Managing Airport Capacity and Demand: An Economic Approach

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Abstract. This paper reviews major research trends and opportunities in airport demand and capacity management from an economic perspective. Airport capacity constraints lead to operational congestion and delays, which have become major threats to the aviation industry. They impose large costs on airlines and their passengers. Uncertainty in demand or unexpected events can cause a mismatch between capacity and demand, resulting in either capacity oversupply, with a decrease in efficiency, or airport congestion over an extended period. Moreover, airport capacity is rather difficult to define due to its multi-faceted and dynamic nature, and it depends both on the available infrastructure and on operating procedures. The non-linear relationship between airport capacity and on-time performance offers guidelines for congestion mitigation through demand and capacity management. This paper explores and produces an in-depth understanding of the capacity and demand balance problem and provides a roadmap for including economic concepts when evaluating airport capacity expansions.

Keywords: airport management; strategic planning; capacity expansion; demand uncertainty; airport development.

1. Introduction: managing airport capacity and demand

Airports play a fundamental role in urban development and connectivity. They stimulate regional economic growth and provide a platform for linking different means of transport. Over the past decades, and despite recent traffic downturns due to the COVID 19 pandemic, airports have accommodated increasing numbers of operations. However, airport throughput is constrained by existing infrastructure and operational procedures. This implies that airports are limited in terms of capacity [1]. This potential imbalance between limited airport capacity and growing demand results in unwanted consequences that depend primarily on access policies. At airports with largely unconstrained access, we can find congestion and delays when demand exceeds capacity [2]. Meanwhile, at airports where access is restricted through coordinated slots, operating restrictions lead to demand loss or displacement to less preferred times or secondary airports [3,4]. Nevertheless, regardless of the established access policy, when expected demand approximates the available capacity, operational congestion appears [2]. Therefore, the growth of the air transportation sector has led to significant air traffic congestion worldwide. Flight delays, cancellations, and misconnections of passengers impose significant costs. The total annual cost of air traffic delays to the European economy was approximately € 17.6 billion in 2018 (in a pre-COVID scenario), with airport congestion being responsible for approximately 10% of this cost [5,6]. In general, there are two approaches to the congestion problem [4]: airports can act on the demand side (demand management mechanisms) or on the supply side (capacity management mechanisms). Related to these approaches, we can find three main categories when seeking measures to adjust the imbalances between capacity and demand [1,4]: (i) demand management, (ii) infrastructure expansion, or (iii) operational enhancements. The last two measures belong to the scope of capacity management, as illustrated in Figure 1.
These three interventions, although interdependent, can be complementary and usually represent a progressive sequence: airports first plan their capacity based on demand forecasts; then optimize operational procedures (on-ground handling and air traffic processes) to maximize capacity and minimize operating costs; and, last, they implement demand management schemes if capacity cannot attend airline demand with a certain level of service. Finally, in the long term, new capacity expansions may be needed to accommodate further growth in demand [7].

Approaches to managing capacity and demand can also be categorized on the basis of timescale relative to flight operations [8]: strategic planning typically occurs months or even years in advance, tactical adjustments arise on a daily basis up to a few hours before operations, and real-time interventions are implemented immediately. While demand management interventions or operational enhancements can be strategic or tactical, infrastructure expansions need time for planning, definition, approval, and implementation; thus, capacity expansion measures usually belong to the strategic class.

