 3 percent busy hour. Dutch airports use the sixth busiest hour, which corresponds to average of the 20 highest hours (Ashford et al, 2013).

ACRP report (TRB, 2013) stated that the most common current practice in the U.S. is to define the design day as peak month average day. It is calculated by identifying the month with the highest number of operations and/or passengers, and then dividing the operations or passengers in that month by the number of days in the month. There are several other design day definitions in use:

- The average week day in the peak month,
- The 15th busiest day of the year,
- The 30th busiest day of the year,
- The 90th percentile—corresponds to the 36th busiest day of the year.

Peak month average day is easy to calculate but it can generate very different design day thresholds from airport to airport, ranging from 20th or 15th busiest day of the year, at an airport with high seasonality to even 100$^{th}$ or 150$^{th}$ busiest day of the year, at an airport with low seasonality, especially one with some day of the week variation in activity.

ACRP report discusses several ways of estimating future design day profiles by:

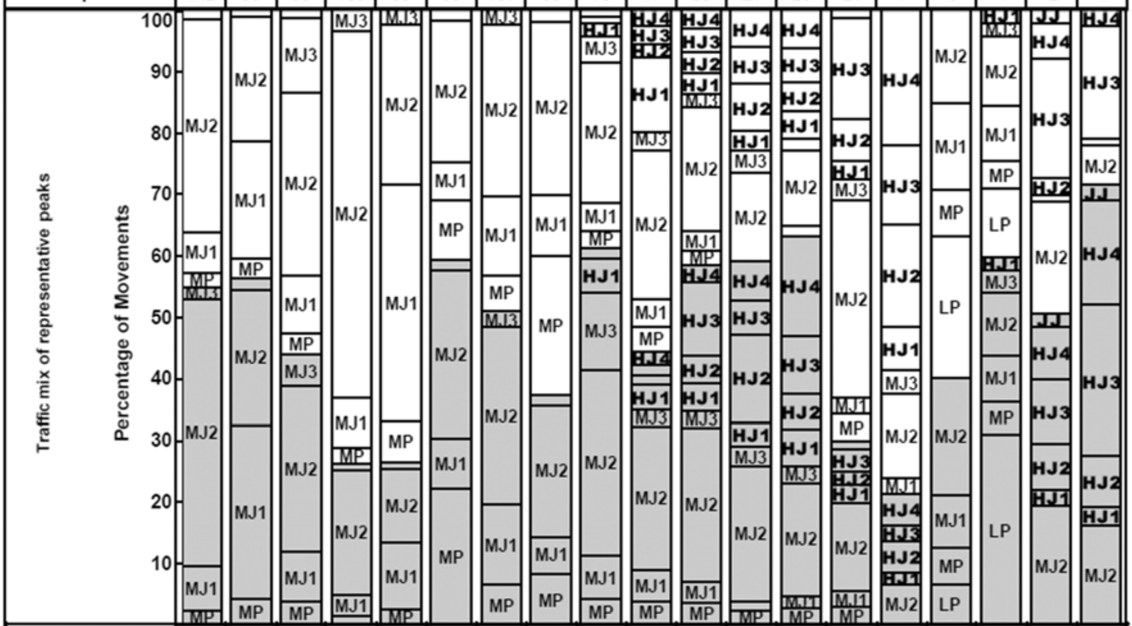
1. Assuming the base year distribution of daily activity will carry forward unchanged into the future.
2. Assuming the peak spreading component based on relationships between airport size and peak period percentage. This dampens the peaks and fills in the gaps in the daily schedule.
3. Generating daily profiles by category of activity (i.e., domestic and international passengers), project each profile to grow at the annual rate of the corresponding activity category, and then aggregate the results to generate an estimated future daily profile.
4. Aggregating a daily profile from a design day schedule.

On the other hand, design day schedule is prepared by modifying an existing schedule to include assumptions on new markets, additional frequencies, and fleet mix changes. In some instances daily profiles are derived from design day schedules. In other instances, previously derived daily profiles are used to guide the addition of flights for future design day schedules. The design day forecast provides control totals for passengers and aircraft operations.

## Appendix 8 – Custer analysis of the world's airports with respect to traffic parameters

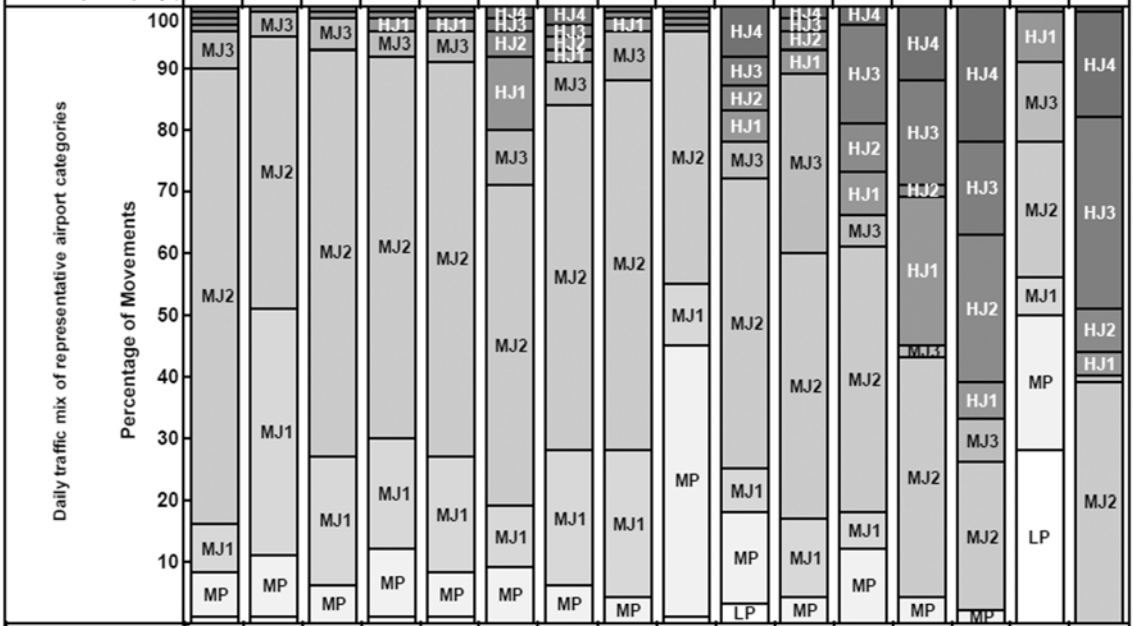
Oettl and Reeb (2012) analyzed 203 airports around the world with more than 18 operations per hour. Seven consecutive days of scheduled operations data (obtained from: OAG, 2008) were taken into consideration. In the clustering process each day is treated as a separate airport, since hourly traffic distribution may significantly differ between the days of the week. Representative peak periods and type of airports with respect to traffic parameters are shown in Figure A8-1 and Figure A8-2, respectively.

