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Capacity dynamics and the formulation of the airport capacity/stability paradox: A European perspective

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A B S T R A C T

Access to capacity is often considered to be uncertain, causing airlines to build buffer times into their flight schedules in anticipation of potential delays. Similarly, air navigation service providers use capacity buffers to overcome potential safety standard violations. However, the use of excessive buffers is detrimental to cost efficiency in the air transport system. This paper improves our understanding of capacity predictability. The concepts of capacity dynamics and stability are taken as integral parts of an airport's plan to mitigate the risk of capacity degradation. Based on the concepts of capacity dynamics and stability, the capacity/stability paradox is introduced and discussed.

1. Introduction

If air traffic doubles by 2020, many European airports will struggle to accommodate demand, with an estimated 60 airports congested and the top 20 airports saturated 8–10 h a day (Eurocontrol, 2004). In April 2004, the European Commission (EC) initiated the Single European Sky (SES) performance-based framework, with the intention of changing the future structure of air traffic control across Europe. The ultimate objective is to replace step-by-step the air traffic management (ATM) working arrangements, which are largely based on national boundaries, by a more efficient ATM system based on flight patterns.

In support of SES, the EC also initiated the SES Air Traffic Management Research and Modernisation Programme (SESAR), an ambitious attempt to response to the ATM challenge. It has the objectives of enabling a three-fold increase in capacity; improving safety by a factor of ten; facilitating a 10% reduction in the environmental impacts of aviation; and providing ATM services at a cost which is at least 50% less than now (SESAR, 2006), which according to Eurocontrol (2005a) is currently €800 per flight gate-to-gate. The target for capacity enhancement is that the European ATM System (EATMS) can accommodate a 73% increase in traffic by 2020, based on a 2005 baseline, whilst meeting the targets for safety and quality of service.

Many factors cause increases in air traffic congestion and delays. According to Caves and Gosling (1999), the most important contributing factors are growing demand, lack of sufficient system capacity, hub-and-spoke networks, and environmental constraints. What is more, airports in particular and the air transport system in general are subject to fluctuations in demand and capacity. According to Janic (2000), the capacity of any airport component can be expressed by four different measures that represent capacity attributes: the physical infrastructure, fluctuations of demand over time, profiles of user entities, and the quality of service provision.

Because of the airport coordination process (European Commission, 2004), including slot scheduling, and air traffic flow management (ATFM), actual delays normally do not originate from lack of declared capacity. Airports have to declare capacity six months in advance and, for those 'scheduled' airports, the surplus traffic in saturated periods is transferred through slot negotiation to less busy periods. However, for a given flight schedule, based on declared capacity, any capacity fluctuation that is uncontrolled, unmanaged, or unpredicted, results in delay. Delay therefore originates from sudden and unpredicted capacity changes or, more precisely, from either inaccurate planning or lack of capacity stability.

Poor weather conditions and industrial actions in Europe are shown to be the most important factors that disrupt airline and airport schedules, generating congestion, delays, diversions and cancellations of flights (Janic, 2003). Meteorological conditions are, without doubt, the more dynamic and certainly the most unpredictable factor (Krollova, 2004). According to Eurocontrol (2005a), around 40% of airport ATFM delays and 10% of en-route delays are due to weather, often made worse by ineffective and reaction-based planning when such conditions occur.

Based on a Eurocontrol (2005a) performance review, the lack of gate-to-gate transit time predictability also incurs major annual

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resource costs for operators. To mitigate unpredictability and satisfy customers, airlines often build in buffer times to their flight schedules. By doing so, flights may suffer a short delay and yet be on time. However, the use of buffers is detrimental to ATM cost-effectiveness (Cook, 2007). For instance, it is estimated that a minute of buffer time for an Airbus A320 is worth €49 per flight. By cutting 5 min off 50% of schedules, some €1 billion per annum could be saved and better used by operators. It is also a common practice by air navigation service providers (ANSP's) to overcome potential safety standards violations through capacity buffers that enable controllers to reduce additional workload and stress caused by sudden and unpredicted capacity shortage.

Better knowledge of capacity fluctuations and mitigation of degradation could save the industry substantial costs. Predictability could be improved through better collaborative decision-making, system-wide information management (SWIM), better management of reaction to bad weather conditions and better control of take-off times. It is clear that the research community needs to pursue innovative approaches to modelling unpredictability in air transport operations to a greater extent and seek more cost effective approaches for operators.

2. Definition and interpretation of directional capacity dynamics

Most analysis has focused on static performance indicators and a deterministic approach to capacity assessment. However, little has been done to address the specific problem of capacity dynamics and planning for extraordinary capacity fluctuations. This often leads to the conclusion that the only way to mitigate airport delays is through capacity enhancement. However, this is by no means the only approach to deal with the problem.

The capacity of a system, airport capacity in particular, is subject to time and space changes. Some factors affecting runway capacity remain relatively static, in particular the number, configuration and inter-dependency of runways and the type of radio-navigational facilities. However, runway system capacity has often been shown to be unstable due to the dynamics and instability of many factors (Stamatopoulos et al., 2003) such as volume and time-dependent pattern of traffic demand, mix of inbound and outbound traffic flows, aircraft fleet mix pattern and meteorological conditions.