A third classification on major research trends and opportunities in airport demand and capacity management focuses on the potential impact on airport infrastructure [9]. This classification considers two approaches. The first one, called ‘hard’ management, is to expand airports (terminals, runways, aprons) so that this change in infrastructure provides a better match between the supply and demand of capacity. This approach solves the capacity shortage directly. However, capacity adjustment can only be achieved in the long term, as the planning and construction of major airport infrastructure is notoriously lengthy [7]. This time lag presents challenges to airport capacity planners and introduces a complex dynamic behaviour of development and investment, creating a demand for more flexible solutions [10]. It also highlights the problem of risk aversion of airport operators and, more generally, the problem of how expectations are formed regarding the likely investment return. The second approach, called ‘soft’ management, relates to strategic planning or tactical adjustments, and aims to control demand by improving the pricing and/or allocating mechanisms of airport capacity [3]. It introduces measures to achieve higher efficiency or enhance planning within the given capacity limitation, as this strategy does not have an impact on the infrastructure itself. Therefore, these ‘soft’ measures include operational enhancements to improve the efficiency, reliability, and sustainability of airport operations, given the available infrastructure, and can also include actions that aim to modify the temporal and/or spatial characteristics of demand through regulation or incentives [3,4]. Scheduling mechanisms can help to manage the expected air traffic based on demand forecasts. Therefore, ‘hard’ management refers to infrastructure expansion, while ‘soft’ management refers to operational improvements or demand management. The relationship between the different ways to classify airport capacity and demand management is depicted in Figure 2.

Figure 1. Schematic representation of demand and capacity management interventions (decisions are indicated in dashed lines).
Figure 2. Mechanisms for solving the congestion problem.

Airport management is driven by several performance metrics and requires the consideration of multiple criteria, such as ensuring safety, maximizing performance, easing operations, and reducing air traffic congestion, minimizing capital expenditures, and operating costs, warranting regional connectivity, and promoting environmental sustainability [11]. These goals can be aligned (e.g., mitigating congestion has a positive environmental impact as it can reduce noise, emissions, and fuel consumption), but can also imply trade-offs (e.g., increasing capacity in the long term requires significant investments and can lead to negative environmental impacts due to the potential increase in traffic). Additionally, airport management includes several stakeholders: airport operators, handling companies, airlines, passengers, air navigation service providers, civil aviation authorities, regulators, and local communities [1]. Managing demand and airport capacity generates complex decision-making processes, which require advanced tools to support and enhance policy and managerial choices. Furthermore, when analysing management measures aimed at easing the mismatch between airport capacity and demand, we need to consider not only the operational consequences of the available solutions, but also the economic structure and implications of these methods. In the long term, with important demand growth, only strategic capacity expansions (‘hard’ measures on the supply side) can solve the congestion problem. These ‘hard’ interventions have the greatest economic impact on airport financing, capital expenditure, and operating costs and therefore need to be adequately evaluated [12]. This paper provides some new insights into the management of airport capacity and demand from an economic perspective and provides a roadmap for including economic concepts when assessing airport capacity expansions.