| Cluster number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Num. peaks | 2839 | 2002 | 897 | 818 | 808 | 792 | 780 | 772 | 669 | 409 | 326 | 202 | 183 | 165 | 85 | 83 | 74 | 17 | 15 |
| Num. airports | 142 | 96 | 86 | 109 | 68 | 60 | 137 | 63 | 70 | 47 | 39 | 21 | 26 | 21 | 7 | 6 | 4 | 2 | 1 |




| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Duration [h] | 2.4 | 2.6 | 2.5 | 2.8 | 2.8 | 2.5 | 6.9 | 2.6 | 2.8 | 3.1 | 2.6 | 2.5 | 2.7 | 2.6 | 3.6 | 2.6 | 2.4 | 5.0 | 3.8 |
| Fill factor [%] | 54 | 54 | 55 | 54 | 53 | 54 | 51 | 53 | 54 | 53 | 53 | 55 | 56 | 55 | 55 | 50 | 52 | 55 | 48 |
| Rel. amplitude [%] | 41 | 49 | 43 | 59 | 61 | 49 | 58 | 51 | 49 | 46 | 44 | 41 | 42 | 55 | 54 | 54 | 55 | 48 | 45 |

Figure A8-1. Representative peak periods (Oettl and Reeb, 2012)




| Cluster number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Num. airports (7 days) | 263 | 255 | 129 | 123 | 120 | 71 | 70 | 62 | 52 | 51 | 38 | 36 | 35 | 28 | 26 | 7 |
| Total peaks | 3 | 3 | 4 | 6 | 4 | 3 | 2 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 3 | 3 |
| Arrival peaks | 3 | 3 | 5 | 3 | 6 | 3 | 4 | 2 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Departure peaks | 3 | 3 | 5 | 3 | 2 | 3 | 3 | 2 | 4 | 2 | 3 | 3 | 2 | 2 | 2 | 2 |
| Fill factor [%] | 61 | 61 | 70 | 66 | 65 | 63 | 81 | 42 | 62 | 70 | 65 | 57 | 59 | 62 | 52 | 72 |
| Relative load [%] | 17 | 16 | 30 | 23 | 22 | 21 | 64 | 15 | 19 | 22 | 20 | 13 | 23 | 19 | 13 | 20 |
| Rel. night rest [%] | 88 | 87 | 80 | 92 | 90 | 89 | 76 | 101 | 94 | 41 | 86 | 99 | 99 | 80 | 100 | 46 |

Figure A8-2. Airport categories with respect to traffic parameters (Oettl and Reeb, 2012)

In addition Figure A8-3 gives the results from a trial to categorize airports with respect to additional traffic parameters related to users and the type of traffic (Oettl and Boeck, 2012).

The parameters selected to describe category of European hubs are:

- available seats to destinations within Europe (ASE);
- share of hub carrier alliance(s) (HAL);
- aircraft size described through share of heavy aircraft (HVY);
- flight distances: Short Range (SR≤1500 km), Medium Range (1500 km <MR< 3000 km), Long Range (LR> 3000 km);
- share of airline types: Home Carrier (HC), Flag Carrier (FC), Intercontinental Carrier (IC), Low Cost and Charter Carrier (LC).

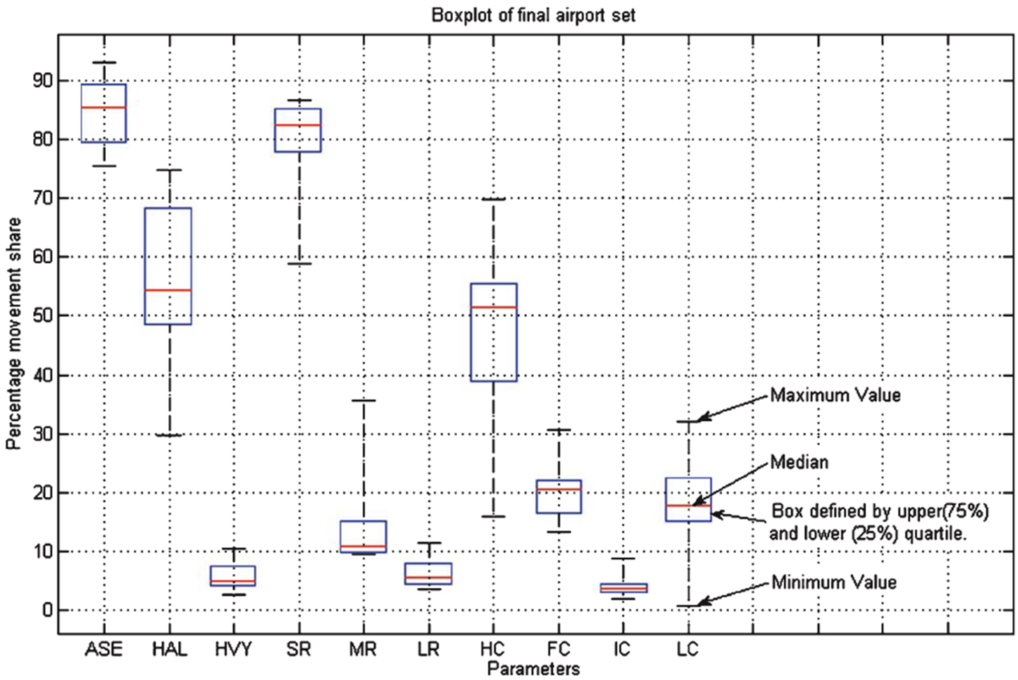



Figure A8-3. Traffic parameters for selected group of European hubs (Oettl and Boeck, 2012)

**Appendix 9 – Models for optimizing available resources utilization**

Before making huge infrastructural investments to expand their existing capacity, airports can do something to increase efficiency of capacity utilization.

