Airport Punctuality, Congestion and Delay: The Scope for Benchmarking

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***Abstract*—Airport performance benchmarking increasingly requires level-of-service (LoS) indicators for a fair comparison among members of the same peer group. For a true performance analysis such inclusion of quality measures is necessary to differentiate airports with similar pure output quantities, i.e. number of aircraft movements. Since variation of scheduled times versus actual times could substantially cause accumulating operating costs for carriers and could furthermore pose the risk and inconvenience of missed connections for the passengers, this article examines determinants of flight delays at airports, and thereby developing performance indicators such as slot capacity utilization, queueing time and punctuality. The essence of underlying phenomena in queueing theory such as *Little's Law*, arrival and departure distributions, and cumulative throughput and demand diagrams are briefly explained. This work's aim is the exploration of ways of measuring and observing performance quality from actual flight schedules with a focus on usability for subsequent airport benchmarking and traffic modeling.**

I. INTRODUCTION

It is largely recognized that transportation – and this of course includes air transportation - is vital for the economic development of countries and markets globally. Developing societies not only require telecommunication to connect them with the rest of the world, but they additionally develop a need for free mobility of people and goods, which serves as a main driver for economic prosperity. In transportation ultimately what drives the choice of one mode over the other is finding the fastest, cheapest, safest, most reliable and (nowadays) environmentally friendliest way to move something from point A to point B.

In contrast to most information networks, which can be expanded quite rapidly and which constantly deliver significant advances in their stages of technological evolution, transportation networks cannot be expanded so well ahead of demand. To maximize throughput and efficiency by procedural changes is constantly being anticipated by stakeholders in a variety of network industries. Because of the magnitude in dimension and long-term impact, infrastructure such as roads, rail tracks, bridges, ports and certainly airports conflicts significantly with our personal sphere and natural habitats.

Particularly airports in Europe are faced with stagnating investment in fundamental infrastructure, as environmental concerns are becoming important for the public and political agenda. In our industrialized economies, politicians as well as our economic managers refrain from taking unpopular decisions such as building new airports or runways. At, say, Frankfurt or London Heathrow airport, it can be assumed that the potential demand, which cannot be met, is substantial. During the last two decades both airports have tweaked out the maximum flights given the currently installed capacity, but at least in the case of London no significant airside capacity expansion is in sight. The consequence is an exercise in traffic flow optimization by continuously minimizing server (i.e. runway, apron or terminal) occupancy times and maximizing punctuality (Eurocontrol, 2005).

In the first part of this article, the declared capacity/available slots of an airport will be related to actual levels of demand to derive the capacity utilization as a *measure of congestion*. This will be exercised on a set of single runway airports.

In the second part, the focus is on developing performance measures, such as schedule adherence (i.e. punctuality, variability and delay), which should be taken into account in any airport performance or benchmarking study.

Furthermore this article discusses an airport's most critical limit, the runway capacity, which is defined as the *maximum service rate* per time unit (μ) and its inverse, the *minimum service time* ($1/\mu$) (this minimum time interval between following arriving or departing aircraft is also called the *headway*) (Gosling et al., 1981). The airports London-Heathrow (LHR) and Tokyo-Haneda (HND) airports have been chosen as they are comparable in terms of amount of annual passengers and mainly operating far-spaced parallel runways (a fourth take-off runway has been added recently at Haneda airport, which will change procedures and capacity considerably). These airports also represent perfect counterparts in terms of punctuality (http://www.travelweekly.co.uk/Articles/2011/05/06/37022/tokyo-airports-defy-disaster-to-turn-in-best-on-time.html).

Based on airport timetables, consisting of information on actual and scheduled gate times and the basics of queueing theory, recommendations for the critical relationships and determinants for benchmarking and performance are derived.

II. Declared Airport Capacity, Demand and Utilization

Although there are still many airports scattered across Europe which could be transformed into civil international airports in the future, this circumstance is of little benefit to the big hub airports which are ultimately needed to accommodate large-scale passenger flows to and from international connections and regional airports. During day-to-day operation airport capacity is either sufficiently available to accommodate any current demand level and "organic", i.e. anticipated, increase in demand, or it may be limited and must therefore be coordinated by an airport slot coordinator. This latter is the case for all "congested" Level 2 and 3 coordinated airports in Europe, which according to the International Air Transport Association (IATA) world scheduling guidelines (WSG) must declare their capacity to the slot coordinator. Each of the airport stakeholders (airport operator, coordinator, airlines and air traffic control) has to work towards maximizing the capacity of the particular processes under his jurisdiction, thereby bringing more available capacity to the table as a result of streamlined processes. During the bi-annual scheduling conference initiated by the IATA, the declared capacity is used as a reference for the scheduling process for the seasonal airline schedules. Each scheduled flight at the capacity constrained airports is assigned a landing and take-off right - a *slot*.

At the currently most capacity constrained airports in Europe, Frankfurt am Main (FRA), London-Heathrow and London-Gatwick (LGW), there is hardly any idle capacity available for growth and/or unscheduled flights (such as general aviation, military or governmental flights). Benchmarking has shown that there are many examples of European airports where we can find capping of capacity at much lower levels than what would be operationally feasible under instrument flight rules (IFR) (see Bubalo, 2009) (Table 1). In general, there is little, if any, available evidence why capacity is declared at exactly the chosen levels.

For example, we could benchmark the airports London-Gatwick, London-Stansted (STN) and Stuttgart (STR) simply based on the *single runway* airport configuration. When looking at the numbers in Table 1, we realize that the declared hourly and daily capacity, i.e. available slots, in the main operating hours between 06:00 and 23:00 differs among this peer group, with 797, 733 and 714 daily slots respectively, and 50, 50 and 42 peak hourly slots respectively. However, one could argue that the maximum capacity should be equal, since these European airports have to operate arrivals and departures on the runway under *mixed mode*. Based on the best-practice, as at the single-runway airport London Gatwick in the example with a capacity of 797 daily and 50 maximum hourly slots, the implication would be that these hourly and daily slots are potentially achievable, given the same technology and controller experience, for all airports within the same peer group.

So why is runway capacity not declared at the same levels for all "mature" single runway airports, such as the ones described? If demand is huge it should be in the public interest to expand the facilities as necessary. It will be explained below that setting capacity at certain levels is only reasonable in connection with LoS standards, which differ among airports.