2. Background: overcoming the traditional planning approach

There is a growing literature on the main opportunities to solve potential imbalances between airport capacity and demand, including the timing and scope of the different mechanisms (see [4], [8] and [13] for a comprehensive survey). However, the literature has primarily investigated the implications of ‘soft’ measures, which can reduce the financial burden of the solution, but are aimed at short/medium time horizons [3,14]. Ryerson and Woodburn [15] pointed out some reasons for airport operators to overlook or deem infeasible the mechanisms associated with demand management: narrow scope and limited impact; policy conflicts and uncertainty; low applicability in the long term; and economic development and airline hub services (large airports pursue capacity expansions to enhance their ability to accommodate flights, remain a hub airport, and provide intangible benefits to the community they serve). Furthermore, Fukui [16] demonstrated that demand management initiatives, such as slot allocation systems or congestion pricing schemes, are sometimes vulnerable to hoarding behaviours by carriers. For these reasons, airport operators may consider capacity expansions as better alternatives to accommodate growing demand while maintaining delay at an acceptable level. ‘Hard’ mechanisms aim to increase potential capacity through the development of new alternative airports or the expansion of existing ones, by changing the infrastructure itself, usually extending the current number of terminals,
runways, etc. These interventions can bring great increases in capacity and therefore solve the imbalances with demand directly. However, past studies [12,17] and recent infrastructure projects have shown that capacity expansions are costly, have a great impact on the volume and nature of the traffic at the airport, and are usually slow to implement. This usually implies a significant delay between expansion decisions and the final deployed capacity: an offset in time that increases the uncertainty underlying the development process, as both traffic demand and the operating environment may vary. Decision-making processes with regards to capacity expansions are likely to be affected by planning uncertainties, particularly variability in traffic demand [18], capacity dynamics and stability [19], and airport business models and airline competition [12]. The Airport Cooperative Research Program (ACRP) Report 76 [20] provides a complete list of uncertainties involved in airport long-term planning. Additionally, airports are part of the transportation network, where the effects of delays and congestion can easily propagate and where many stakeholders are involved. This increases the complexity of capacity extensions. To face uncertainties during the expansion process, de Neufville and Odoni [7] developed the concept of dynamic strategic planning in airports, which aims to develop flexible solutions beyond traditional what-if or sensitivity analyses. This concept evolved to the notion of dynamic adaptive planning [10] with the inclusion of modular solutions. A more flexible approach to airport planning should be complemented with a critical alignment of infrastructure development with the airport business and customer strategy [21]. As Leucci stated [21], airports are capital-intensive enterprises, so in order to manage the risk on large capital expenditure programs more efficiently, airport managers should adopt flexible solutions and a step-by-step approach to capacity increase. From an economic perspective, the varying and uncertain nature of airport capacity expansions also raises the problem of risk and loss aversion of airport managers as well as the issue of how expectations are framed as to the potential investment return. After briefly reviewing the economic implications of airport capacity and demand management measures, this paper focuses on the issues that ‘hard’ mechanisms entail, assessing the problem of capacity expansion with an economic approach.

3. Economic implications of airport capacity and demand management measures

As reviewed before, there are different available interventions for demand and capacity management, from marginal capacity increases to strategic initiatives to adjust demand, as well as tactical measures in response to dynamic real-time events like bad weather or schedule disruptions [8]. In the process of reducing the imbalances between demand and capacity, it is essential to appraise the economic implications of each possibility, highlighting the factors that can support the underlying policy, managerial, and operational decisions. From an economic perspective, ‘soft’ measures like airport demand management fall into the broader subject area of externality management. Specifically, the potential differences between demand and capacity create the scope for congestion externalities, and demand management aims to design welfare-maximizing strategies to allocate scarce airport capacity to airlines. Main economic issues for demand management approaches, such as congestion pricing or slot allocation process (e.g. auctions), are related to information requirements, time scale, airport mandate, monetary transfers, property rights, market concentration, and airline strategic incentives [3]. Other ‘soft’ interventions, such as operational enhancements, also involve airport management issues related to operations research and the theory of the firm (marginal analysis, rational choice, profit maximization and information symmetry). ‘Hard’ measures are related to the problem of capacity expansion. The economic rationale of investment decisions with respect to the development of an airport project requires identifying and measuring the benefits and costs (including externalities) during the life of the project. This poses several economic issues: the calculation of the net present value of the flow of net benefits and costs; the definition of feasible alternatives to the project; the institutional constraints of the market; and the government, airport, or airline policies. Economic benefits of airport expansions relate to relief congestion, comfort to passengers, reduction in access and waiting time, avoidance of traffic diversion to alternative travel modes or competing airports, reduction of operating costs, improvements in service reliability and predictability, and increases in traffic (deviated and generated). Finally, capacity expansion projects need to be evaluated considering: (i) economies of density: arising from increasing throughput through the existing infrastructure; (ii) economies of scale: arising from increasing
throughput by increasing infrastructure capacity, while keeping throughput density constant; and (iii) economies of scope: arising from combining different types of output through the existing infrastructure, while keeping density constant (as in airlines, output segmentation may consist of passenger and freight).