In the past 20 years, when it was obvious that airports were becoming the most critical area in the air transport network in terms of capacity-demand imbalance, many decision support tools for available (limited) airport resources management have been developed, tested and introduced in practice. As expected, the first tools were developed for runway system capacity management, since the major bottlenecks on the airside come from the runways.

It began with AMANs (Arrival Manager-s), which were developed to support arrival sequencing in order to increase runway throughput and avoid generation of delays in peak periods (e.g. Beasley et al. (2000); Venkatakrishnan et al. (1993); one of the commercial solutions: CALM - Computer-assisted Approach and Landing Management, developed by Barco, for Zurich Airport; Barco (2004)). Then, a series of DMANs (Departure Manager-s) were developed, for sequencing departing aircraft in order to minimize waiting time and queue lengths (e.g. Anagnostakis et al. (2000); Boehme (2005); Feron et al. (1997); Hasselink and Basjes (1998); Jonge et al. (2005)). Coordination between AMANs and DMANs followed (e.g. Boehme et al. (2007)), as well as the development of SMANs (Surface Managers) (e.g. Atkins and Brinton (2002); Lowson (1997)), for surface movement optimization and TMANs (Turnaround Managers) for turnaround process optimization (one of the commercial solutions: GS Hub Control, Inform (2013)).

The general tendency is to integrate all those managers into a single overall manager aimed at optimization of available resources utilization or exploitation from the viewpoint of all stakeholders throughout (Airport) Collaborative Decision Making (e.g. Guenther et al. (2006) describing the operational concept and logical architecture of TAM - Total Airport Management; Pick (2007), describing test results of CLOU - Co-operative Local resOUrce planner, at Frankfurt Airport; Pina *et al.* (2005), presenting research results on LEONARDO - Linking Existing on Ground, Arrival and Departure Operations, tested at Madrid Barajas Airport).

Based on the existing tools, it is clear that the optimization of airport airside utilization is mainly focused on the runway system. Not only on arrivals and departures managers, but other optimization tools (optimization of surface movements and the turnaround process) also aimed at achieving better runway system utilization. They are locally focused on certain airside elements, but, when integrated, they have a common goal function, which is runway performance improvement. There is no such optimization tool focused on improving the efficiency of apron resources (stands and gates) utilization. At least, not the ones that observes aprons as part of the airside.

The majority of apron optimization tools observe the apron (precisely contact stands i.e. gates) from the perspective of the terminal complex (landside).

A very common, and widely addressed, optimization problem in the area of apron utilization optimization is the gate assignment problem (optimization of gate/stand utilization). Many papers deal with this issue (some of the earliest: Babic *et al.* (1984), Mangoubi and Mathaisel (1985), Hamzawi (1986); and one of latest: Genc et al. (2012)). The majority of them are based on the minimization of passenger walking distances from check-in to gate and from gate to baggage claim area, as well as from gate to gate for transfer passengers. Cheng (1997); Haghani and Chen (1998); Dorndorf et al. (2007) give a thorough literature overview on research results in this area, classified by methods, goal functions, etc. These models result in aircraft stand assignment schemes considering the contact stands (gates) from the perspective of the landside. The objective is to improve and maintain a certain level of service in the terminal building.

Ding et al. (2005) expand the gate assignment problem by considering over-constrained cases, where the number of aircraft exceeds the number of available gates. They address both the objectives of minimizing the number of ungated aircraft and minimizing total walking distances.

**Appendix 10 - Comparison of the analytical model and FAA graphical method**

For quick estimation of apron-gate capacity U.S. FAA has proposed graphical method (FAA, 1983). An example from AC 150/5060 is used and the results from graphical approach are compared to results from the extended analytical model.

<u>*Example 6, from AC 150/5060*</u>: An apron has 10 stands allocated to three airlines, X, Y and Z. Apron X has 4 stands for small (narrow-body) aircraft and 1 stand for large (wide-body) aircraft, apron Y has 2 stands for small and 1 for large aircraft and apron Z - 2 stands for small aircraft. During an hour, airline X schedules 13 small aircraft with an average stand occupancy time (SOT) of 45min, and 2 large aircraft with an average stand occupancy time of 55min. Airline Y schedules 8 small (SOT=40min) and airline Z 4 small aircraft (SOT=35min).

When the numbers of flights are expressed by the shares in total demand, as given in Table A10-1 (Column 4), extended apron capacity model provides the following results:

Table A10-1. Demand structure and average stand occupancy times in Example 6

| number of stands | user | aircraft class | share in population (%) | avg. stand occupancy time (min) |
|---|---|---|---|---|
| 4 | airline X | 1 | 48 | 45 |
| 1 | | 2 | 7 | 55 |
| 2 | airline Y | 1 | 30 | 40 |
| 1 | | 2 | 0 | 0 |
| 2 | airline Z | 1 | 15 | 35 |

$$C = \min\left(C_{11}, C_{12}, C_{21}, C_{31}\right)$$

$$C = \min\left(\frac{4+1}{0{,}48 \cdot 45 + 0{,}07 \cdot 55} \cdot 60, \frac{1}{0{,}07 \cdot 55} \cdot 60, \frac{2+1}{0{,}3 \cdot 40} \cdot 60, \frac{2}{0{,}15 \cdot 35} \cdot 60\right)$$

$$C = \min(11{,}8;15{,}6;15;22{,}8) = 11{,}8 \quad aircraft/h$$

Apron capacity is limited by the first (of four) group of stands.

The FAA's graphical method, shown in Figure A8-1, estimates apron-gate capacity expressed in movements/h as: $G^* \cdot S \cdot N$ , where: $G^*$ is the hourly gate capacity base, $S$ is the gate size factor and $N$ is the number of gates.