The relation between actual demand and slot capacity is the capacity utilization (λ/μ), which is a strong first indicator of congestion (particularly for figures above utilization rates of 75%). For the airports Gatwick, Stansted and Stuttgart this means a peak daily demand in 2009 of 678, 408 and 370 flights respectively and consequently a peak daily slot utilization of 85%, 56% and 52% respectively, and a peak hour demand of 49, 38 and 35 flights and peak hourly slot utilization of 98%, 76% and 83%. These numbers decreased to rather low levels in 2009 due to the global financial crisis, but demand stabilized slightly in 2010. However, demand levels at these airports in April 2011 still show evident signs of recession, with current levels of 647, 372 and 301 daily flights (81%, 51% and 42% capacity utilization), respectively, and 45, 35 and 27 peak hourly flights (87%, 70% and 64% capacity utilization), respectively (http://www.flightglobal.com/articles/2011/03/24/354731/recession-obscures-european-airport-capacity-crunch.html).

Airport	IATA	Passengers in millions	Flights in thousands	Load Factor	Passengers per flight	Daily Capacity	Daily Capacity Utilization	Slots per hour	Peak Hourly Capacity Utilization	Runway Service Time (Inverse of hourly slots) in seconds
		2010	2010	2010	2010	2009	2009	2009	2009	2009
London-Gatwick	LGW	31.4	233.5	78.7%	134	797	85%	50	98%	72
London-Stansted	STN	18.6	143.0	76.9%	130	733	56%	50	76%	72
Stuttgart	STR	9.3	111.7	71.0%	83	714	52%	42	83%	86
Birmingham	BHX	8.6	84.8	74.1%	101	680	45%	40	70%	90
Berlin-Schoenefeld	SXF	7.3	65.5	75.3%	111	448	41%	26	65%	138
London-City	LCY	2.8	60.0	63.6%	47	646	37%	38	95%	95
Average		13.0	116.4	73.3%	101	670	53%	41	81%	92
Std. Dev.		10.4	65.1	5.4%	33	120	17%	9	13%	25

Table 1: Peak Daily and Hourly Slot Capacity and Utilization for Selected Single Runway Airports (Data from Eurostat, Slot Coordination and Flightstats.com).

III. AIRPORTS AS SYSTEMS OF QUEUEING SYSTEMS

For a better understanding of airport capacity and congestion problems, queueing theory gives great insights. As de Neufville and Odoni (2003: pp. 819-863) point out, all airport facilities can be described as systems of queueing systems, where arrivals at a service facility are randomly distributed, waiting lines form and users are therefore delayed and have to wait before being served.

A. *Free Flow for Free Mobility*

In the simplest case, objects, carrying information (i.e. bits or passengers), flow in a *first-come-first-served* (FCFS) sequence through a hub and spoke (node and link) network from origin to destination. If an aircraft traversing a link has to reduce speed to maintain a minimum separation to a preceding object, then this drop in velocity could feed back to the last object in a queue, when there are insufficient buffers to compensate for speed differences induced by leading flights. These *reactionary delays* propagate to all following flights in sequence without sufficient buffer times and therefore could result in additional costs to aircraft arriving hours later. An example of this process might be cars on a single lane road approaching a slow moving tractor in front. This will, in a short time, create a long queue behind the tractor; but in road traffic in general there are admittedly opportunities to overtake a slower vehicle that do not exist at or in the vicinity of airports.

So to avoid queues altogether, each flight needs to be able to move freely and seamlessly, *as if it were the only aircraft operating in the system*. In general airport capacity must be seen as a continuous flow of aircraft passing through the airport and airspace system, where each flight requests service at the airport and is in most cases served immediately or added to the end of a waiting queue in a FCFS discipline (de Neufville and Odoni, 2003: pp. 367-407). ATC manages the landing and take-off sequence and also handles communication with pilots. The critical common approach path is a defined space leading to the landing-end of the runway, which is shared by all aircraft approaching a particular runway during IFR conditions (Fig. 1).

Collectively Fig. 1, 2 and 3 show the different stages of a flight approaching an airport. Fig. 1 illustrates the flight approaching an entry gate of the terminal airspace area, where flights arriving from different directions are concentrated and separated for the final approach on the common approach path (Swart, 2003). Because of the bundling of flights, these are significant potential points of congestion and aircraft may be held at the entry in holding airspace. Fig. 2 is the typical graphic representation of the time and space separations applied by ATC and the varying aircraft speeds during the final approach beyond the entry gate in a so-called time-space diagram (Trani, 2005). The prime concern at airports is the maintaining of safety separations, because of the risk of an encounter with *wake turbulences* caused by the wings of a leading airplane. The airport management in collaboration with ATC seeks to *minimize* these separations to increase airport capacity to just about the legal safety minima. The last stage of a flight is the touchdown, where various deceleration maneuvers are conducted, before the aircraft exits the runway onto the taxiway system (Fig. 3). Here the airport management could influence the runway occupancy time (ROT) by building adequate runway exits for the prevalent aircraft categories.

Since the capacity is ultimately limited by the safety requirement of not allowing more than one aircraft on the runway at any one time, the capacity of a runway under mixed mode operation is in practice therefore mainly determined by the mean acceleration and deceleration speeds of departing and arriving aircraft and hence the headways between the aircraft (Table 2). London-Gatwick airport with a runway service time of 72 seconds per flight or a service rate, i.e. capacity, of 50 flights per hour is a prime example of an airport which utilizes its single runway to the maximum and allows very little idle runway time between subsequent flights (see Table 1).

As we can see in Table 2 not only the mandatory separation minima have an influence on overall capacity, but also the different speeds and the mix of different aircraft categories based on maximum take-off weight (MTOW). Today, the lowest separation between aircraft is 2.5 nautical miles (NM) under IFR on final approach (about 10 NM distance from the runway) given the required controller training and experience, runway configuration and radar equipment. In this case headways as low as 55 to 65 seconds and consequently capacities as high as 55 to 65 flights per hour could be achieved for a single runway.

Combinations of Heavy preceding Light aircraft in the sequence of arrivals or departures imply the most significant loss of precious server time and hence capacity, therefore a homogeneous mix of aircraft, which require only 3 NM, is most efficient in terms of capacity utilization (Table 2).

