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An empirical analysis of airport capacity expansion

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ABSTRACT

Theoretical analyses of the impact of airport capacity expansion must model or make assumptions about the effect of capacity on demand, airline competition, aircraft types, fares and other characteristics of a given airport. In this paper, we use empirical data on historical schedules, fares, delays and demand for the busiest 150 airports in 2015 to examine the typical impact of historical capacity expansions. We find significant diversity in outcomes, with over half the expanded airports either using less than their pre-expansion capacity or remaining constrained even at post-expansion capacity by 2016. Many of the expected impacts, such as reductions in typical aircraft size, either do not materialise or are dominated by other effects (for example, recessions; airlines beginning or ending operations at an airport; changes in regulation). Behaviour on expansion is affected by slot control regulations and whether the airport is initially capacity-constrained. In particular, slot-controlled airports typically add new destinations and carriers on expansion rather than making significant changes to existing schedules.

1. Introduction

The expansion of airport capacity can be a contentious issue. Demand for air travel is projected to continue growing at an average rate of 4–5% per year (Airbus, 2018; Boeing, 2018). However, capacity for growth at the world's major airports is limited. Typically, runway capacity is the most stringent constraint on growth, ahead of airspace, aircraft parking, or terminal capacity. In 2008, up to 15% of all flights were from capacity-constrained airports, a figure projected to rise significantly over time (Gelhausen et al., 2013; Boeing, 2015). Airports seeking large-scale expansion therefore typically seek to add runways. However, runway expansion is often opposed by local communities who are likely to be subject to increased noise and pollution if the runway expansion goes ahead, and by environmental campaigners concerned about the global CO_2 emission impacts of aviation growth. The end result is that expansion projects may be subject to multiple rounds of impact assessment and legal challenge, decisions are often made and then reversed, and in some cases runway infrastructure is constructed but subsequent application of regulations makes it impossible to use.

Because of the controversy surrounding airport expansions, careful assessment of how the utilisation of the expanded airport may change, and how this may affect local populations, is important. However, as discussed by Flyvbjerg (2009), major infrastructure projects such as airport expansion are often based on incorrect projections. Typically demand estimates are optimistic by more than 20% and the accuracy of forecasts has not improved over time. For example, the demand forecasts used to justify expanding the apron area at Hamburg (HAM) airport in 1996 projected 195,000 aircraft movements for 2010, in contrast to an actual value of 137,000 (OECD/ITY 2014). *Ex post* analysis of major project costs and benefits is rare. Hansen et al. (1998) examine the empirical impacts of the 1996 expansion of Dallas-Fort Worth (DFW) airport. They find that the overall impacts of expansion in terms of delay reduction and transfer time were small and/or short-lived. Although some airlines sharpened their operational peaks (i.e. running more flights at busy times by moving flights from less busy times) the total number of operations remained unchanged. Outcomes may also have been affected by American Airlines, the airport's primary tenant at the time, having an ongoing dispute with pilots over pay and conditions. Similarly, Hansen (2004) investigates the practical impact of the year-2001 capacity expansion at Detroit airport from a delay modelling point of view. Hansen et al. (2001) examine what impacts airport capacity constraints may have on airline fleet mix, but find little impact for Los Angeles International Airport, likely due to the combined impact of other operational constraints on airlines. Fageda and Fernández-Villadangos (2009) analyse the impact of capacity increases on airline competition at Spanish airports, specifically the 2006 and 2004 new runways at Madrid Barajas (MAD) and Barcelona El Prat (BCN) airports. They find increases in airline competitive behaviour after airport expansion only for routes from non-hub airports; however, this was affected by concurrent expansion in low-cost carrier networks

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and high-speed rail.

Theoretically, the expansion of a capacity-constrained airport should lead to greater airline competition (e.g. Evans and Schäfer, 2014). Competition modelling assuming airline profit maximisation has been successful in reproducing both the fares charged and the frequencies offered by airlines (e.g. Doyme et al., 2019). In this framework, when capacity constraints are removed airlines are able to more freely compete on frequency, using smaller aircraft and/or lower load factors to provide more services per day. This may lead both to a drop in average aircraft size and an increase in frequency to major destinations. Airline fare competition may also increase, for example because more airlines are able to use the airport. This in turn may lead to lower fares (e.g. Burghouwt et al., 2017). Analysis by the Airports Commission (2015) suggests that fares at constrained airports in the UK could be up to 10% higher than at airports without capacity pressures. Capacity constraints may also affect the type of destination served by the airport. For example, it has been suggested that airlines at constrained airports concentrate on more lucrative long-haul destinations at the expense of domestic routes, which could be reversed if extra capacity were provided (Airports Commission, 2015).

However, many factors exist in real-world airport expansions that can complicate this picture. For example:

- In order to fund the expansion, the airport may substantially increase its landing fees, which in turn may have an upwards impact on fares and/or affect airline decisions about which airport to fly from;
- A condition of expansion being approved may be meeting more stringent noise, emissions or regional connectivity requirements, with consequent impacts on movements;
- There may be constraints on how, and by who, new flights are added, or on how much existing schedules at the airport can be altered, for example from slot control regulations;
- The primary intended benefit of expansion may be to reduce delays and congestion for the same number of movements, rather than to accommodate increased demand;
- Increases in movements due to additional runway capacity may be offset by some years because subsequent increases in airspace and/or terminal capacity are required to take full use of them;
- The expansion may allow for the operation of larger aircraft from the airport than was previously possible, leading to a net increase in aircraft size;
- The long timeframes between expansion plans being suggested, approved and built may mean that the extra capacity is no longer required or cannot legally be used by the time the expansion is complete (for example because of recession, airline bankruptcies, changes in fuel price, or wider changes in regulation);
- The airport's response to capacity expansion may be affected by the presence and actions of a nearby competitor airport; or
- The impact of global trends in airline fleets, business models, market liberalisation or routing behaviour may dominate over local effects due to expansion.

To assess empirical outcomes for historical capacity expansions, this study examines data for the top 150 global airports (as measured by scheduled flights in 2015) between 2000 and 2016. During this time period, 55 of these airports underwent at least one major runway capacity expansion (including replacement of older airports by new ones with the same IATA code; excluding runway lengthening projects, rapid exit taxiways, A-CDM and other small-scale capacity-expanding measures).

1.1. *Airport capacity*

The capacity of an airport can be defined as the expected number of runway movements that can be operated per unit time (typically per hour) under conditions of continuous demand (De Neufville and Odoni, 2013). At most airports, the main constraint on this value is runway capacity, although airspace, terminal or aircraft parking capacity may also have an impact (Berster et al., 2015). The exact value in any given hour depends on multiple factors, including weather conditions, the distribution of arrivals and departures on different runways, and whether the airport is slot controlled or not. Projections of airport utilisation following capacity expansion are usually given in terms of yearly movements. However, the relationship between hourly and yearly capacity is typically straightforward (Wilken et al., 2011). In other cases, effective airport capacity is limited by regulation. For example, Düsseldorf (DUS) airport was expanded to two runways in 1993, but remained only able to operate at single runway capacity because of environmental restrictions (OECD/ITF, 2014).