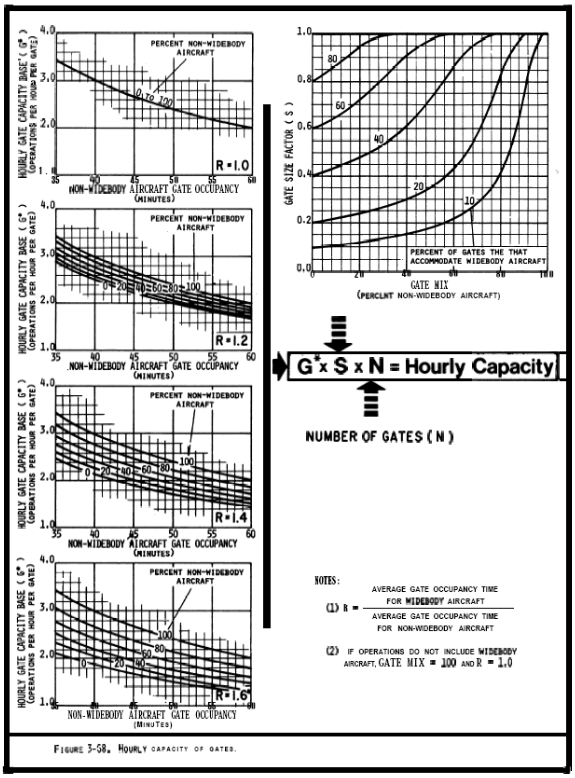



Figure A10- 1. FAA's graphical method for calculating gate capacity (FAA, 1983)

For the given example (Table A10-2) apron-gate hourly capacity is: 13 movements/h for apron X, 9 movements/h for apron Y and 7 movements/h for apron Z. Overall apron-gate capacity is estimated (incorrectly) as a sum of these three capacities which makes 29 movements/h.

Table A10-2. Parameters derived for graphical approach in Example 6

| Gate group | Demand | | No. Gates | | Gate mix | | Average gate time | | Gate occupancy ratio | Hourly capacity base | Gate size | No.Gates | Hourly capacity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | W | N | W | N (%) | W (%) | N ($T_n$) | W ($T_w$) | ($T_w/T_n$) | G* | S | N | G* S N |
| X | 13 | 2 | 4 | 1 | 80 | 20 | 45 | 55 | 1,22 | 2,6 | 0,97 | 5 | 13 |
| Y | 8 | 0 | 2 | 1 | 67 | 33 | 40 | 0 | 1,00 | 3 | 1,00 | 3 | 9 |
| Z | 4 | 0 | 2 | 0 | 100 | 0 | 35 | 0 | 1,00 | 3,4 | 1,00 | 2 | 7 |
| | | | | | | | | | | capacity of the terminal: | | | 29 |

In order to compare the results from FAA's graphical method and analytical model, let us observe aprons X, Y and Z separately. It makes the following:

For apron X: $C_x = \min\left(\frac{5}{0{,}87\cdot 45 + 0{,}13\cdot 55}\cdot 60, \frac{1}{0{,}13\cdot 55}\cdot 60\right) = 6{,}5 \quad aircraft\,/\,h$

(The share of wide-body/non-wide-body aircraft if only flights of airline X are considered, is 87/13 %.)

For apron Y: $C_y = \frac{3}{1 \cdot 40} \cdot 60 = 4{,}5 \quad aircraft/h$

For apron Z: $C_z = \frac{2}{1 \cdot 35} \cdot 60 = 3{,}4 \quad aircraft/h$

(Airline Y and Z operate all flights, 100%, with non-wide-body aircraft.)

Capacities set by each apron calculated from the graphical method (expressed in movements/h) are double than values calculated analytically (expressed in aircraft/h). As a quick approximation, one can multiply the dynamic capacity of the apron by two to convert it to movements per hour, as the occupancy of a stand is associated with two movements on the runways, an arrival and a departure (De Neufville and Odoni, 2003). If this approach is applied, then the same result is obtained as by FAA's graphical method (for each apron).

Nevertheless, the final result from the graphical method leads to the wrong conclusion as it overestimates capacity of the entire apron. As discussed before, capacities of individual areas should not be summed. Each area restricts overall apron capacity to the certain level, depending on mix of users in demand. Capacity restriction set by each apron has to be calculated respecting the share of each airline in total demand (respectively 55%, 30% and 15% for airline X, Y and Z) and minimum adopted as total apron capacity. This implies that overall capacity of the apron is not:

$$C = C_x + C_y + C_z = 6.5 + 4.5 + 3.4 = 14.8 \quad aircraft/h$$

but it should be determined as:

$$C = \min\left(\frac{C_x}{0{,}55}, \frac{C_y}{0{,}3}, \frac{C_z}{0{,}15}\right) = \min(11{,}8;15;22{,}8) = 11{,}8 \quad aircraft/h$$

which is the same result as obtained analytically.

**Appendix 11 – Apron with flexible layout with respect to aircraft classes**

For estimating capacity of the apron with flexible contact stands area, in the first step several typical (most often) layout configurations have to be defined, e.g. I, II and III.

Capacity is calculated for each of them individually (like they are separate aprons).

$$C_I = \min_{ij}\left(C^{I}_{ij}\right) = \min_{ij}\left(\frac{N_{ij}'}{\bar{t}_{ij}'}\right)$$

$$C_{II} = \min_{ij}\left(C^{II}_{ij}\right) = \min_{ij}\left(\frac{N_{ij}''}{\bar{t}_{ij}''}\right)$$

$$C_{III} = \min_{ij}\left(C^{III}_{ij}\right) = \min_{ij}\left(\frac{N_{ij}'''}{\bar{t}_{ij}'''}\right)$$

Apron capacity is maximum capacity provided by different apron configurations:

$$C = \max\left(C_I, C_{II}, C_{III}\right)$$

It is the one which to a highest degree matches to demand structure with respect to aircraft classes.

## Appendix 12 – Ideal wave with intercontinental and continental flights

The ideal wave accounting for both intercontinental and continental flights is given in Figure A12-1 (Bootsma, 1997; cited in: Burghouwt (2007)).