Aircraft Categories (1)			Radar Separation (1)		Radar Separation Headway at Take-off Speed		Inverse Radar Separation (Capacity)	
Preceding aircraft	Succeeding aircraft	MTOW	Nautical Miles (NM)	Kilometers (km)	250 km/h	300 km/h	250 km/h	300 km/h
Heavy	Heavy	>136 tons	4 NM	7.4 km	106 sec	89 sec	34 Ops/hr	40 Ops/hr
	Medium	7-136 tons	5 NM	9.3 km	134 sec	112 sec	27 Ops/hr	32 Ops/hr
	Light	< 7 tons	6 NM	11.1 km	160 sec	133 sec	23 Ops/hr	27 Ops/hr
Medium	Light	< 7 tons	5 NM	9.3 km	134 sec	112 sec	27 Ops/hr	32 Ops/hr
Other combinations and same categories			3 NM	5.6 km	81 sec	67 sec	44 Ops/hr	54 Ops/hr
Minimum on final approach			2.5 NM	4.6 km	66 sec	55 sec	55 Ops/hr	65 Ops/hr

Notes: (1) ICAO Doc 4444-RAC/501 (PANS-RAC) Part V Section 16 & Part VI Section 7.4

Table 2: Variation in headway and capacity due to different aircraft weights, separation minima and speeds

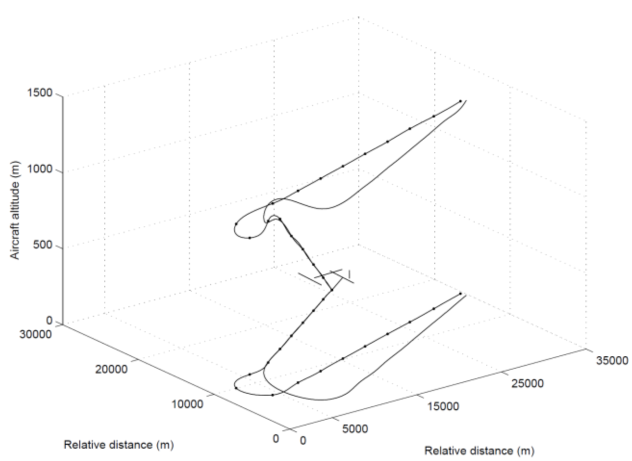

Fig. 1: Paths of two subsequent flights at Amsterdam Schiphol in 3-D space and as 2-D ground projection (Swart, 2003; http://www.math.leidenuniv.nl/scripties/Swart.pdf).

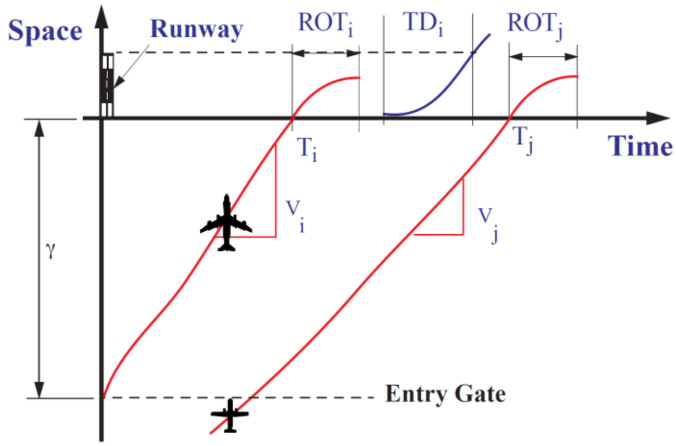

Fig. 2: Occupancy of time-space in runway occupancy time for landings and in take-off distance for departures on a mixed mode single runway (Trani, 2005; http://128.173.204.63/courses/cee3604/cee3604_pub/Time_space_diagrams_cee3604.pdf).

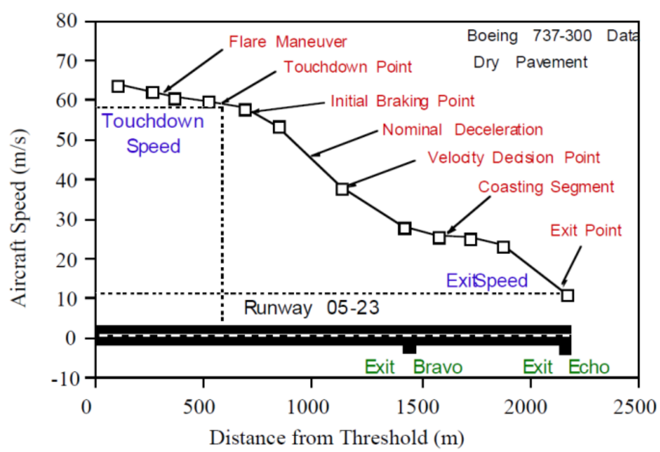

Fig. 3: Deceleration speeds during phases of a landing on a runway (Trani, 2000; http://www.nasug.com/200009/rot.pdf)

B. The Significance of Delays

Delays occurring during airport operations frequently become the center of attention (Vaze, 2009). In any "costs" of time, such as lost productivity from business travelers, these escaped opportunities increase non-linearly and accumulate quickly among the passengers concerned. Delays foremost induce considerable operating costs for airlines, such as fuel and crew costs. Due to the fact that random variation of traffic results in delays, these can accumulate even under normal conditions. Any overload conditions over prolonged periods during the day will result in significant delays. A rule-of-thumb is, therefore, that on average a server/queueing system, e.g. a runway, should never be utilized more than 75% of its capacity. Providing buffer- and idle server time between flights remains necessary for queues to dissolve after periods of dense traffic.

The buildup of aircraft delay for landing aircraft at airports was first studied theoretically by Bowen and Pearcey (1948). However, delays not only occur at runways and their respective holding areas, they can occur at any bottleneck (point of congestion) in the process chain of an airport as well. This may be the runway, the apron, the terminal facilities or any other "server", serving passenger, freight or aircraft.

C. Punctuality and Traffic Variability

Since air transportation is primarily a scheduled service, airlines significantly depend on punctuality of arrivals and do not appreciate a lot of variation in their operations, mainly to ensure the "turn-around" (unloading, refueling, loading, etc.) is accomplished on schedule to clear the aircraft for subsequent departure (EUROCONTROL, 2005). Moreover, from a commercial perspective airport management is interested in the timely freeing of space for subsequent arrivals with new passengers.

Variability of traffic is driven by probability distributions, whether from human, technical or natural variation. Technical variation is understood as disturbances resulting from different aircraft types, with regard to weight, flown distance and speed. Although weather and human factors are said to be unpredictable, even here certain regular patterns are widely recognized or currently under study, e.g. the study of seasonal effects.