1.2. *Airport responses to constrained capacity*

As demand for flights approaches capacity, an airport will become increasingly congested. Airports typically handle congestion in one of two ways. The first way is to limit the number of movements by applying slot controls (IATA, 2017). A slot is a take-off or landing right at an airport in a specified time period (e.g. Lenoir, 2016). The number of slots allocated per hour is determined based on infrastructure capacity and compliance with regulations, with the aim of limiting delay to acceptable levels given typical weather and use conditions. Typically, slots are allocated to airlines based on their previous use of the airport ('grandfather rights'). Slot controls are common at major European airports but are rarer in North America. As of 2016, only 2 of the world's 180 IATA Level 3 (slot-controlled) airports are in the US (New York JFK and Newark (EWR)), compared to 93 in the EU and 50 in the Asia-Pacific region (Lenoir, 2016). Airports provide declarations of the number of slots available (ACL, 2018). Quoted maximum capacities are typically given as the maximum number of hourly slots, and (in theory) cannot be exceeded. The second method is to let congestion itself limit demand, via increasing delays and unpredictability at the airport. This is the case at many US airports. This approach leads to fewer barriers for airlines to access airports and higher effective capacity under good conditions, but the build-up of delay at peak times can be substantial. FAA (2014) provide estimates of the hourly capacity compatible with acceptable delay levels at major US airports under different conditions. However, scheduled movements are allowed to exceed these values at peak times.

A third method would be to use landing charges to manage demand throughout the day. However, airlines tend to oppose congestion-related pricing (e.g., higher landing charges at peak periods) and as a result this is infrequently applied. In the EU, directive 2009/12/EC limits the charges that airports with over 5 million passengers per annum can apply. This means in practice that congested airports may not be able to set landing charges at a level that matches demand with supply (Burghouwt et al., 2017), and airports often are required to set landing charges close to costs. However, airlines still have an incentive to charge higher fares, as their objective is to maximise shareholder return. Consequently, airlines may experience higher yields at congested airports, which in turn may contribute further to congestion. For slot-controlled airports with trading, one outcome of this is that traded slot prices may be much higher than landing charges. Trading prices for slots at Heathrow airport are reportedly around £15 million for an early morning slot pair, falling to £10 million at midday and £5 million in the evening (Haylen and Butcher, 2017). For comparison, this is greater than a year's worth of airport landing charges on a daily flight by a large aircraft (RDC, 2016).

Whether an airport is slot controlled or not affects how airlines behave at that airport, including in response to constrained capacity or to capacity expansion. Under IATA guidelines (IATA, 2017), slots are allocated on a 'use it or lose it' basis and an airline will forfeit a slot that it operates less than 80% of the time. Slots are valuable to airlines and the grandfathering process leads to the risk of 'slot hoarding'/'babysitting' processes whereby airlines which cannot profitably make use of slots continue to use them, potentially with small aircraft or low load factors, to avoid giving them up to competitors. At the busiest European airports, less than 3% of slots are typically given up by airlines per year (Lenoir, 2016). Airlines often hold onto slots even when demand reduces, for example in the case of New York to East Coast cities also served by Amtrak (OECD/ITY 2014). They may also choose not to operate flights above the 80% limit. Studies in the US have indicated smaller aircraft sizes on average at slot-controlled airports; however, this effect seems small at European airports when compared to long-term growth trends (Lenoir, 2016).

In some cases, secondary trading in slots is allowed (e.g. in the US and UK). However, slot trades are relatively rare (EC, 2011). Auctioning new slots has also been suggested as a way of improving slot utilisation. However, this is opposed by airlines and would face considerable practical implementation problems as many flights require a co-ordinated take-off slot at the origin airport and landing slot at the destination airport.

1.3. *Capacity expansion*

Initially, airports approaching capacity will experience congestion and/or full slot utilisation at peak hours only. Gelhausen et al. (2013) use the concept of 5% peak hour (i.e. if all the yearly traffic volumes are ranked in order, the 95th percentile value), as used by airport planners, to define how close airports are to capacity. As demand increases, movements at traditionally non-peak hours increase (‘schedule flattening’), moving the average and daytime minimum movements per hour closer to the maximum value. However, the potential to do this at hub airports is limited by the need to co-ordinate inbound and outbound flights (Berster et al., 2015). Airlines may change their schedules in other ways to maximise profits subject to constraints, for example increasing aircraft size or partnering with other airlines (e.g. Wilken et al., 2011; Boeing, 2015; Berster et al., 2015). Airports may also seek to make smaller-scale capacity increases via runway lengthening, rapid exit taxiways, A-CDM or changes in the way that the existing runways are utilised. Airlines may also seek to utilise capacity across multiple airports serving the same region (e.g. OECD/ITY 2014). Disadvantages to airlines operating across multiple hubs (for example, British Airways operating at Heathrow and Gatwick airports) include a dilution of the connectivity and density economies available from using a single hub, and additional complexity costs. However, there are also several advantages, for example strategic positioning to deter the entry of competing airlines at the secondary hub.

FAA guidance is to begin planning for a new runway once an airport has reached 60–75% of existing capacity (GAO, 2003). Capacity decisions may also be driven by one-off events; for example, the Japanese government has explored capacity expansion options for Toyko Haneda (HND) and Narita (NRT) Airports prior to the 2020 Olympic Games. Similarly, the construction of the third runway at Seoul Incheon (ICN) Airport was brought forward to provide capacity for the 2008 Olympic Games in Beijing. However, there is usually a substantial time delay between the start of the planning stage and the opening of any new runway. GAO (2003) find median times to construction of 10 or more years for a sample of US airport expansions. As noted in Flyvbjerg (2009), long planning and construction timescales make major infrastructure projects inherently risky. In the case of airports, many other processes which can have a significant impact on capacity use (for example: airline bankruptcies; changes in airline business models; changes in local, regional, national or global regulation; economic cycles) can operate on shorter timescales. For example, Auckland (AKL) Airport stopped construction on a second runway in 2009 because a downturn in demand meant that it was no longer needed (NZ Herald, 2010).

Airport capacity expansions are complex, expensive infrastructure projects. The proposed Heathrow North-West Runway expansion has been projected to cost more than £15 billion ($20 billion; PWC, 2014); the 2011 fourth runway at Frankfurt International cost €600 million ($700 million; Reuters, 2011), and the 2008 third runway at Seattle Airport cost around $1 billion (Seattle Times, 2008). In-practice total costs usually exceed the estimated costs in *ex ante* impact assessments (Flyvbjerg, 2009). The costs of capacity expansion may be funded in several different ways. Broadly, funding may come from passengers (e.g. through increased fares); airlines (through reduced costs or operating margins); airports (e.g. via increased non-aeronautical revenues or cost efficiencies); or government (PWC, 2014). Funding may also be derived from the specific airports or airlines affected by the capacity change, or more generally via system-wide charges. For example, in the US the FAA applies a Passenger Facility Charge (PFC) of up to $18 to round-trip tickets specifically “to fund FAA-approved projects that enhance safety, security, or capacity; reduce noise; or increase air carrier competition” (FAA, 2018). The fifth passenger terminal at Singapore Changi airport is planned to be part-funded by government, with the remaining costs being shared by Changi Airport Group, aviation stakeholders and passengers, with landing charges potentially being increased before construction to pre-fund the project (FlightGlobal, 2018). The detailed financing of the planned expansion of Heathrow and/or Gatwick airports is assessed by PWC (2014). The airport plans specify the expansion will be financed mainly by the airports themselves via corporate bond purchase, with per-passenger landing charges assumed to increase in line with airport costs. These charges are currently of order 5% of ticket prices at Heathrow and Gatwick Airports (RDC, 2016; PWC, 2014). PWC (2014) project likely increases on expansion of £9/passenger to £12–23/passenger at Gatwick, and from £20/passenger to £24–34/passenger at Heathrow in real terms over the time period to 2050. However, Intervistas (2018) note that airline congestion-related costs (both operating- and customer service-related) may decline when an airport is expanded. The extent to which airlines pass through increases in costs onto ticket prices at congested airports is uncertain (e.g. Vivid Economics, 2007). If costs are passed through, this will have an impact on demand on existing routes from the airport.