Although it is recognised that the lack of robustness of capacity assessment is heavily dependent on fluctuations of various factors, the marginal impact of those factors has rarely been analysed. Many factors affecting capacity are interdependent and influence each other. The rate of change of capacity is, therefore, not necessarily proportional to the rate of change of some specific factors, considered on an individual and isolated basis: one factor might be significantly improved and another slightly reduced yet the result is enhanced capacity. For instance, a reduction in runway occupancy time has little impact on capacity in some conditions of in-trail spacing minima. Similarly an increase in approach speed has little impact: although higher approach speed contributes to lower in-trail spacing minima, usually entailing higher runway occupancy time blocking out the potential benefit of lower in-trail time.

Capacity change can be analysed through a 'bottom-up' approach based on an *a priori* understanding of the system to be modelled. Seeking capacity optimisation by looking for sensitivity or 'what-if' scenario analyses cannot with certainty obtain the solution to represent a global optimum. Hence, the capacity dynamics concept aims at addressing and proposing a possible solution using such a 'bottom-up' approach, contributing to an *a priori* understanding of the system to be modelled. The purpose of the capacity dynamics concept is to quantify the instantaneous rate of capacity change, by estimating how quickly a change can occur at any specific point for use in goal-seeking optimisation.

If F={$f_1,\ldots,f_n$} represents the vector variable, a set of all the factors f_i that impact on capacity γ in varying degrees, then airport capacity is defined by a complex relationship $\gamma = \theta(f_1,\ldots,f_n)$ between all the factors f_i that affect it. Capacity can also be defined as a dynamic system characterised by a given state. The capacity state is the vector variable $\overrightarrow{S} = (v_1,\ldots,v_i,\ldots,v_n)$ determined by the collection of values v_i assigned to each factor f_i in such a way that, $\gamma = \theta(v_1,\ldots,v_i,\ldots,v_n) = \theta(\overrightarrow{S})$. Capacity can therefore be defined as a function of the n-dimensional capacity state, and the complex relationship that links each factor can be represented in a very general way by,

$$\theta : \Re^+ \times \ldots \times \Re^+ \to \Re_0^+ : \gamma = \theta(\overrightarrow{S}) \tag{1}$$

The capacity dynamics with respect to the various factors f_i is defined as the gradient of capacity γ with respect to these factors f_i. This capacity dynamics is noted $\delta(\theta(f_1,\ldots,f_i,\ldots,f_n))$, $\overrightarrow{\delta(\gamma)}$ or $\overrightarrow{\delta_\gamma}$, and is formulated as,

$$\overrightarrow{\delta_\gamma} = grad(\theta) = \nabla_{f_1,\ldots,f_n}\theta(f_1,\ldots,f_n);\ \forall f_i \in F \tag{2}$$

Whilst using the Leibniz notation, capacity dynamics can also be expressed as a column vector whose components are the partial derivatives of the capacity influencing factors f_i, as,

$$\overrightarrow{\delta_\gamma} = \begin{pmatrix} \frac{\partial\gamma}{\partial f_1} \\ \vdots \\ \frac{\partial\gamma}{\partial f_n} \end{pmatrix} \tag{3}$$

If capacity is expressed with respect to its possible states (Eq. (1)), then capacity dynamics is the gradient of capacity with respect to those states, and provides the direction to the most promising capacity state, i.e. the capacity optimum:

$$\overrightarrow{\delta_\gamma} = \overrightarrow{grad(\theta)} = \overrightarrow{\nabla_S\theta(\overrightarrow{S})} \tag{4}$$

The capacity dynamics vector shows the direction in which capacity changes most quickly. At any point, it describes the measure of the capacity slope: steepness, fall or incline. Some measure of the magnitude of this capacity change can be represented by a scalar. Let the 2-norm represent this measure. The 2-norm of a vector $\overrightarrow{v} = (v_1,\ldots,v_i,\ldots,v_n)$ corresponds to the Euclidean length and is defined as $\|\overrightarrow{v}\| = \sqrt[2]{\sum_i v_i^2}$. In particular, the magnitude δ_γ of the capacity change represented by the capacity dynamics vector $\overrightarrow{\delta_\gamma}$ is defined as,

$$\delta_\gamma = \left\|\overrightarrow{\delta_\gamma}\right\| \tag{5}$$

The capacity dynamics gradient also indicates how capacity changes in directions other than the direction of the largest change. It provides the airport planner with a quantification of the inclination of the field of capacity change potential at any point along a given trajectory of change, i.e. the magnitude of capacity dynamics indicates to airport planners and decision-makers how fast capacity changes in a given planning direction. Indeed, given the surface representing the field of capacity change potential, and given a unit vector on that surface, the inclination or grade of the surface in a particular direction is the dot product of the capacity dynamics with that vector. By analogy, consider a walker who attempts to reach the top of a hill, but who does not set off to climb a mountain. The gradient, at the point where the walker stands, points at the direction of the steepest slope. For instance,