Whereas in Fig. 4a we have Tokyo Haneda (HND) as a prime example of a punctual airport which exhibits very little variation in schedule, mainly due to serving short-haul domestic routes and a homogeneous mix of mostly Heavy type (see Table 2) aircraft, we see to the contrary London Heathrow (LHR) (Fig. 4b) an airport with a poor punctuality record, serving long-distance markets and a broader spectrum of aircraft types. At Haneda, 63% of the flights are on-time to the minute, whereas at Heathrow only about 5% of the flights were on-time during the days sampled. Other days of observation have been chosen to underline the differences in each case.

For airline scheduling, airport flow management but also for benchmarking purposes punctuality is expressed in *percentage of flights delayed less than 15 minutes*. Again, both airports presented certainly show extreme differences, with 98% of the flights being "on-time" at Haneda airport, i.e. delayed less than 15 minutes, and consequently only 2% of the flights severely delayed to only about 70% of the daily flights being on-time at Heathrow and up to 30% of flights severely delayed (Fig. 4a and 4b). On average (50% of the flights) we observe no delays at Haneda and about 4 to 5 minutes per flight at Heathrow. In practice, various literature suggests to never exceed an average LoS of 4 to 5 minutes.

In these examples the deviation from the scheduled times ranges from about 20 minutes before scheduled time to 20 minutes after scheduled time at Haneda airport, and from about 50 minutes before scheduled time to 70 minutes after scheduled time (thereby omitting some extreme outliers) at London-Heathrow. Recent studies take v*ariance* from the average as a measure of traffic variability from expected travel time.

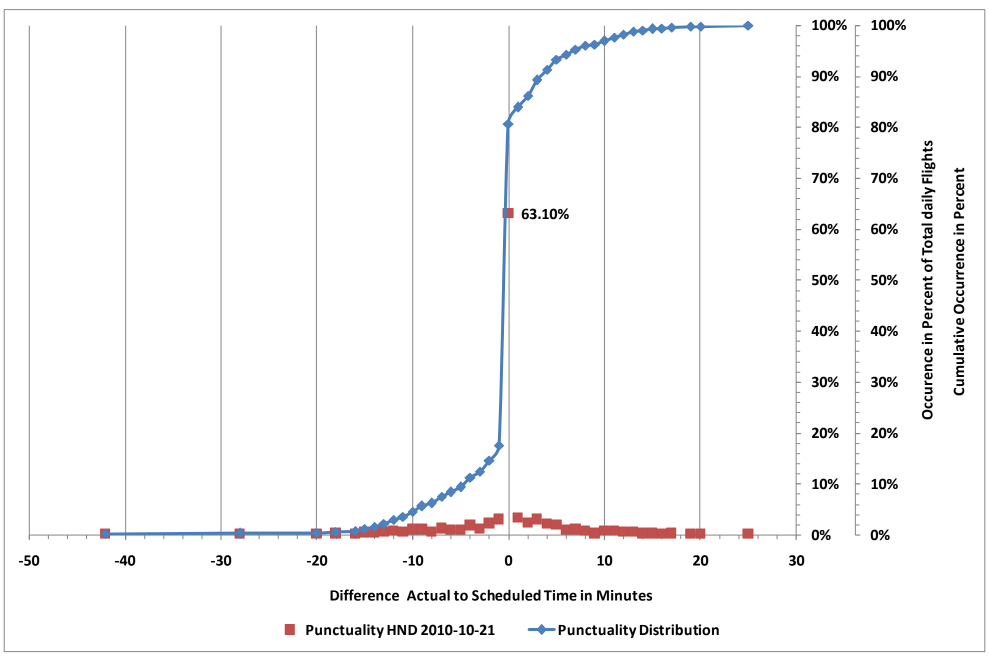

Fig. 4a: Punctuality at Tokyo Haneda airport in October 2010

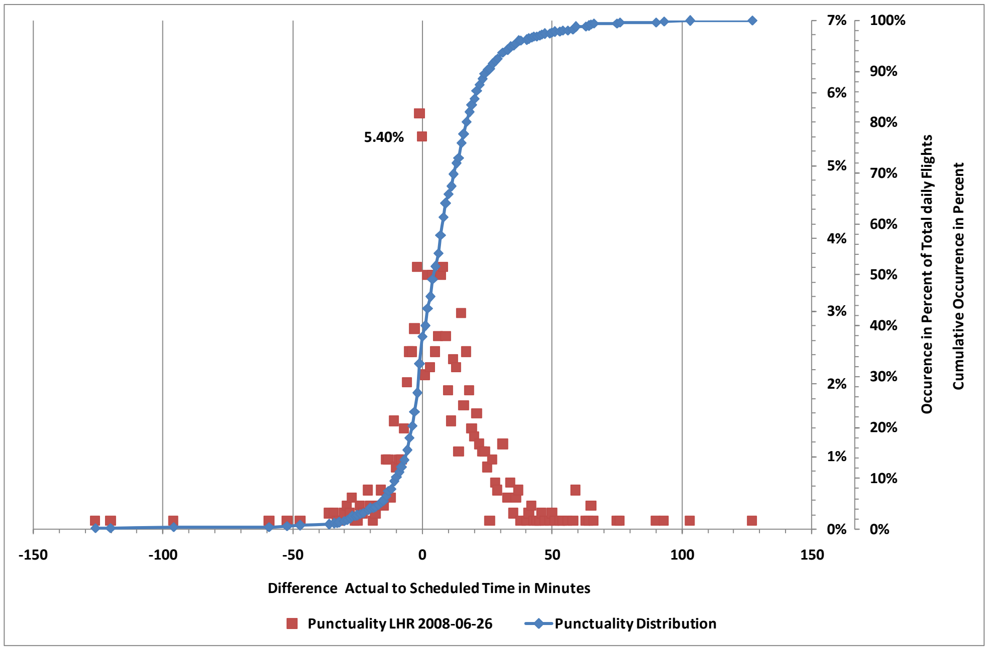

Fig. 4b: Punctuality at London Heathrow airport on a Peak Day in June 2008

D. Little's Law and Cumulative Diagrams

An outstanding contribution by J.D.C. Little (Little and Graves, 2008) provides the proof and broad applicability for approximating the average waiting time in a queue from the number of people in a queue and people arriving at the queue in a particular time, "Little's Law":

$$\text{(Mean) Waiting time (W) (in minutes)} = \frac{\text{(Mean) Number of Objects in the Queuing System (L)}}{\text{(Mean) Number of Objects Arriving } (\lambda) \text{ (per minute)}}.$$

Little's Law is particularly important for calculating an unknown in a queueing system, when the other two variables are known. In practice it could be easier (or cheaper) to control or to observe some variables than others, for example regarding a management decision to invest in surveillance equipment to monitor the service quality by observing number of people or objects in a particular queue. One astonishing fact that derives from Little's Law is that ultimately an airport system can be broken down into smaller units of interconnected queuing systems, consisting of waiting lines and persons in service, and resulting in an average waiting time for the passenger (Little and Graves 2008), where the output (passengers or aircraft) of one queue serves as an input for the next queue. Especially in the terminal facilities, passengers have to stay in the system for further processing, so no "information" is lost and passenger flows can be aggregated to be served from a few servers, i.e. runways, or disaggregated to be served by many servers, i.e. security lanes and check-in counters.