If a slot-controlled airport is expanded, a decision must be made about how to distribute the newly-available slots. IATA rules require fifty percent of non-allocated slots (either new or unused ones) to be offered first to new entrants (IATA, 2017). In an EU context, a new entrant is defined as a carrier that would hold less than 5 daily slots at the airport if the slot were granted, and/or is applying to operate an intra-EU route with limited competition at two or fewer rotations per day, with priority given to carriers who meet both criteria (EC, 2011). This limits the scope for incumbent airlines to use new capacity to increase frequency. Expansion of airport capacity may also undermine the value of the slots an incumbent airline already has at an airport. At airports that are already major hubs, new entrants are more likely to be low-cost carriers, small airlines, or international airlines based in other countries, as the major domestic legacy carriers are likely already present at the hub. In this case the new entrants rule encourages longer-haul flights with large aircraft and/or lower-cost flights with single-aisle aircraft. However, at congested EU airports, historically new entrant slots have had lower utilisation than other slots and around half of new entrants were not operating the slots two years later (EC, 2011). Additionally, under normal operation it is rare for 50% of pool slots to be allocated under the new entrant rule, and the new entrant rule is often not invoked by carriers which would be eligible to apply under it due to the additional operational restrictions associated with its use (EC, 2011). In some cases, airport expansion may also be subject to other conditions, for example domestic regional connectivity requirements.

Finally, capacity expansion may also be used to improve flight system predictability and reliability for the same number of flights, for example by offering more options for landings and takeoffs under specific weather conditions, or by an overall reduction in delays. For example, the main impact of the year-2006 expansion of Atlanta (ATL) airport was a small increase in flight time predictability (Woodburn and Ryerson, 2014), and Frankfurt (FRA) Airport’s 2011 fourth runway led to a 14% increase in on-time arrival performance. Capacity expansion without increases in total movements can be used to allow more rigorous night curfews to be adopted, to allow noise respite periods for affected communities, or to implement better schedules for more efficient hubbing (Airports Commission, 2015).

1.4. Data

We examine data on the top 150 airports, as ranked by scheduled flight departures, in 2015. The airport dataset is derived from data used in the AIM global aviation systems model (Dray et al., 2019). Data on monthly scheduled aircraft movements, and on passenger movements, is derived from Sabre (2017). Fare data, where used, is derived from Sabre (2017) and BTS (2018); delay data is derived from Flightstats (2016) and BTS (2018). Additionally, we obtain expansion details and declared capacities for each airport in terms of movements per hour from literature and media reports (e.g. FAA, 2014; ACL, 2018; Odoni and Morisset, 2010; Zhang et al., 2018; Senguttuvan, 2006). Over this time period, 55 of the 150 airports either added runways or were replaced by new, higher-capacity, airports with the same IATA code. Fig. 1 shows the distribution of additional runways by region and year. Initially, North American and European airports dominate. However, growth in Asia (particularly in China) becomes substantial after 2005.

Not all of the airports in our sample are capacity-constrained. There are several ways that an airport's closeness to capacity can be assessed. One is to compare actual use against declared capacity, on an hourly, monthly or yearly basis. Declared capacity may have several interpretations, as discussed in Section 2 above, and it may be possible for an airport to schedule more many flights per hour than the official capacity if airlines are prepared to accept increased delays. As an airport approaches capacity at peak hours, airlines will increasingly schedule flights in off-peak hours, leading to a flatter schedule. Gelhausen et al. (2013) use the concept of Capacity utilization Index (CUI) to assess this effect. The CUI is the ratio of hourly movements in an average (daytime) hour at the airport to those in the 95% peak hour. Gelhausen et al. (2013) use a CUI of 0.7 as a threshold above which an airport is likely congested.

To assess the airports in our sample, we plot the ratio of 95% peak hour movements to declared capacity against CUI in the year before expansion (for airports that were expanded) or in 2015 (for airports that were not expanded). This data is shown in Fig. 2. Airports are identified by their three-letter IATA codes (e.g. IATA, 2018; also shown in Table 1). Note that slot control designations are from 2018, so airports marked as slot controlled may not have been slot controlled in the pre-expansion year. We exclude Bangkok Suvarnabhumi and Don Mueang airports as, although Suvarnabhumi inherited the BKK IATA code when it opened, Don Mueang airport did not close and still falls within the top 150 global airports. The movement data we use only contains scheduled movements and excludes non-scheduled and freight flights, which may account for up to around 10% of total movements (e.g. CAA, 2017). For US airports, the FAA provides a range of capacities (FAA, 2014) depending on weather, including Visual (VMC), Marginal and Instrument (IMC) Meteorological Conditions, where VMC typically result in higher effective capacity. On average, VMC applied to around 83% of operations in 2007 across a set of 34 major US airports (Odoni and Morisset, 2010). Given this, we use the lower end of the VMC capacity range given for these airports. Whilst major expansion impacts on declared capacity are captured, some more minor ones (e.g. A-CDM adoption) are neglected where data is not available.

Airports can be divided into four broad groups. We use a CUI threshold of 70%, as in Gelhausen et al. (2013) to divide airports into those that have flat schedules likely indicative of congestion (CUI > 70%), and those that have more peaked schedules (CUI < 70%). We also use a 95% hour/declared capacity threshold of 80% to divide airports into those that are approaching capacity at peak hour from those that are not (given non-scheduled and freight movements, as discussed above, this in practice means peak hour capacity use closer to 90%; at typical variation in schedules by time, this value was chosen to select airports

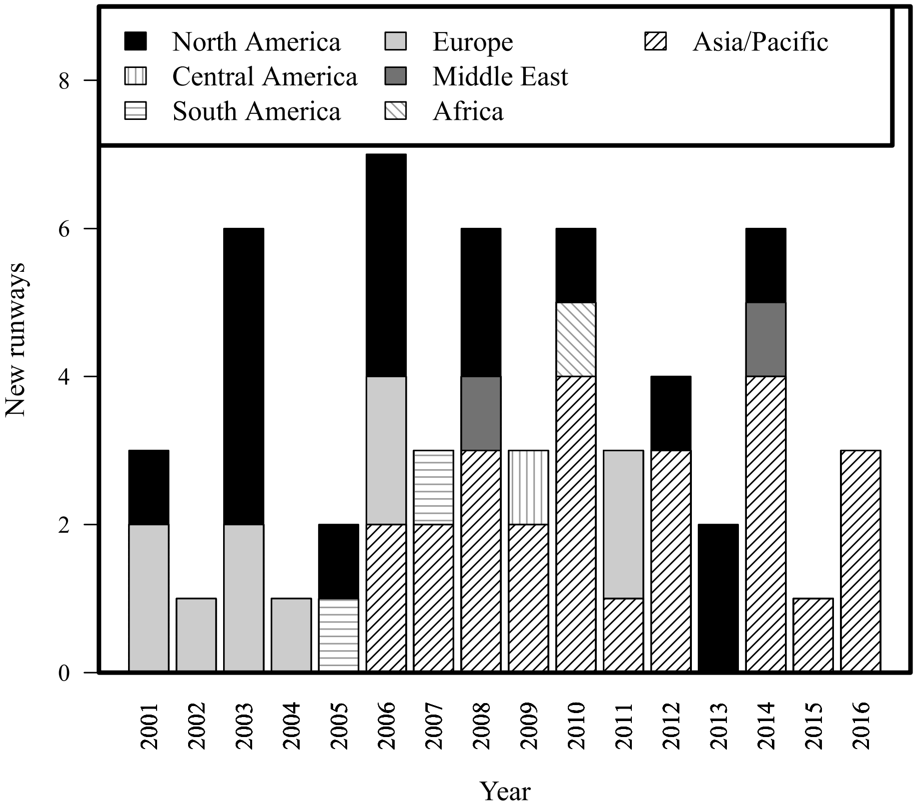

Fig. 1. New runways 2001–2016 by world region.