4. The problem of capacity expansion

Capacity planning is the process of determining the path of capacity provision levels over a planning horizon. In the context of the expected long-term demand growth, the core of this strategic planning process is intended to determine the optimal timing and level of capacity acquisition or ‘expansion’. The non-linear interactions between demand and supply for airport operations have long been recognized and studied [9]. Delay functions related to airport facilities are inherently non-linear, with average delays rising very rapidly and non-linearly as delays approach ultimate capacity. Therefore, airport expansion models should consider the non-linear response of delay to the system capacity utilisation rate. Moreover, a marginal change in capacity at congested airports may have a great impact on demand distribution, airline competition, airport types, fares, operating revenues, route map, and other characteristics of a given airport [12]. Behaviour after capacity expansion is highly dependent on the slot allocation structure: changing infrastructure may not merely affect the volume of traffic (operations, passengers, or cargo), but also the nature of this traffic and operations at the airport. In fact, larger airports are often more diversified to offer a greater variety of commercial facilities, which is intensified by capacity expansions. Additionally, overall social welfare is generally affected after changes in infrastructure in terms of increased connectivity, economic benefits, and negative externalities, including noise and local pollution. Regarding the method for determining the timing of new expansion projects, traditional airport master plans generally appeal to the trigger point approach [22]. For instance, when traffic reaches 90% of current capacity, predefined facility expansion projects are initiated. Such a timing approach is helpful when traffic keeps increasing steadily, but competitive conditions frequently lead to significant over- and under-utilization as the market adjust consumer and supplier responses. This policy can provide only guidance on the development of a single facility, and it would not apply to a group of interrelated facilities. In that regard, we can find two categories of capacity expansion approaches [7]: (a) macro-approaches: they address the airport as a whole, considering the interactions between components of the system (coordinated development); and (b) micro-approaches: they focus on individual components of the airport, isolating their needs (independent development).

Three main issues arise when approaching the capacity expansion problem: the definition of capacity, the stochastic nature of traffic demand and the economic perspective of the decision-making process.

4.1. Defining airport capacity

An important and challenging question for air transportation regulators is the definition and specification of capacity. Airport capacity is rather difficult to describe due to its multi-faceted and dynamic nature, and it depends both on the available infrastructure and on operating procedures. We can define capacity as the ability of a part of the airport to process entities (aircraft, passengers, luggage, goods, vehicles, etc.) during a specific interval of time [1,11]. It is measured in values such as passengers/year or operations/hour. However, this definition does not consider the implications of a required level of service and the possible presence of traffic congestion or acceptable delays. This particularity leads to the two commonly used concepts to describe airport capacity: throughput and practical capacity [7]. Throughput capacity is defined as the ultimate rate at which aircraft operations may be handled without regard to any small delays that might occur because of imperfections in operations or sudden random events. For a service facility to realize its throughput (maximum or ultimate) capacity there must be a continuous demand for service. Throughput capacity is truly the theoretical definition of capacity and is the basis for airport capacity planning [23]. Practical capacity is understood as the number of operations that may be accommodated over time with no more than a nominal amount of delay, usually expressed in terms of maximum acceptable average delay (level of service). Therefore, an important difference in these two measures of capacity is that one is defined in terms of delay and the other is not. The theoretical relationship between capacity and delay is illustrated in Figure 3 (a), which shows that delay is not a phenomenon occurring only at the limit of capacity. Some amount of delay will be experienced long before capacity is reached (leading to the formation of queues), and it grows exponentially as demand
increases. The term congestion describes a situation where demand is high in relation to capacity, and normal operations are thus compromised. On-time performance is highly sensitive to airport capacity and flight schedules [24]. This non-linear relationship between capacity and delay offers guidelines for congestion mitigation through demand and capacity management. From a supply perspective, airport performance is highly sensitive to even small variations in airport capacity. Figure 3 (b) shows a typical distribution of delays encountered by aircraft at a particular level of demand, in this case data are obtained from a busy day at a large European hub. Note that most delays are of short duration and that, even though the average delay is low (5 min), there are a few aircraft encountering relatively long delays of 15 min or more. The magnitude of delay is greatly influenced by the pattern of demand [2].