Little's formula is explained by a vivid example: For reasons of business travelling you need to make a flight on very short notice, and you have already arrived at the airport late. As you pass the check-in area, you are annoyed to find a queue some 75 meters long waiting in front of the security check. As your flight is scheduled in 30 minutes, it is vital to know how long you will have to wait to get through security. (For simplicity we will assume that everybody is getting inside, that people have already been entering the security check for some time and that the length of the queue remains stable for the time you are waiting).
You start with some simple observations and order-of-magnitude assumptions: Observing the queue for a few, say 4, minutes, you discover that 10 people arrive in the queue per minute on average and that there is, 1 meter between rows of people and one row consisting of two and a half people on average (Single individuals arrive as well as small groups of people). You quickly calculate that there are 188 people in the queue (2.5 people x 75 meters / 1 meter). While doing this you have moved 15 meters forward. Now there are some 60 meters of queue in front of you with about 150 people. Quickly applying your knowledge of Little's Law,

you learn that you have 15 minutes further to wait (150 people in the queue divided by 10 people arriving per minute) before entering the security check.
Passing through security check would take a few, say 5, additional minutes. From experience you know the walk to the gate will not take longer than 5 to 6 minutes. So now you can relax knowing you will make it to the gate in 25 to 26 minutes and hence to your flight on time.
What does this have to do with airport capacity you might ask? Well, this intuitive example can as well be applied to many operational problems, dealing with flows of passengers, cargo and/or aircraft at the airport. If an LoS is defined by airport management (e.g. a *maximum average delay of 4 to 5 minutes per flight* or maximum length of a particular queue), it is possible to control and manage the airport queuing system(s), and to translate this value to a certain maximum sustainable level. When this level is surpassed, an additional server would need to be opened to maintain the LoS or service time would need to increase. Such control and management systems would collect the necessary information from sensors and collectors in the airport process chain such as light barriers, cameras or wireless signal detectors for subsequent identification of objects and current state of condition of a particular queue or system.

The distribution of arrivals in a queuing system has been observed by Erlang (1909) for telephone connections to a call center. Similarly for airports as queueing systems, Fig. 5a and 5b show the distribution of intervals between actual succeeding arrivals and departures at London-Heathrow and Tokyo-Haneda airports, with scheduled flights shown separately. It is obvious that airlines prefer to schedule flights in bunches within the same minute at airports, or at 5 or 10 minute intervals. The distribution of actual flights does not fit the scheduled flights distribution, which means the inter-arrival times exhibit quite significant variations as compared to the schedule. At London-Heathrow (Fig. 5a) this is far more obvious than at Tokyo-Haneda airport (Fig. 5b).

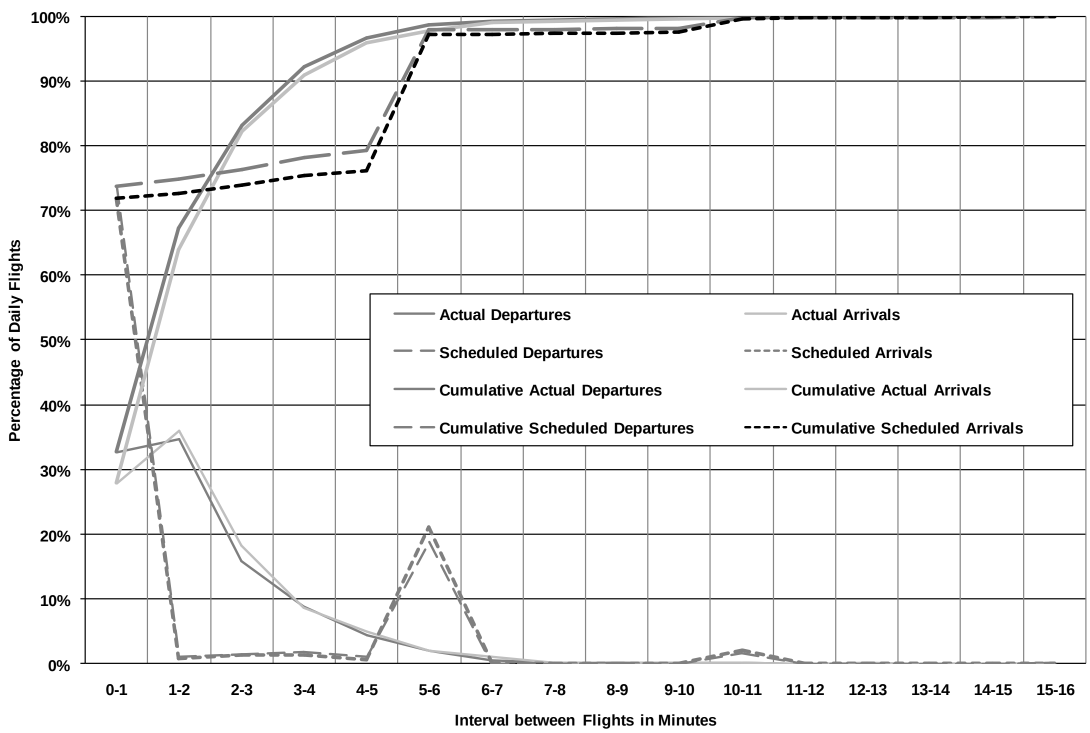

Fig. 5a: Scheduled and actual interval times of flight at London-Heathrow airport