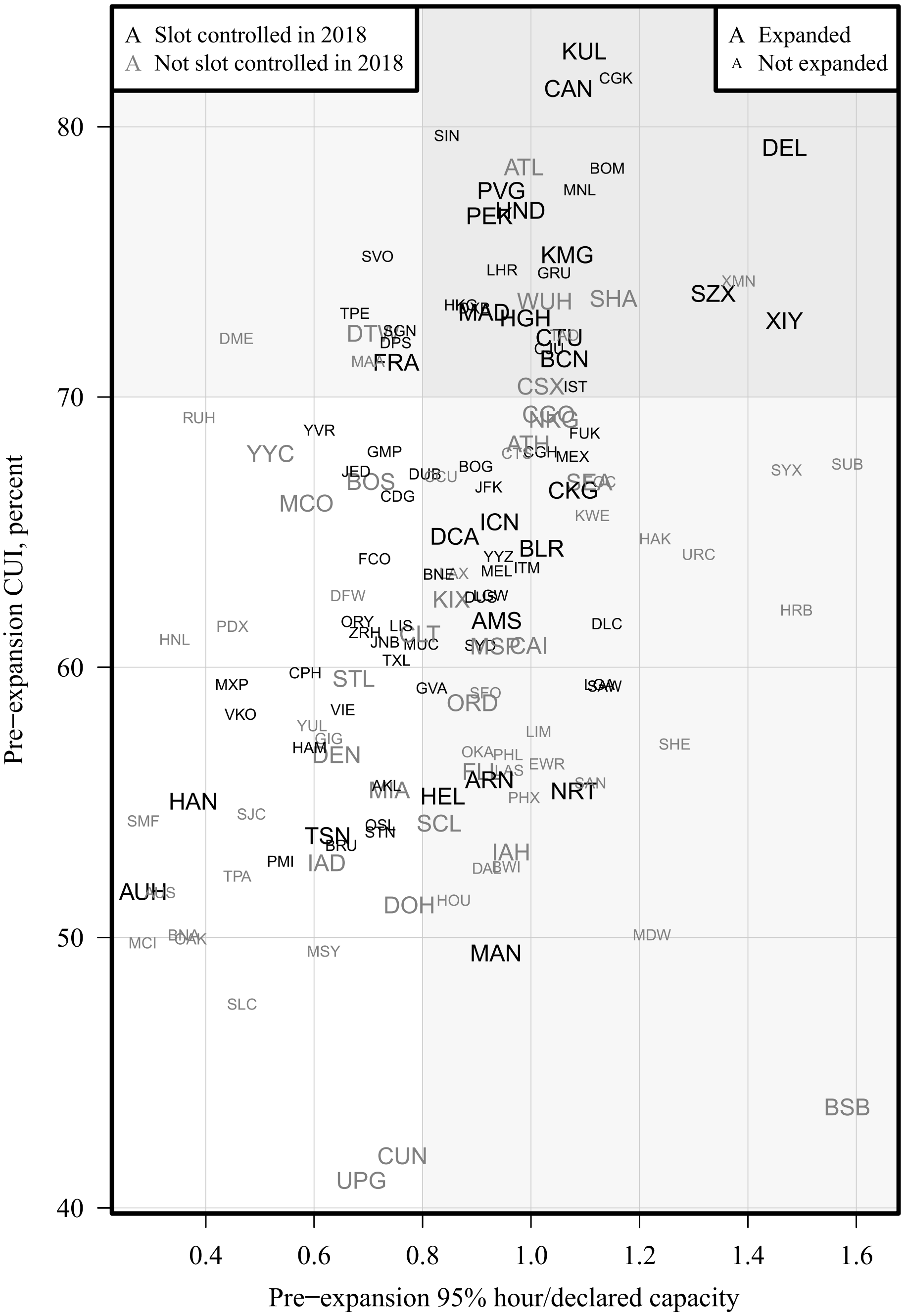

Fig. 2. Capacity constraints, expanded and non-expanded airports.

that have a high probability of operating at or beyond maximum peak capacity on at least some days or seasons).

Those with CUI above 70% and peak hour movements approaching or exceeding declared capacity have strong capacity constraints (group 'Strong Capacity Constraints' (SCC) in Table 1). Of the 32 airports fulfilling these criteria, 17 were expanded between 2001 and 2016; two have a new runway under construction (CGK, SIN); six have been or are about to be supplemented or replaced by a higher-capacity airport (XMN, BOM, DXB, IST, CJU, TAO); three (MNL, LHR, HKG) have put forward expansion plans that are moving through the official approval process, and only one (GRU) has no current large-scale runway capacity expansion plans. The data on airport classification is summarised in Table 1. Since both expansion and slot control are responses to constrained capacity, it might be expected that slot-controlled and expanded airports cluster primarily in this category. However, as demonstrated by Fig. 2 and Table 1, both expanded and slot-controlled airports occur across a wide range of values for capacity metrics.

Airports with CUI below 0.7 but peak-hour movements approaching or exceeding declared capacity are typically more moderately constrained, with additional growth likely to come from adding flights at non-peak hours (group 'Around peak hour capacity' in Table 1). This group includes airports which are at, or exceed, peak-hour capacity but where off-peak flights may be constrained by operational reasons (e.g., the time zone of the airport in relation to its main destinations, for example at New York JFK airport). Similarly, some of these airports may have greater numbers of flights missing from off-peak than peak schedule data (e.g. if the airport has substantial numbers of off-peak non-scheduled or freight flights).

Few airports have CUI above 0.7 but peak-hour scheduled movements far from declared capacity (group 'Flat schedules' in Table 1).

Table 1
Classification of airports. Only the ‘strong capacity constraints’ (SCC) and ‘Relatively Unconstrained’ (RU) groups are included in later analysis. SC/NSC = slot controlled/not slot controlled. EX/NEX = expanded/not expanded.