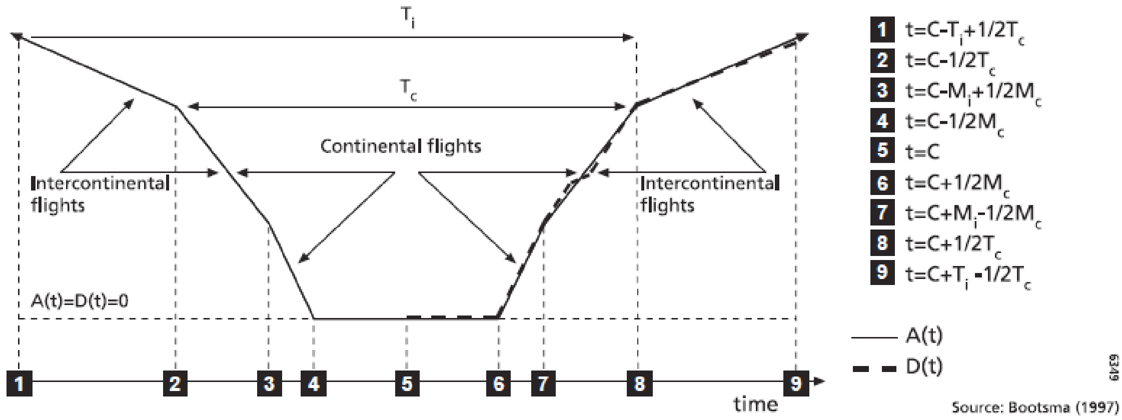



Figure A12-1. Ideal wave involving both continental and intercontinental connections (Bootsma, 1997, cited in: Burghouwt, 2007)

Where:

C – represents the wave center,

$T_c$ – the maximum acceptable connecting time for continental connections,

$T_{i/c}$ – the maximum acceptable connecting time involving intercontinental connections,

$M_c$ – the minimum connecting time for continental connections, and

$M_{i/c}$ – the minimum connecting time involving intercontinental connections.

The same wave is given in Figure A12-2, in the form used in the thesis.

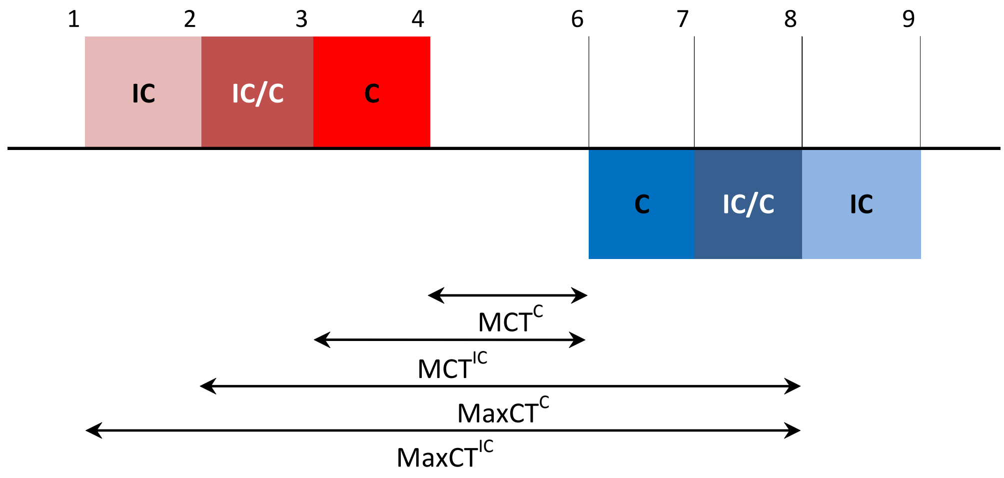



Figure A12-2. Ideal wave involving both continental and intercontinental connections

In this case we have:

$$N_{los}^{C+IC/C} = \frac{MaxCT^{C} - MCT^{C}}{2 \cdot \overline{t_{A}}}$$

$$N_{los}^{IC} = \frac{MaxCT^{IC} - MaxCT^{C}}{\overline{t_{A}}}$$

$$N_{los} = N_{los}^{C+C/IC} + N_{los}^{IC}$$

$$N = \min\{N_{a/c}, N_{los}\}$$

$$SOT = TAT + ST$$

$$TAT^{C} = ARR_{tw}^{C} + MCT^{C}$$

$$TAT^{IC/C} = ARR_{tw}^{C+IC/C} + MCT^{IC}$$

$$TAT^{IC} = ARR_{tw}^{IC} + MaxCT^{C}$$

## Appendix 13 – An impact of the runway system performance on apron capacity

*Example 7* assumes the minimum separation between all aircraft classes on approach is 6Nm, and the minimum separation between all departing aircraft is 120sec. The apron is of the same structure as in Example 3 - 22 contact stands (of which 12 for aircraft class 2, and 10 for aircraft class 3) and 8 remote stands (of which 5 for aircraft class 1, and 3 for aircraft class 2). Hubbing parameters are the same as in Example 3a - WRC is 180min; MCT is 30min and MaxCT is 150min.

The demand structure is the same as given in Table 9 (Table A13-1). A modified O/D example is used to be comparable to hub with mix of coordinated and other (point-to-point) flights.

Table A13-1. Demand structure for Example 7

| flight type | aircraft class | HUB pure | HUB exclusive/ preferential | O/D |
|---|---|---|---|---|
| coordinated | 1 | 0,2 | 0,08 | 0 |
| | 2 | 0,6 | 0,24 | 0 |
| | 3 | 0,2 | 0,08 | 0 |
| other | 1 | 0 | 0,36 | 0,44 |
| | 2 | 0 | 0,24 | 0,48 |
| | 3 | 0 | 0 | 0,08 |

Runway capacity decreases to 21 arrivals/h, 41 operations/h (alternating arrivals and departures) and 30 departures/h. The impact of runway performance on apron capacities is shown in Figure A13-1.