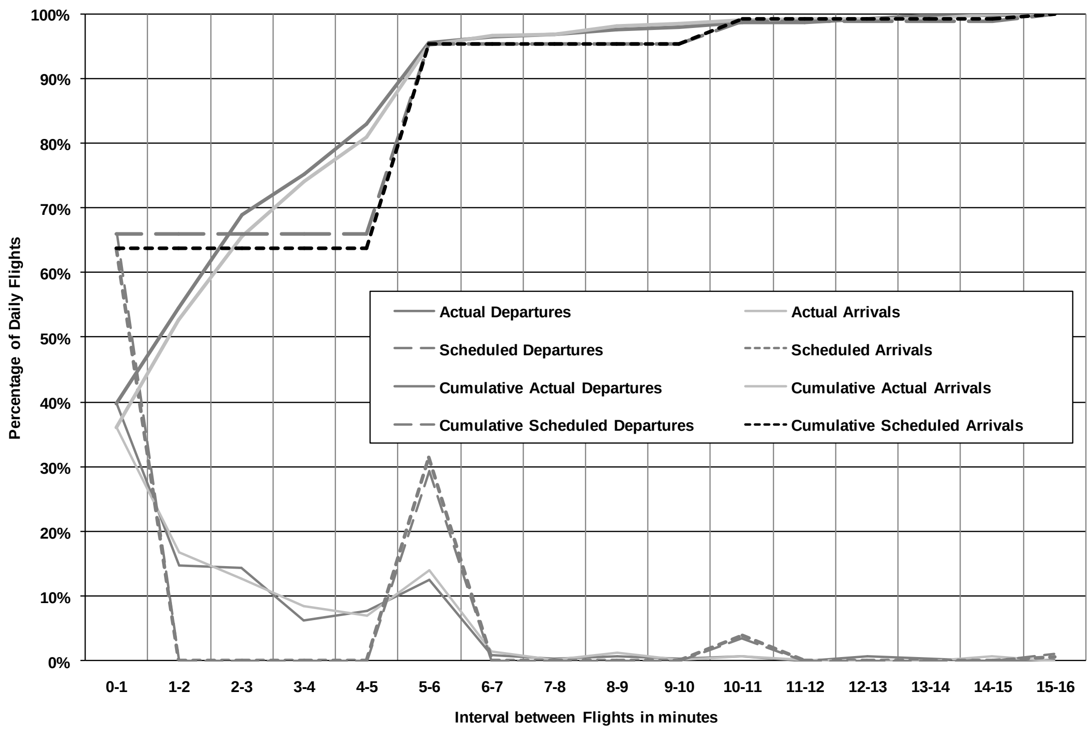

Fig. 5b: Scheduled and actual interval times of flights at Tokyo-Haneda airport

At Heathrow about 75% of the daily arrivals and departures are scheduled within a minute of each other; 20% of the flights are scheduled at 5-minute intervals; and about 3% are scheduled at 10-minute intervals. Of these flights only about one in three are actually operated within the same minute (corresponding to a demand rate of at least 60 flights per hour per runway), 35% of all flights are operated at intervals of more than one minute, but less than 2 minutes (corresponding to a demand rate of 30 to 60 flights per hour per runway) and about 15% of the flights are operated under 3 minutes (corresponding to a demand rate of 20 to 30 flights per hour per runway).

On average subsequent arrivals or departures are served in intervals of 60- and, say, 90-seconds (corresponding to a demand rate of about 40 flights per hour. This corresponds in order-of-magnitude to the inverse of the slot capacity of arrivals (44 per hour) and departures (44 per hour) at Heathrow of 82 and 82 seconds, respectively (Fig. 5a).

In contrast, at Haneda airport about 65% of the daily flights are scheduled in bunches of flights within a minute of each other, 30% are scheduled in intervals of between 5 and 6 minutes and about 5% are scheduled in intervals of less than 11 minutes. Of these scheduled flights, up to 40% are actually operated within a minute of each other, 15% are operated at an interval of between 1 and 2 minutes and surprisingly around 13% (compared to Heathrow with only about 3%) are operated with a 5 to 6 minutes headway between flights.

Haneda manages to reduce its delays by allowing larger breaks between arrivals and departures to relax the traffic flow. On average flights seem to be operated within 90 seconds and 2 minute intervals, which would correspond to a demand rate of 30 to 40 flights per hour per runway (Fig. 5b).

Since the flight schedule data only allows the calculation of the headway or interval between flights by the minute, it is not possible to derive more accurate distributions. The data already suggests, that arriving and departing flights follow more or less the same distribution. Consequently this means that airport management is not flexible enough to reduce the variation of the incoming flights in favor of the scheduled departing flights, by, for example, adjusting the turn-around times according to the delays.

However, it should be mentioned that the traffic mix at Haneda is different compared to that of London-Heathrow, with a higher percentage of Heavy aircraft. Hence Haneda manages to operate the airport with fewer flights but more average passengers per flight to achieve the same number of annual passengers as London-Heathrow (Table 3).

										Capacity in Flights per hour at AC Speed:					
Airport	PAX (2008)	Flights (2008)	PAX per Flight	% Heavy	% Medium	Daily Flights (08 - 20h)		Avg. Separation Minima in Nautical Miles		250 km/h		300 km/h		250 km/h	300 km/h
	in millions	in thousands				ARR	DEP	ARR	DEP	ARR	DEP	ARR	DEP	Total	Total
Tokyo Haneda	66.8	339.6	197	60%	40%	363	373	3.83	3.85	35	35	42	42	70	84
London Heathrow	67.0	478.5	140	40%	60%	532	556	3.63	3.66	37	37	45	44	74	89

Table 3: Descriptive data and capacity estimates for Tokyo-Haneda and London-Heathrow airports from aircraft sequences in actual flight schedules (Source: ACI, Flightstats.com)

During the main operating hours, the separation minima between the sequence of arrivals and departures at Tokyo-Haneda and London-Heathrow airport are applied to each flight according to its MTOW and turbulence category (distances of 2.5 NM have not been assigned in this example). This gives us a weighted average minimum distance of 3.84 NM for the flows in and out of Haneda airport and a distance of 3.65 NM for the flows at Heathrow airport. Depending on the most likely average speed of the aircrafts, these translate for example for average approach and departure speeds of 250 kilometers per hour into hypothetical total airport capacities of about 70 and 74 flights per hour, respectively over the main operating hours, and for 300 kilometers per hour into capacities of about 84 and 89 flights per hour, respectively (Table 3).
So this illustrates the calculation of maximum capacity in *average aircraft speed divided by average spacing* for arrivals and departures just by summing the minimum distances over a certain period of time. In fact capacity is directly proportional to aircraft speed and inverse proportional to the minimum separation (Gosling et al., 1983: p. 51).