Group	Slot control (2018)	Expanded 2000–2016	Airports (IATA code)
Strong capacity constraints (SCC)	SC	EX	Beijing Capital (PEK); Tokyo Haneda (HND); Shanghai Pudong (PVG); Guangzhou Baiyun (CAN); Kuala Lumpur Int’l (KUL); Delhi I. Gandhi (DEL); Madrid Barajas (MAD); Kunming Changshui (KMG); Shenzhen Bao’an (SZX); Chengdu Shuangliu (CTU); Xia’an Xianyan (XIY); Barcelona (BCN); Hangzhou Xiaoshan (HGH)
		NEX	Dubai Int’l (DXB); London Heathrow (LHR); Jakarta Soekarno-Hatta (CGK); Hong Kong Int’l (HKG); Istanbul Atatürk (IST); Singapore Changi (SIN); Mumbai C. Shivaji (BOM); São Paulo Guarulhos (GRU); Manila N. Aquino (MNL); Jeju (CJU)
	NSC	EX	Atlanta Hartsfield-Jackson (ATL); Shanghai Hongqiao (SHA); Wuhan Tianhe (WUH); Changsha Huanghua (CSX)
		NEX	Xaimen Gaoqi (XMN); Qingdao Liuting (TAO)
Relatively unconstrained (RU)	SC	EX	Abu Dhabi Int’l (AUH); Tianjin Binhai (TSN); Hanoi Noi Bai (HAN)
		NEX	Paris C. de Gaulle (CDG); Munich Int’l (MUC); Rome Fiumicino (FCO); Jeddah King Abdulaziz (JED); Paris Orly (ORY); Zurich (ZRH); Copenhagen (CPH); Oslo Gardermoen (OSL); Brussels Nat’l (BRU); Vienna Int’l (VIE); Johannesburg Tambo (JNB); Berlin Tegel (TXL); Vancouver Int’l (YVR); Seoul Gimpo (GMP); London Stansted (STN); Lisbon H. Delgado (LIS); Palma de Mallorca (PMI); Milan Malpensa (MXP); Auckland (AKL); Hamburg (HAM); Moscow Vnukovo (VKO)
	NSC	EX	Denver Int’l (DEN); Orlando Int’l (MCO); Miami Int’l (MIA); Charlotte Douglas (CLT); Boston Logan (BOS); Doha Hamad (DOH); Washington Dulles (IAD); St. Louis (STL); Cancun (CUN); Calgary (YYC); Makassar Sultan Hasanuddin (UPG)
		NEX	Dallas-Fort Worth (DFW); Tampa Int’l (TPA); Salt Lake City Int’l (SLC); Riyadh King Khalid (RUH); Portland Int’l (PDX); Honolulu Daniel K. Inouye (HNL); Oakland Int’l (OAK); Nashville Int’l (BNA); Rio de Janeiro Galeão (GIG); Austin-Bergstrom Int’l (AUS); Louis Armstrong New Orleans (MSY); Kansas City Int’l (MCI); Montréal Trudeau (YUL); San Jose Int’l (SJC); Sacramento Int’l (SMF)
Around peak hour capacity	SC	EX	Amsterdam Schiphol (AMS); Seoul Incheon (ICN); Tokyo Narita (NRT); Chongqing Jiangbei (CKG); Washington Reagan (DCA); Stockholm Arlanda (ARN); Bangalore Kempegowda (BLR); Manchester (MAN); Helsinki (HEL)
		NEX	New York JFK (JFK); Sydney (SYD); Toronto Pearson (YYZ); Mexico City Int’l (MEX); New York La Guardia (LGA); Melbourne Tullamarine (MEL); London Gatwick (LGW); Bogotá El Dorado (BOG); Istanbul Sabiha Gökçen (SAW); Brisbane (BNE); Dublin (DUB); Düsseldorf (DUS); São Paulo Congonhas (CGH); Fukuoka (FUK); Dalian Zhoushuizi (DLC); Geneva (GVA); Osaka Itami (ITM)
	NSC	EX	Chicago O’Hare (ORD); Seattle-Tacoma Int’l (SEA); Houston George Bush (IAH); Minneapolis-Saint Paul (MSP); Fort Lauderdale Int’l (FLL); Osaka Kansai (KIX); Brasília Int’l (BSB); Nanjing Lukou (NKG); Zhengzhou Xinzheng (CGO); Cairo Int’l (CAI); Santiago Int’l (SCL); Athens Int’l (ATH)
		NEX	Los Angeles Int’l (LAX); Las Vegas McCarran (LAS); Phoenix (PHX); San Francisco Int’l (SFO); New York Newark (EWR); Baltimore/Washington Int’l (BWI); Chicago Midway (MDW); Philadelphia Int’l (PHL); San Diego Int’l (SAN); Dallas Love Field (DAL); Surabaya Juanda (SUB); Ürümqi Diwopu (URC); Houston Hobby (HOU); Sapporo New Chitose (CTS); Haikou Meilan (HAK); Harbin Taiping (HRB); Sanya Phoenix (SYX); Okinawa Naha (OKA); Lima (LIM); Shenyang Taoxian (SHE); Guiyang Longdongbao (KWE); Fuzhou Changle (FOC); Kolkata Int’l (CCU)
Flat schedules	SC	EX	Frankfurt am Main (FRA)
		NEX	Taiwan Taoyuan (TPE); Moscow Sheremetyevo (SVO); Tân Sơn Nhất Int’l (SGN); Bali Ngurah Rai (DPS)
	NSC	EX	Detroit Metropolitan (DTW)
		NEX	Moscow Domodedevo (DME); Chennai Int’l (MAA)

These airports may have relatively high numbers of freight or charter flights (e.g. Frankfurt airport; Fraport, 2018), i.e., in reality the flat schedule arises from capacity constraints, but a large part of that constraint comes from flights that are missing from this analysis as they are not listed in schedules. They might also have some other reason for running a flat schedule, or they may have maintained a depeaked schedule after a previous capacity expansion, as discussed in Section 4.4 below.

Airports with CUI under 0.7 and peak-hour movements far from declared capacity are relatively unconstrained (group ‘Relatively Unconstrained’ (RU) in Table 1). If using a threshold of 80% of declared capacity for peak-hour movements, this includes 13 airports which were expanded. These airports may have added capacity in anticipation of future growth (for example, FAA guidance is to begin planning for a new runway once an airport has reached 60–75% of existing capacity; GAO, 2003) or to ease other operational constraints.

It is also possible to compare 95% peak hour capacity use in 2016 for expanded airports with their pre- and post-expansion capacities. Of the 55 expanded airports, 15 were still operating peak hours at under 90% of their *pre-expansion* capacity in 2016, and 11 at under 80%. Even with charter and freight flights added, these airports (mainly North American and European airports affected by slow growth and/or demand decreases) would likely have been able to continue operating normally without expansion. In contrast, 19 airports which were expanded were operating peak hours at 90% or more of their *post-expansion* capacity in 2016 (15 at 95% or more), suggesting that expansion provided only a temporary relief from congestion. These airports are mainly in Asia. These types of outcome are not edge cases across the 2000–2016 time period, but affect over half of the expanded airport set. This suggests that more attention should be given in pre-expansion analyses to assessing impacts both in the case that the new capacity is not used and in the case that the airport remains capacity-constrained after expansion.

2. Results and discussion

To analyse the impact of expansion, we compare the most-constrained (SCC) and least-constrained (RU) groups of airports, additionally dividing into airports that were expanded and those that were not, and airports that are slot-controlled and those that are not.

2.1. Aircraft size and flight frequency

Fig. 3 shows the average aircraft size, monthly flight frequency to most common destinations, and proportion of shorter-haul (under 1500 nmi) flights for the SCC and RU airport groups. Narrow lines show the range of outcomes for individual airports and are intended only to give an idea of individual airport-level variability. Thick lines show average outcomes across all airports within a group, divided into slot controlled/non slot controlled and expanded/non-expanded subgroups. We omit average trends for non-expanded, non slot-controlled airports in group SCC and expanded slot-controlled airports in group RU due to the small number of airports in these groups (2 and 3 respectively). The metrics in

Fig. 3 might all be expected to display the impact of airline competition on capacity expansion outcomes. In a scenario where an airport is initially capacity-constrained and becomes unconstrained after expansion, with no limitations on new flight times or airlines, we might expect increased airline competitive behaviour to manifest by increases in flight frequency on busy routes, using smaller aircraft (e.g. Evans and Schäfer, 2014). In this case, the average size of aircraft used at capacity-constrained airports (Group SCC) that were expanded should decrease over time compared to the average size of aircraft used at other airports. It has also been suggested that capacity constraints may squeeze out shorter-haul and/or regional connectivity routes in favour of more lucrative long-haul routes, a situation which could be reversed by capacity expansion (Airports Commission, 2015). In this case, we might expect the fraction of short-haul routes at airports in group SCC that were expanded to increase over time compared to that at other groups of airports.

We observe significant diversity in outcomes between airports. This manifests as the wide background ranges in Fig. 3, but is also demonstrable via individual examples. Demand at Seattle (SEA) airport decreased following the 2008 opening of the third runway due to the financial crisis; aircraft sizes and flight distances at Tokyo's Haneda (HND) and Narita (NRT) airports were strongly affected by the 2007 decision to allow HND to host international flights; and large short-term fluctuations in movements at Washington Dulles (IAD), Sydney (SYD) and Melbourne (MEL) airports can be traced to and the 2006 and 2002 collapses of Independence Air and Ansett Australia, respectively.