The blue and red lines represent runway capacity (arrivals/h) in mix mode, for Example 3 and Example 7 respectively. In Example 3 airside capacity is limited by the runway capacity for the O/D airport, and by apron capacity for hub airport (all cases). In Example 7 airside capacity is limited by the runway capacity for all airport types.

In the case of an O/D airport, apron capacity remains the same regardless of runway capacity; the consequent mismatch between the two is higher in Example 7 (40 vs. 21 arrivals/h) than in Example 3 (40 vs. 33 arrivals/h).

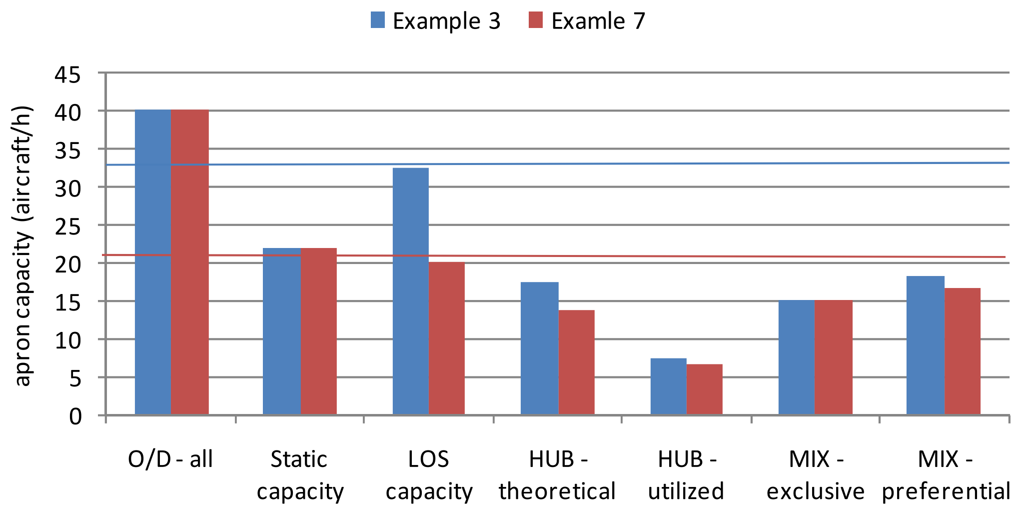



Figure A13-1. Apron capacity sensitivity to runway system performance, comparison of Example 3 and Example 7

At hub airports, the influence of runway capacity on apron capacity can be seen in all cases (except the case of exclusive use).

In Example 7, $N_{los}$ (20 aircraft) becomes more constraining than static apron capacity ($N_{a/c}$=22 aircraft). Also, apron capacity at the hub airport changes.

As it can be seen in Figure A13-1, theoretical and utilized capacity of the hub airport serving only coordinated flights is somewhat lower.

The impact of the decrease in the runway performance on apron capacity can also be seen for hub airports serving mixed coordinated and point-to-point traffic in the preferential use case. There, it is constrained by the (utilized) capacity of the group of stand for coordinated flights. In the exclusive use case, the influence of the runway performance is not visible since apron capacity is limited by the capacity of the group of stands for other flights/aircraft class 2.

## Appendix 14 – Apron capacity estimation tool – basic user guide

An apron capacity estimation tool was developed as a supplementary material to this thesis. It is available at: http://apron.comze.com/ (login password: bojana).

The tool offers apron capacity estimation for origin-destination (O/D) airports and for hub airports. It contains the following input data:

1. Number of airport users,
2. Number of aircraft types,
3. Total number of contact and remote stands,
4. Hubbing parameters: arrival only runway capacity, departure only runway capacity, arrival runway capacity that allows one departure between two arrivals, minimum connecting time, maximum acceptable connecting time, and wave repeat cycle,
5. Number of contact stands by user and aircraft class,
6. Number of remote stands by aircraft class,
7. Rules on contact stands use,
8. Rules on remote stands use,
9. Turnaround time by user and aircraft class,
10. Separation time by user,
11. Demand structure by user and aircraft class,
12. Coordinated/other flights share – derived from 11, only for hub case.

Inputs 4 and 12 apply only for hub airports. All other inputs are common for O/D and hub airports.

For O/D airports the tool delivers the following outputs:

1. Apron capacity of contact stands only, and
2. Apron capacity of all stands (contact + remote).

For HUB airports it delivers the following outputs:

1. Maximum number of aircraft in a wave, and
2. Apron capacity.


Figure A14-1. Apron capacity estimation tool - input data

For O/D airports output 1 and output 2 provide information about gate capacity and additional capacity when remote stands are engaged, respectively. Output 2 is useful for airports with significant variations in daily, weekly and yearly traffic, where remote stands may be used to deal with traffic overflow. When analyzing additional capacity provided by remote stands the user should carefully define the rules on stand usage in order to catch desired relations. For example, remote stands should be assigned as additional resources only to one user in the exclusive use case, while in the preferential or common use cases remote stands can be allowed for various users that share contact stands at the same time.


Figure A14-2. Apron capacity estimation tool - output for O/D airports

For hub airport cases, the assumption is that coordinated flights use contact stands (in order to facilitate transfers more efficiently), while other flights do not have their own contact stands, i.e. number of contact stands for other flights should be set as zero. Other flights use remote stands only, in the exclusive use case. In addition to remote stands, other flights also use contact stands of coordinated flights in the preferential use case.

For hub airports output 1 provides information on the maximum number of coordinated aircraft that can be scheduled within a wave. It takes into consideration static apron capacity and constraints imposed by the level of service in passengers' transfer and runway system performance (given in hubbing parameters input).

Output 2 delivers apron capacity for pure hub (all flights are coordinated) and for hub with mixed coordinated and other (non-coordinated) flights in demand. The difference between exclusive use and preferential use cases is controlled by the rules on contact stands use. For the preferential use case, there is also the possibility of analyzing apron capacity when coordinated flights use additional remote stands. This is not applicable in the exclusive use case.