Some argue that Little's Law is of small value when dealing with airports and fluctuations of daily and hourly demand, because processes in the airport are never stable over time and relevant queues rarely disappear completely (Vaze, 2009). Furthermore, the servers may operate above capacity at overload levels and therefore show rapidly increasing delays. At airports, the end of each operating day marks a natural break from further arriving demand, which gives room for any queues and accumulations of delayed flights to dissolve. To visualize the determinant of Little's formula and to further understand the fluctuation of demand, service rate and length of queue, we will now look at cumulative diagrams.
Generally applicable to traffic congestion problems are the *Newell*- or cumulative-diagrams. The data required to plot such diagrams are usually provided by the output of simulation programs (Fig. 6a and 6b), but can also be observed in reality given the financial resources, technology and manpower. Various sources, such as de Neufville and Odoni (2003) and Little and Graves (2008), point out the importance of such cumulative diagrams in revealing periods of heavy congestion, during which customers are queued and therefore delayed.

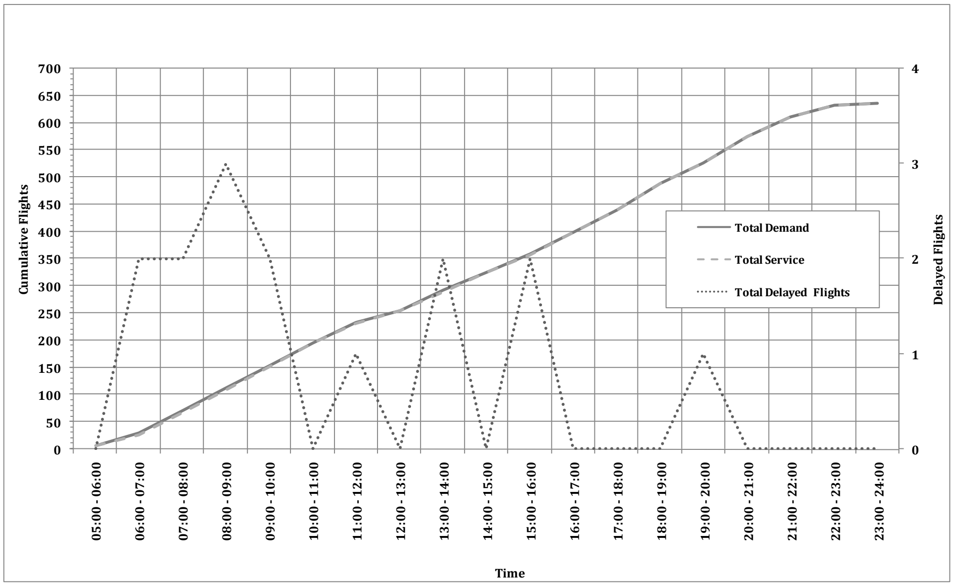

Fig. 6a: Cumulative diagrams of Berlin-Brandenburg International (BBI) airport baseline simulation output

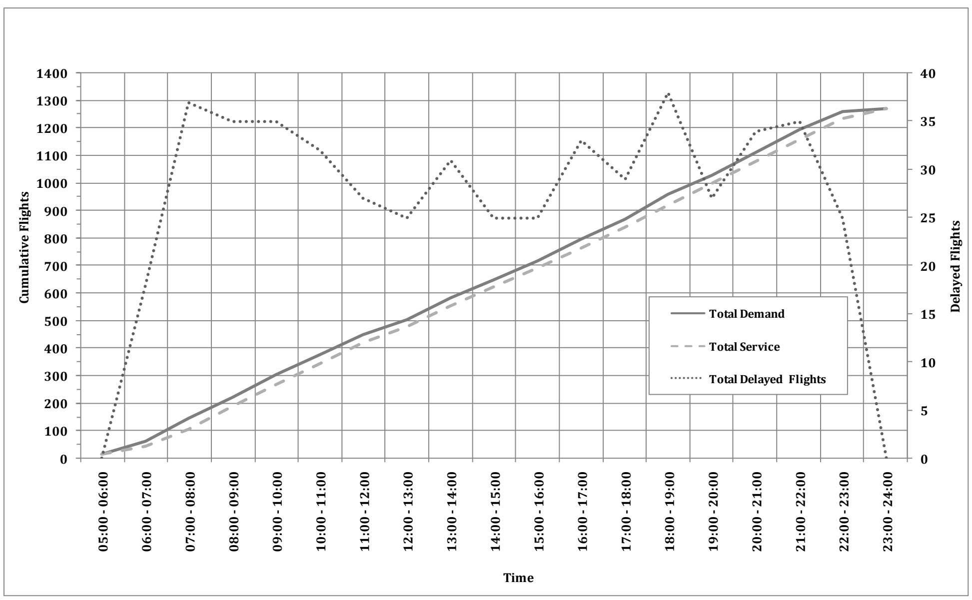

Fig. 6b: Cumulative diagrams of Berlin-Brandenburg International (BBI) airport 100% growth scenario simulation output

The three plotted functions in the figures 6a and 6b that are primarily required for interpretation stem from a simulation study of the Berlin-Brandenburg International (BBI) airport (currently under construction and scheduled for a summer 2012 opening), which was conducted with the airport/airspace simulation environment SIMMOD (developed by the Federal Aviation Administration [FAA] in the U.S.). The graphs illustrate the cumulative flights over time of day (demand rate), the flights requesting service over time of day (service rate/capacity) and the difference of both (vertical distance), the accumulating flights in queue. In the simulation study of BBI, first the baseline demand of 640 daily and 48 peak hourly flights of the combined schedule of the two airports to be phased out, Berlin-Tegel and Berlin-Schönefeld, was simulated; this revealed negligible delays (Fig. 6a). Then in a second step the baseline lights in the simulated schedule were doubled on the independent parallel runway configuration under construction at BBI in segregated mode (Fig. 6b).
The interpretation of the cumulative diagrams of the simulation output reveals that the 100% increase over the baseline demand and up to 90 peak hourly flights will be too much for BBI to handle. Subsequent studies have shown that the sustainable/practical capacity would be reached at a level 80% above the baseline

demand, at about 1100 daily and around 80 peak hourly flights, because from this point the LoS of 4 to 5 minutes of average delay per flight is clearly exceeded.

Compared to the baseline, Fig. 6b shows how the demand and service flows diverge and the number of delayed flights increases. Almost all the daily flights, but mainly the departures, from 07:00 onwards are queued and therefore delayed. The hypothetical waiting queue could reach a length of up to around 40 aircraft, and the average waiting time remains high at about 20 to 30 minutes per aircraft (measured in horizontal distance between demand and service function) (Fig. 6b). The slope of each cumulative graph defines the rate in aircraft per time unit.