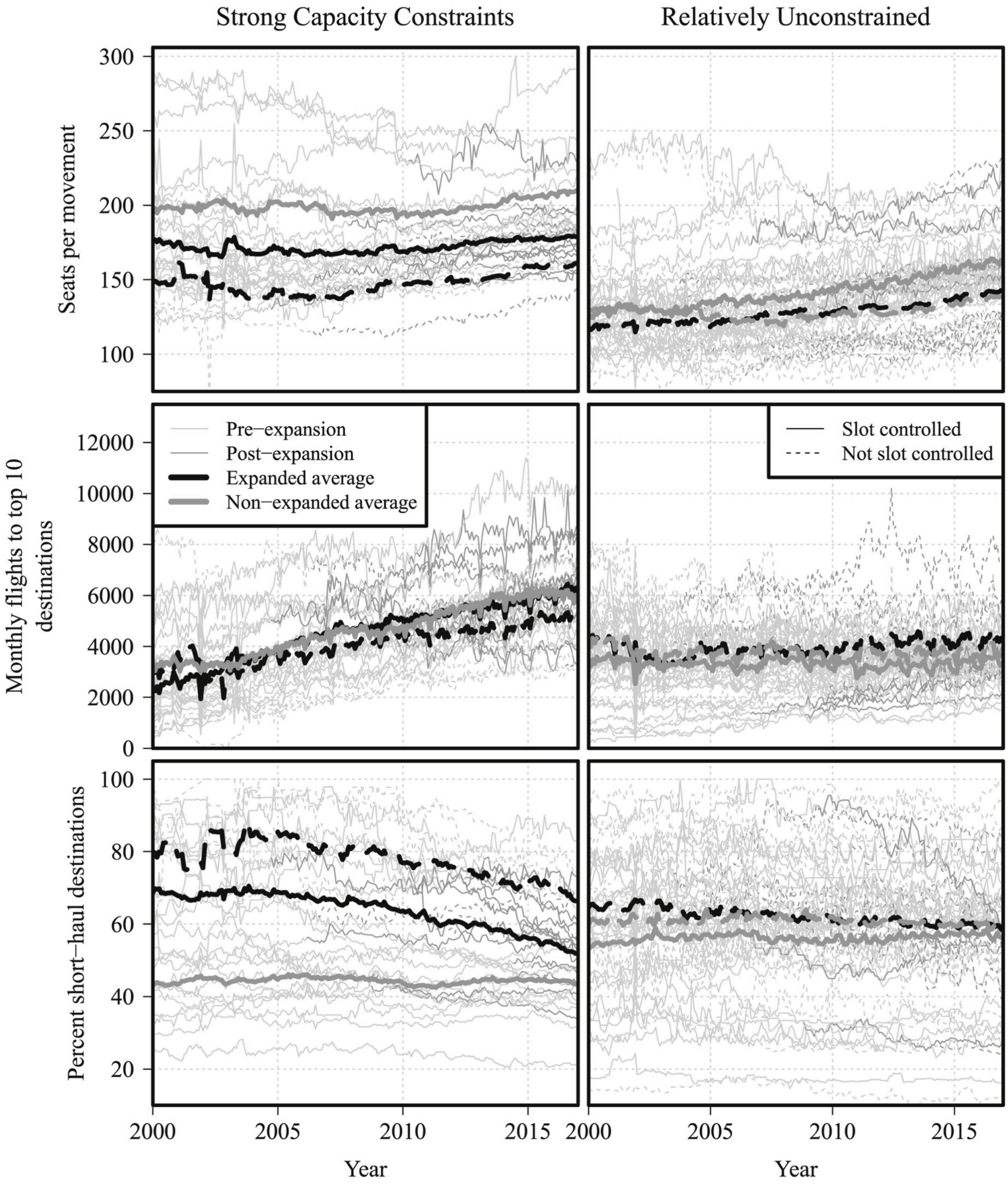

Fig. 3. Average aircraft size, flight frequency to top destinations, and proportion of short-haul flights, by airport type and expansion status.

Because of airport-specific events such as these, there is no single airport which represents an ‘ideal’ theoretical test case for the impacts of expansion. However, it is still possible to examine aggregate outcomes of airports with similar characteristics (for example, slot-controlled airports in group SCC that were expanded).

Aggregate metrics need to be treated with caution, as the individual airport groups have different geographical contexts. For example, the non slot-controlled group contains a higher proportion of US airports, which have also experienced slower growth over the 2000–2016 time period than other world regions, and were also more-affected by 9/11 and the subsequent consolidation of US airlines (e.g. Bhadra, 2009). Similarly, the expanded group of airports does not become wholly unconstrained after expansion because at some airports, particularly Chinese airports where demand is rapidly increasing, the extra space rapidly fills up with new flights. However, most expanded airports experience a period of reduced constraints after expansion. This noted, some general trends are observable in the aggregate data which diverge from the expectations about behaviour on expansion discussed above. Average seats per movement across all constrained, slot-controlled airports that were not expanded (10 airports) are around 16% higher than those across all constrained, slot-controlled airports that were expanded (13 airports) in 2002, before any of the expansions had taken place, and also in 2017, after all the expansions had taken place. This suggests that capacity expansion does not have a significant effect on the size of aircraft used at capacity-constrained airports. Similarly, flight frequency to top destinations increased at similar rates between expanded and non-expanded airports in this group. Together, these outcomes suggest that aircraft size-related competition effects are small at slot-controlled airports. Although the growth in top destination frequency is higher for constrained slot-controlled than non slot-controlled airports, this is likely due to the slow growth of US airports in the non slot-controlled group.

As noted by Berster et al. (2015), average aircraft size has tended to increase globally over this time period. However, seats per movement at the non-capacity constrained airports (Group RU) in the sample, both expanded and non-expanded, have grown faster than those in Group SCC. Non-expanded airports with slot control in Group RU (21 airports) saw increases in average seats per aircraft of 30% over the whole 2000–2017 period. Slot-controlled airports in Group SCC that were expanded experienced only 1% growth, and those that were not expanded experienced 6% growth. The non-constrained airports still have smaller average aircraft size than the constrained airports by 2017. Taken together, this suggests that constrained airports tend to have larger average aircraft sizes but, when constraints are eased, they do not tend to return to smaller aircraft sizes – i.e. airline behaviour with respect to capacity constraints being imposed and being lifted may not be symmetric. This may be a function of inertia in existing schedules, particularly at slot-controlled airports where slots are a valuable and hard-to-obtain resource. It may also reflect expectations that the new capacity will rapidly fill up.

The bottom panels of Fig. 3 show the proportion of shorter-haul (here defined as under 1500 nmi) flights at the airport. Here expanded airports diverge significantly from non-expanded ones. Airports in Group SCC which were not expanded maintain a roughly constant proportion of short-haul flights between 2000 and 2017. Those that were expanded saw a decrease from 68 to 51% short-haul (slot-controlled) and 79 to 66% short-haul (not slot-controlled). Non-constrained airports also see relatively little change over this time period. In aggregate, this suggests capacity-constrained airports tend to add longer-haul flights on expansion rather than returning to operating shorter-haul routes that may have been abandoned due to capacity constraints.

2.2. Carriers and destinations

Fig. 4 shows how the number of carriers, destinations and CUI varies by airport group. As with Fig. 3, there is significant variation between individual airports. However, in aggregate, expanded slot-controlled airports in Group SCC added both carriers (black solid lines, top left panel in Fig. 4) and destinations (black solid lines, centre left panel in Fig. 4). Other groups of airports tended to either remain constant or lose carriers over the same time period (e.g. non-expanded, slot-controlled airports in Group SCC; grey solid lines, top left panel in Fig. 4).