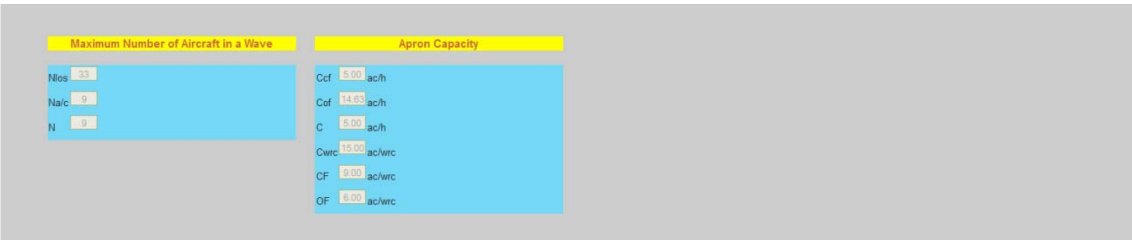



Figure A14-3. Apron capacity estimation tool - output for hub airports

In order to obtain capacity estimates for different airport types with respect to the nature of traffic at the airport, it is necessary to define properly stand occupancy times:

1. For O/D airports the turnaround times matrix should be filled in with different values depending on the user and aircraft class. The appropriate separation time depending on the user should be entered in the separation time's matrix.

2. For HUB airport fields for coordinated flights in the turnaround times matrix are automatically filled in by $ARR_{tw}$+MCT (derived from the maximum number of aircraft is calculated), while fields for other flights should be filled in with different values depending on the user and aircraft class. The appropriate separation time should be entered in the separation time's matrix.

When calculating apron capacity the tool recognizes when to use WRC (filled in the hubbing parameters input set), and when SOT (determined as $ARR_{tw}$+MCT+ST), depending on the case modeled (exclusive or preferential).

The tool delivers apron hourly saturation capacity, which is "divided" between users accounting for their share in total demand. For hub airports, the tool also provides apron capacity per WRC, which gives a better picture of the system performance than hourly capacity, in this case.

## Appendix 15 – Stand allocation at Zurich Airport after Switzerland entry into the Schengen zone[54]

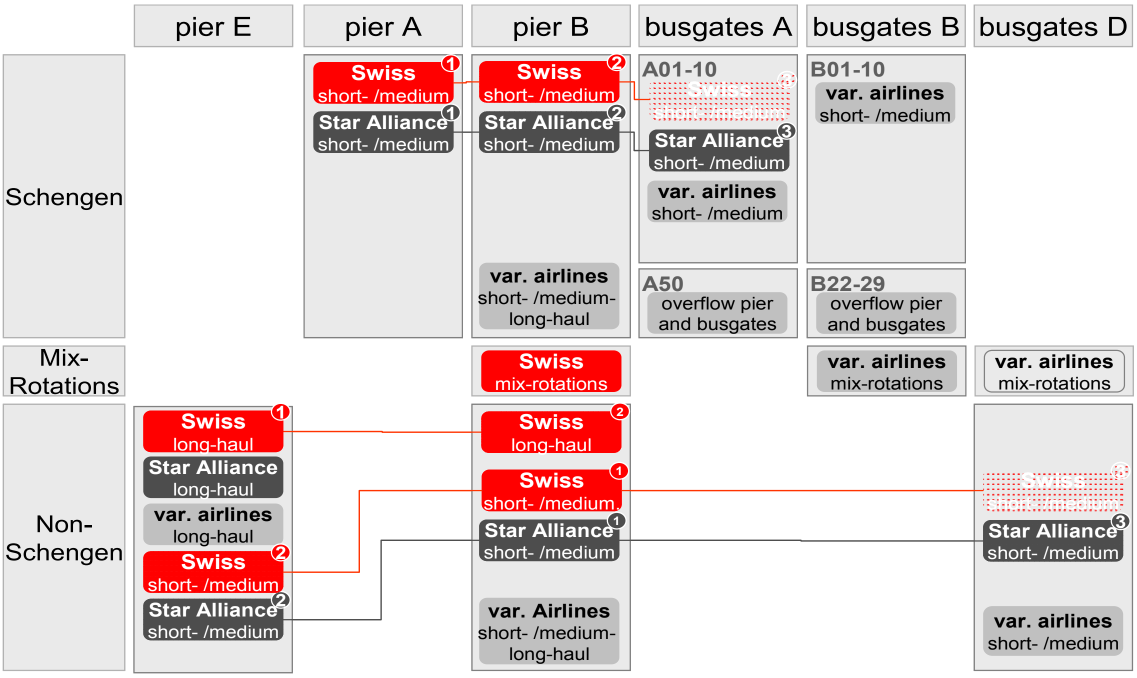



Figure A15-1. Schengen user concept at Zurich Airport, Switzerland - final concept plan (ZRH, 2008)