IV. CONCLUSION

In this article the main determinants of air traffic punctuality and congestion at airports have been presented, in particular with regard to maintaining a sustainable LoS. We, as air transportation customers, expect seamless service and high schedule adherence, so capacity and service facilities must be expanded and planned in line with and even slightly ahead of demand.

To make some order-of-magnitude calculations with regard to congestion and delay, it is a good start for an analysis to begin with some basic capacity utilization figures from actual demand and declared capacity (Table 1). Furthermore airport management should closely monitor the punctuality of arriving and departing flights compared to schedule (Fig. 4a and 4b). Here the most popular determinant of punctuality is the percentage of flights delayed less than 15 minutes. From the same figures the determinant of LoS in average delay per flight can be isolated. This is certainly an inexpensive way for airport management to calculate adequate capacity for its airport and subsystems with regard to LoS, i.e. service quality, because if schedule adherence is high it could well be assumed that capacity equals demand at any given time.

When capacity is planned and slots are distributed, queuing from random distributions should be taken into account in the airport schedules, as was shown for Haneda airport (Fig. 5b). Therefore buffers should be implemented or slots should be restricted to relax the traffic flow from time to time during the day, to allow for queues to dissolve and for punctuality to return. It would therefore make sense for airport management to influence the scheduling of flights to smooth the traffic flow and minimize congestion delays by assigning flights to a particular minute or to introduce intermediate intervals of 2 to 5 minutes between flights, according to the actual arrival and departure distributions (Fig. 5a and 5b).

The application of Little's Law and the cumulative diagrams of arriving and departing aircraft from a particular queueing system could deliver further insights about the particular state of congestion (Fig. 6a and 6b). Here the objective for airport management should be in balancing the delay to an average of not more than 4 to 5 minutes per flight. The cumulative diagrams show that when overload situations occur, immediately waiting queues and therefore delays accumulate disproportionally. However, cumulative diagrams require the most information (especially regarding the customers arriving at and leaving a particular queuing system over time) from field observations and a large amount of preparation and calibration time to create a simulation scenario. Based on flight schedules and observed random distributions, we are now able to simulate both airport operations and future scenarios with increased "realism".

Ideally queues rarely form, and the service rate is equal to the demand rate, as was shown for Haneda airport and the BBI baseline scenario.

Results of such an airport capacity analysis could not only be reasonably represented by cumulative diagrams, but should nowadays (to reach a broader audience) be presented in the form of (4-D [3-D plus time]) animations of the queues as well. Adding data from Geographic Information Systems (GIS) (which could combine various sources of information such as satellite imagery, floor plans, population densities, noise or gaseous emission footprints etc.) to the mix of planning tools already discussed give those responsible for airport management a greater capacity for planning by looking the environmental impact involved (Fig. 7). In this manner the determinants of airport flight delays can be utilized to develop practical performance indicators to aid not only in planning capacity for the future but also to aid in increasing passenger and community satisfaction.

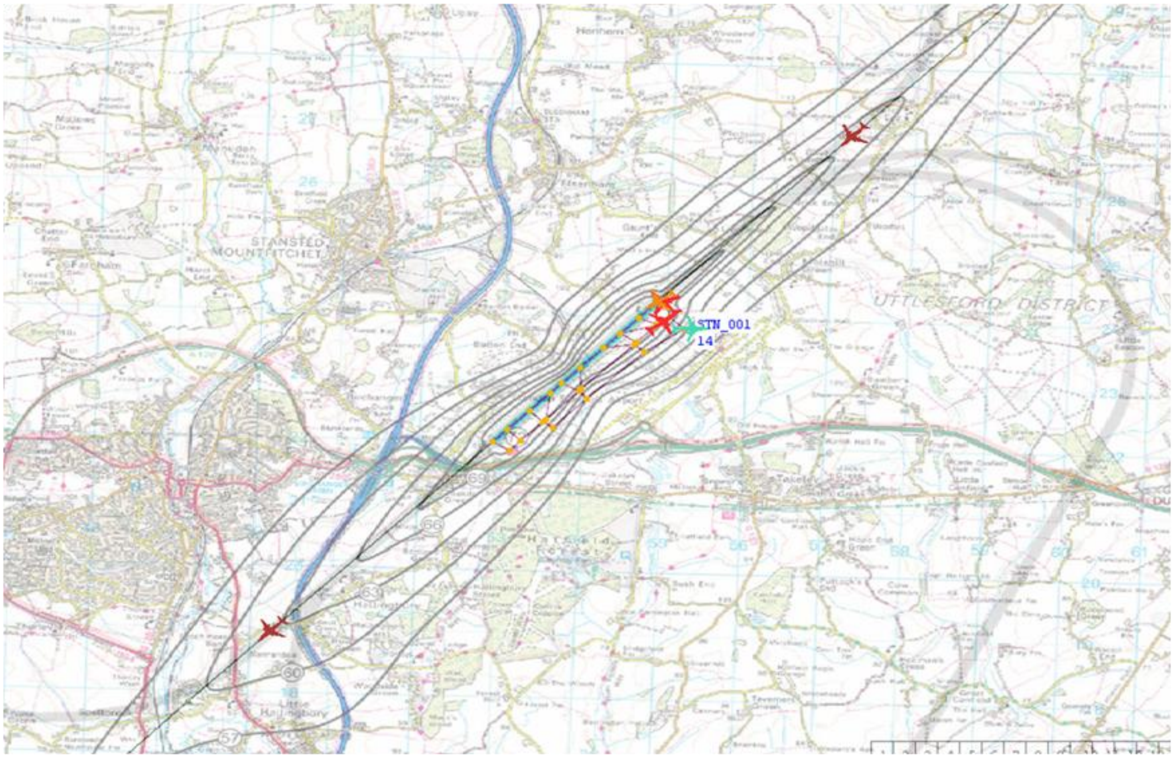

Fig. 7: Overlay of Noise and Population maps on airside traffic animation (and associated departure queue) at Stansted airport

ACKNOWLEDGEMENT

For the 50th edition of the Aerlines magazine, I want to personally thank the editors for their continuous voluntary commitment to maintaining this publication despite insufficient financial support. Especially for young aviation researchers, Aerlines magazine provides a forum where ideas, research efforts and interim results can be made public to laypeople as well as to specialists in the field. It also offers the opportunity to newcomers writing in the field to gain professional experience.

I wish Aerlines magazine a bright future and many more editions to come. Furthermore I hope young researchers will use this platform extensively in the future to reach interested readers and to promote their own original and creative work.

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