Although most groups of airports added destinations, the fastest growth in destinations was in the slot-controlled, expanded airports in Group SCC. Some of this is likely explained by rapid network growth in the Asian airports in the sample (11 of 13 constrained, slot-controlled airports that were expanded are in Asia, compared to 5 of 10 of the constrained, slot-controlled airports that were not expanded). However, it is also likely that outcomes at slot-controlled airports are affected by the IATA requirement that 50% of new slots go to new entrants, as discussed in Section 2. A higher degree of seasonality is also apparent at non-constrained airports; for constrained airports, off-season capacity is typically utilised as well as off-peak capacity.

Similarly, slot-controlled airports in Group SCC that were expanded experienced on average a 50% growth in the number of carriers between 2000 and 2016. Slot-controlled airports in Group SCC that were not expanded saw an overall *decrease* in carriers over the same time period (by around 20%), and non slot-controlled airports in Group SCC that were expanded saw 30% growth. Airports in Group RU saw relatively flat trends in carrier numbers, whether slot controlled and/or expanded or not. This is consistent with much of the growth at expanded slot-controlled airports in Group SCC coming from new entrants and/or new routes. For airports in Group SCC that are not slot controlled, new carriers and routes are still added on expansion, but to a lesser extent; for airports that are not congested, expansion has minimal impact on how and by who the airport is used.

The bottom panels of Fig. 4 show how the CUI changes for different groups of airports. For subgroup averages, a 12-month rolling mean is shown to distinguish changes over longer timescales from within-year variability. As discussed above, CUI is a measure of how peaked the schedule is. It increases over time for slot-controlled airports in Group SCC, both those that were expanded and those that were not – i.e., even on expansion, slot-controlled airports do not seem to return to the more peaked schedules that they had before expansion. As with aircraft size, this may be a function of schedule inertia in a slot-controlled environment. Airports that are not slot-controlled, and those that are not congested, show flatter trends. This behaviour is discussed further in Section 4.4, below.

2.3. Delay and fare

Insufficient delay data was available to carry out a full analysis of all airports. For individual expanded airports, typically a short-term decrease in average delay is seen on expansion, as found by Hansen et al. (1998) for DFW airport. However, most of the airports for which delay data is available across the expansion period are non slot-controlled airports in the US. Similarly, global fare data is available only between 2010 and 2015. Across this time period, slot-controlled airports in Group SCC which were not expanded consistently had higher average fares than those which were expanded, but this was at least in part a function of the different markets served. Economic theory suggests that airport capacity constraints are likely to lead to higher ticket prices, and this is supported by empirical data on airport fares (PWC, 2013; Frontier Economics, 2017; Burghouwt et al., 2017). For example, PWC (2013) find fare revenue per passenger mile is 18% higher for ‘severely constrained’ airports, and Frontier Economics (2017) find fares at London Heathrow to be 24.4% above those at less-congested European hub airports. Burghouwt et al. (2017) find a 10% more stringent capacity constraint to be associated with a 1.4–2.2% increase in fares at European airports, with a likely exponential relationship between capacity constraint and fare.

In 2010, average fares at the non-expanded airports in Group SCC in

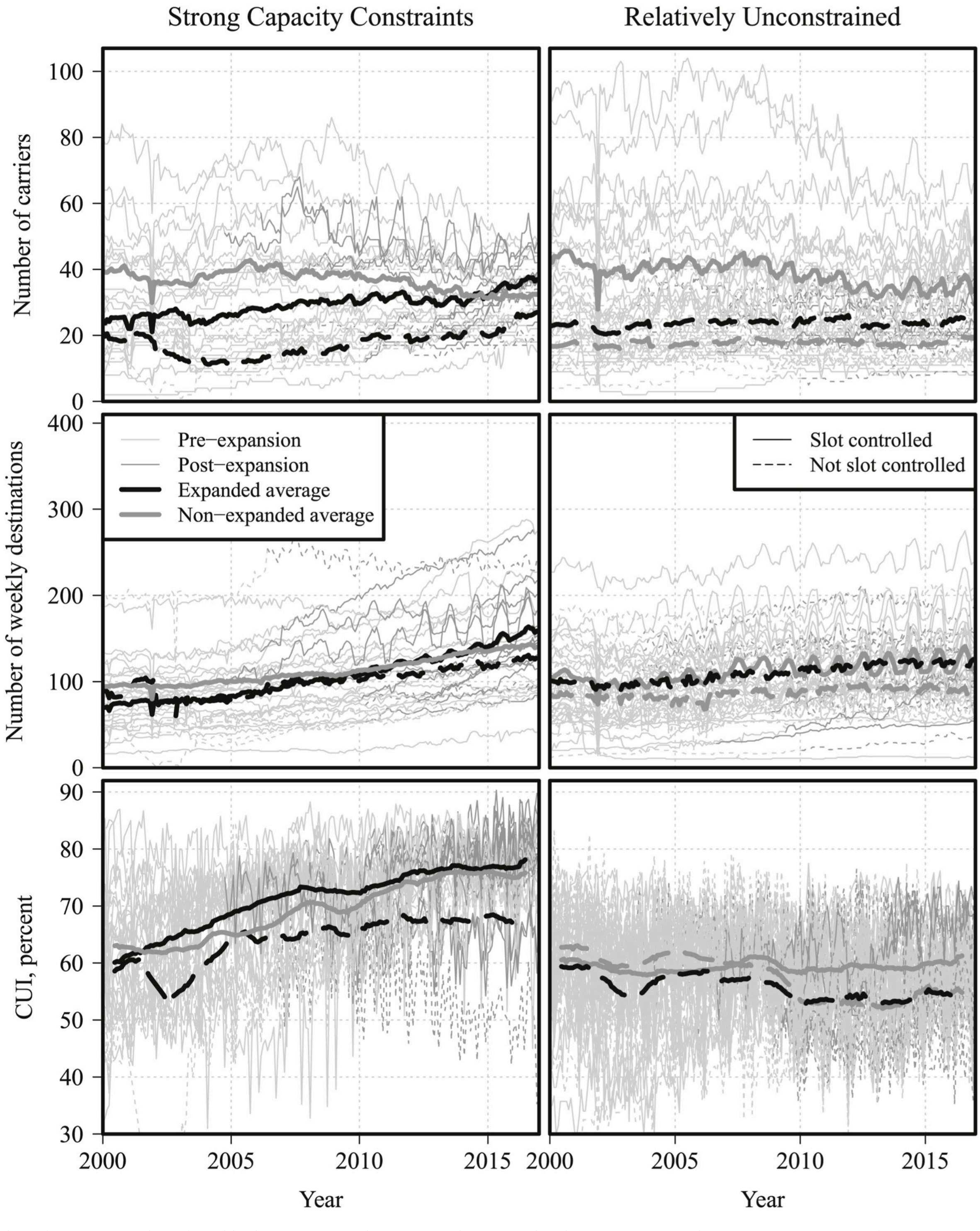

Fig. 4. Number of carriers, number of weekly destinations, and capacity utilization index, by airport type and expansion status. Note that CUI averages use a 12-month rolling mean.

2010 were about 50% higher than those at the expanded airports. This largely reflects different typical routes served rather than necessarily being an indication of capacity constraints. The non-expanded group contains long-haul hubs such as London Heathrow, Singapore and Hong Kong airports whose average fare is high in part because of the higher fare associated with longer-distance flights. For example, the average fare at Shenzhen airport (expanded 2011) in 2010 was only 41% of that at Hong Kong International (not expanded) but this largely reflects that 70% of destinations served by Shenzhen in 2010 were under 1500 km distance and none were over 3000 km, compared to only around 50% under 1500 km and 32% over 3000 km for Hong Kong International.