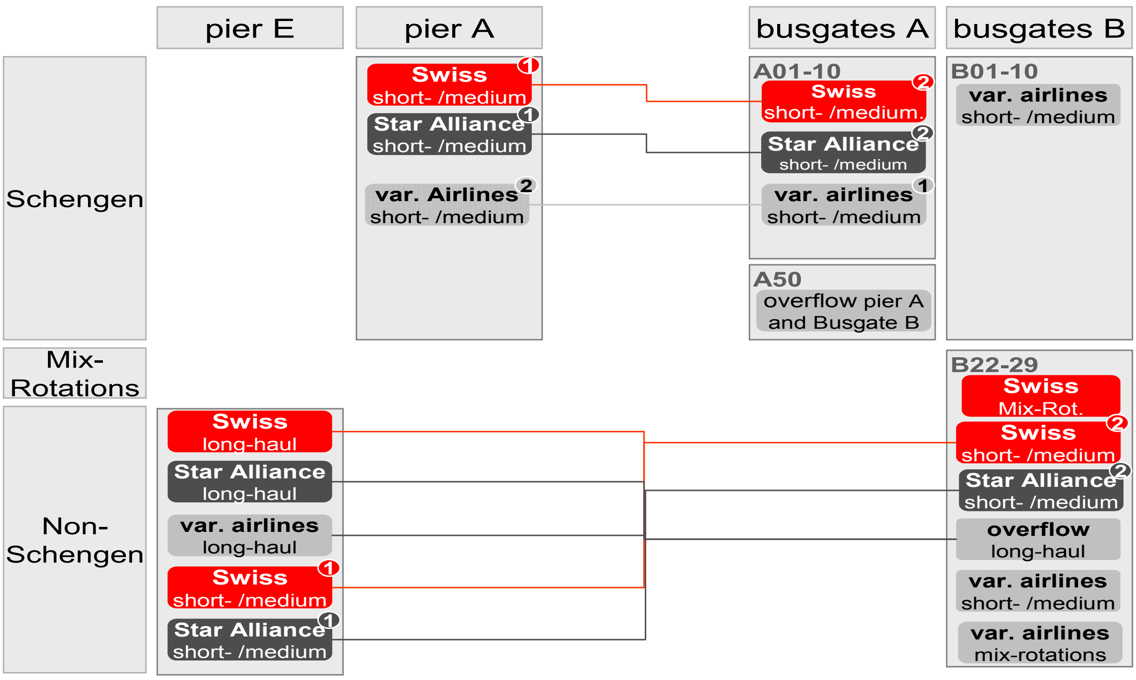



Figure A15-2. Schengen user concept at Zurich Airport, Switzerland - transition period (ZRH, 2008)

[54] Provided through the courtesy of Operations Planning, Planning and Engineering, Zurich Airport

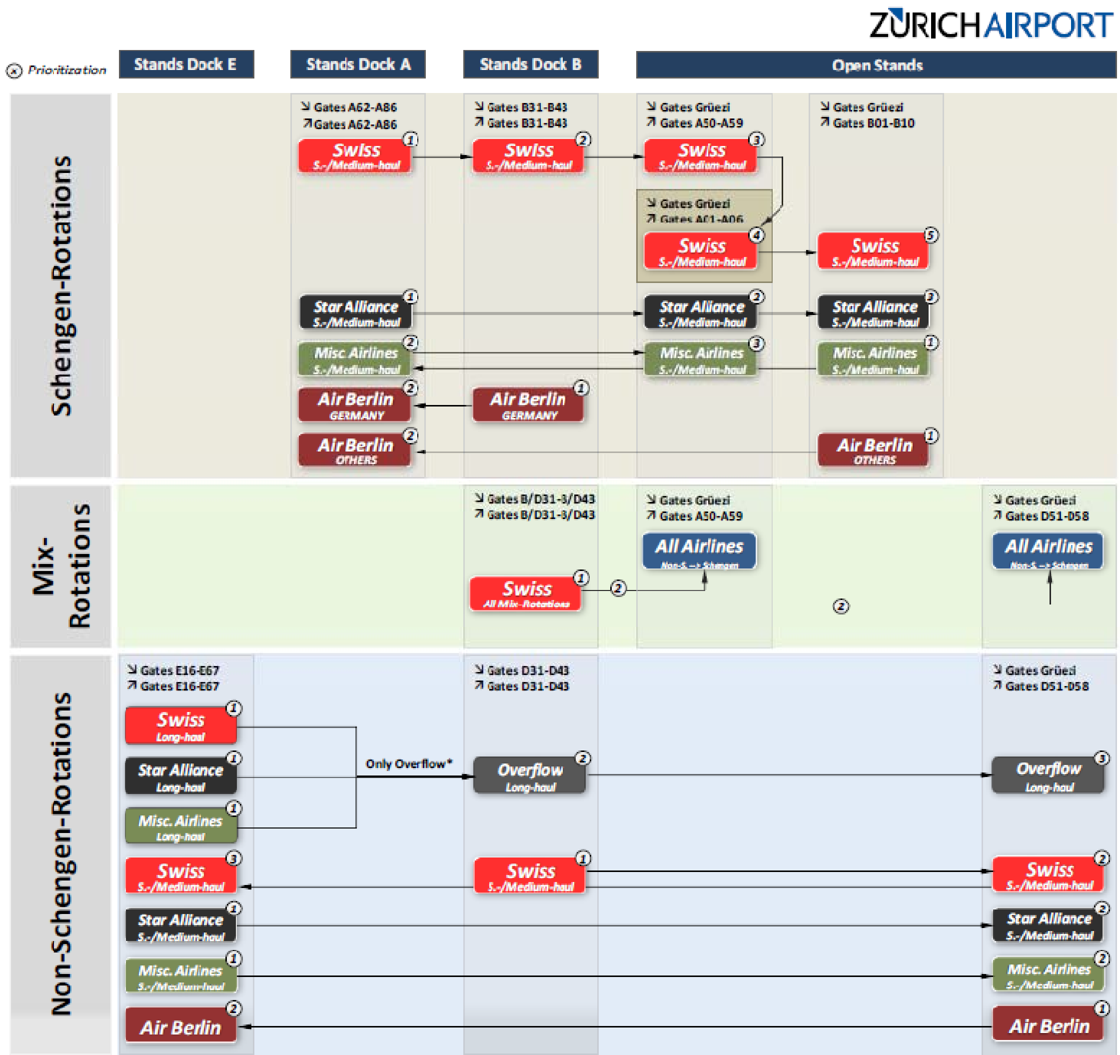



Figure A15-3. Schengen user concept at Zurich Airport, Switzerland - final concept (ZRH, 2012b)

# 12 Biography

Bojana Mirković was born in G. Milanovac, 28.07.1980. She finished primary and secondary school in Ljig.

She graduated from Faculty of Transport and Traffic Engineering in 2005 and obtained her Master degree in 2008, both from the Department of Air Transport and Traffic. The research topic for her PhD was accepted by the University of Belgrade in December 2010.

She has been employed at Department of Air Transport and Traffic since December 2005, as a teaching and research assistant. During eight years of her teaching experience she has been engaged in labs for all undergraduate courses at the Division of Airports Traffic Safety and the Airports 3 course of the Master's studies.

She has interned at three European airports: Tenerife Sur, Spain (2004), Munich Airport, Germany (2005) and Zurich Airport, Switzerland (2008); and attended ten certified aviation courses/seminars/workshops, one of which she has organized.

She has taken part in 12 science and professional projects.

She is the coauthor of two textbooks, one practicum and 12 published and/or presented papers.

Her fields of interest are airports - design, planning and operations; and air traffic analysis, modeling and forecasting.

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