By 2015, average fares at the expanded airports in Group SCC were at a similar level to their year-2010 values, but average fares at the non-expanded airports had decreased, so that the difference in average fare between the groups in 2015 was only 23%. This is likely the result of several factors. First, oil prices in 2015 were nearly half of their year-2010 values. Fuel is typically 20–30% of airline operating costs, with higher values for longer-haul flights. As noted above, the non-expanded airports in Groups SCC include some major long-haul hub airports. Flights from these airports will have experienced a larger relative operating cost decrease from reductions in oil price, leading to decreases in fare, as observed. In contrast, fares do not decrease (on average) at the expanded airports over this time period. This is counter-intuitive, given that the removal of a capacity constraint should in theory result in reductions in fare. However, two factors act to increase average fare in this situation. First, initial fare increases on expansion, which are observable in some of the individual airport data, likely reflect increases in landing charges to fund the expansion as discussed in Section 2.2. Second, the expanded airports tend to add long-haul flights which have a higher average fare, increasing the airport-level average. For example, average fare at Shenzhen airport in 2015 had increased by around 15% from year-2010 values, but the share of destinations under 1500 km also decreased from 70 to 55%.

The initial part of this time period is also strongly impacted by financial crisis-related demand decreases (e.g. EC, 2011) which may also affect average fare.

2.4. *Asymmetric behaviour on expansion*

As discussed in Sections 4.1 and 4.2, it is notable that the behaviour of a slot-controlled airport which becomes capacity constrained and is then expanded is different to that of an unconstrained slot-controlled airport. In the slot-controlled airports in our sample, typically only limited de-peaking occurs on expansion and aircraft size on existing routes does not change much. This likely arises because even off-peak slots are valuable assets which airlines may have designed their schedules around, so there is a high level of inertia involved in switching flights to peak times on expansion. If flights also have slot-controlled destinations, the necessity of changing slots at the destination airport will also act as a barrier. Therefore de-peaking is likely to occur only in that the new peak slots available will be more attractive to operate. In contrast, non slot-controlled airports may de-peak their schedules to a greater extent when expanded, because there are fewer constraints on changing flight time. Fig. 5 gives examples of this type of behaviour, for Madrid Barajas (MAD) and Atlanta airports (ATL). Both airports were expanded in 2006, mainly serve relatively mature aviation markets, and were similarly affected by the 2008 financial crisis.

When capacity was added at MAD, which is slot-controlled, CUI initially remained at a similar level (i.e. the schedule was not significantly de-peaked) but the ratio of peak hour movements to declared capacity decreased. Subsequently, through the financial crisis period, a small amount of de-peaking occurred but only in conjunction with a reduction in capacity use throughout the schedule. In contrast, when capacity is added at ATL in 2006, both CUI and the ratio of peak hour movements to declared capacity decrease, indicating that much more de-peaking is taking place; peak hour movements remain much closer to declared capacity than at MAD. These behaviours are representative of those displayed by other expanded airports. They suggest that barriers associated with changing schedules at slot-controlled airports mean that flight schedules at slot-controlled airports which were previously congested but are not congested any more will (at least over a 10-year timescale) still behave similarly to those at congested airports, rather than returning to their pre-congestion state.

3. Conclusions

Airport expansion projects may be subject to repeated rounds of impact assessment, controversy and review before approval is finally given or denied for runway construction. However, relatively little attention is often given to the actual outcomes of the expansion once it has been constructed. In this paper, we examine data on the top 150 airports by scheduled aircraft movements in 2015 over the 2000–2016 time period. During this time, 55 of these airports added runways or were replaced by new, higher-capacity airports with the same IATA code. Examining how traffic, schedules and capacity use developed at these airports in comparison to similar non-expanded airports leads to several broad conclusions.

First, there is significant diversity in outcomes between airports based on individual circumstances. Recessions, airline bankruptcies, changes in regulation, external events (for example, the Covid19 pandemic), and changes in the effective capacity of other airports serving the same city can all affect how and whether additional capacity is used. The typical timescale from start of planning to construction of a runway is more than ten years (GAO, 2003). Several examples were found of airports where unexpected demand decreases led to new capacity remaining unfinished (AKL) or unneeded (SEA), or where extra capacity was not useable because of regulatory limits (DUS). In other cases (e.g. SZX), new capacity rapidly filled with flights and the airport became capacity-constrained again. Of the 55 expanded airports, over half were either operating at below their pre-expansion capacity or very close to their post-expansion capacity in 2016. These outcomes are not edge cases but need to be seriously considered in impact assessments.

Second, expanded airports behave differently depending on whether they are slot-controlled or not. Slot control regulations include the requirement to offer 50% of newly-available slots to new entrants, although in practice takeup is usually lower than this (EC, 2011). On average, slot-controlled airports which were constrained and then expanded added carriers and destinations rather than increasing flights to existing destinations, consistently with this requirement being applied. For non slot-controlled airports, it has been argued that capacity increases will lead to increased airline competition (e.g. Evans and Schäfer, 2014), with increases in frequency on competitive routes and a consequent reduction in aircraft sizes used. In the non slot-controlled airports that we examine, this effect seems to be largely drowned out by system-wide trends towards increasing aircraft size. For all airports, new flights after expansion tended to be weighted towards longer-haul destinations, again reflecting system-wide trends towards longer flights with larger aircraft.

Third, over the timescales examined, slot-controlled airports do not transition back to their pre-congestion schedules once they have been expanded. Instead, they tend to maintain depeaked schedules, likely as a result of the difficulty of changing slots. The relative difficulty of changing schedules may also be a factor in airlines maintaining flights with the same aircraft sizes after expansion rather than switching to

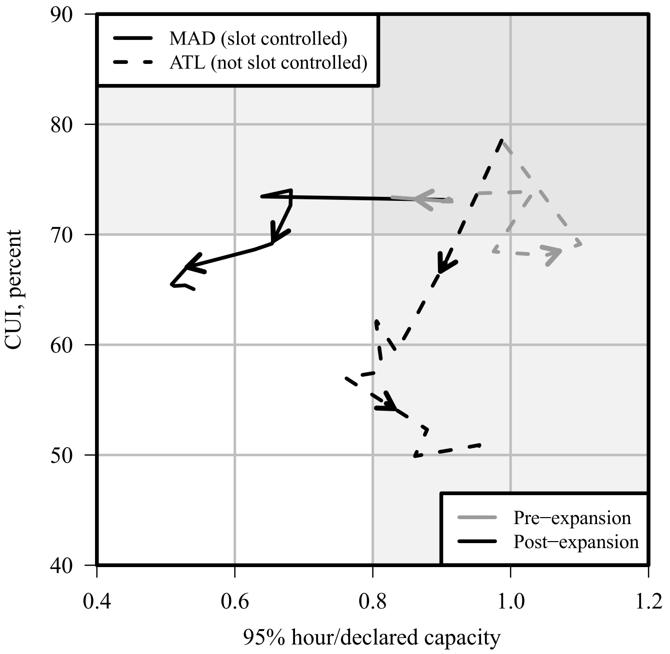

Fig. 5. Example behaviour of slot-controlled and non-slot controlled airports on expansion. Arrows show the direction of movement over time.

more frequent, smaller flights.

Taken together, these conclusions suggest two broad recommendations. First, impact assessments of airport expansions need to consider a greater diversity of outcomes, including a realistic range of demand projections. Second, models which analyse aviation systems, airport expansion and/or airline competition need to account for different behaviour between slot-controlled and non slot-controlled airports, and between expansions of capacity-constrained and non capacity-constrained airports.

CRediT authorship contribution statement

Lynnette Dray: Conceptualization, Methodology, Formal analysis, Writing - review & editing.

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