![Figure 3. Dynamics of capacity and delay [11].](image)

There has been a general lack of agreement on the specification of acceptable levels of delay applicable to all airports and their airfield components [23]. Because policies, expectations, and constraints differ from airport to airport, the amount of acceptable delay differs from airport to airport. Airport throughput can be reported in terms of annual or hourly traffic statistics [11]. Although annual figures can be useful for economic or financial viability studies, these measures do not effectively describe airport ‘operating’ capacity because they are mostly demand-driven: an airport with the same annual throughput can present different seasonal or daily patterns, or traffic peaks. Traffic peaking patterns, and hence hourly capacity should be considered for design or operational studies [4]. Many factors affect airport capacity: existing infrastructure, demand characteristics, airfield layout and passenger terminal configuration, process times, available resources, operational procedures, business models, external features, and airport curfews (which reduce the number of hours of airport operations) [23,25]. Indeed, airport throughput is highly conditioned by the factors that shape capacity and delay and shows significant variability when these factors are modified. Furthermore, an airport is a complex transportation facility, designed to serve aircraft, passengers, cargo, and surface vehicles. The capacity of a system can be understood as the lowest capacity of the components of the system [7].

4.2. Uncertainty in demand

Many sources of uncertainties are inherent in the airport development process [20]. These uncertainties can affect the overall volume of air traffic levels (e.g., annual or hourly enplanements, total or hourly number of aircraft operations, and cargo figures) as well as the mix of traffic (e.g., domestic versus international passengers and wide-body versus narrow-body aircrafts). Because of various uncertainties, traffic level can build up quickly to create severe congestion and it can also drop even faster, resulting in underutilized facilities [18]. Traditional airport planning approaches for incorporating uncertainty in the airport planning, such as what-if analysis and sensitivity analysis, are insufficient and can only provide a shallow understanding of future risks [22]. Beyond traditional planning analysis, with rigid and deterministic approaches to expected demand, the industry needs adaptive decision tools that establish the economic value of adding (or withdrawing) airport capacity, by considering the variability in airport activity levels. The influence of uncertainty on demand management mechanisms has been widely analysed [26]. Particularly, Sun and Schonfeld ([22]): Xiao, Fu and Zhang ([18]), and Wang and
Sparrow ([27]) explored the influence of demand on capacity expansion problems. They all reached the conclusion that high volatility in traffic demand requires to model airport capacity choice considering the presence of demand variability.

4.3. An economic perspective for capacity expansion

There are three main economic approaches to the capacity expansion problem: airport valuation (AV), cost-benefit analysis (CBA), and capacity/demand balancing (CDB). AV refers to the process of assessing the value of an airport or part of it [9]. CBA is the process used to measure the benefits of a decision (usually launching or not a project) minus the costs associated with taking that action, considering externalities such as environmental impact or regional connectivity, or even intangible effects like customer satisfaction [17]. CDB is the process of determining the optimal timing and level of capacity acquisition or expansion [7]. These approaches are interrelated but present some differences: AV refers to a potential expansion, CBA evaluates a given capacity project, and CDB tries to discover the timing and scope of the optimal project. Although AV and CBA can incorporate demand uncertainties (e.g., with a stochastic approach to cost functions that depend on traffic), the inclusion of variability in demand arises naturally and is a fundamental issue in CDB (with demand scenarios and non-deterministic demand models). Regarding airport capacity and demand management, the economic framework should evolve to the process of assessing the value of additional passengers or additional capacity at an airport. It should aim to qualify and quantify the main relationships and trade-offs between capacity, quality of service, and profitability [9]. This is particularly challenging when considering the value of a marginal change in capacity in congested airports, due to the non-linear relationships between the variables involved and the varying and uncertain nature of traffic demand [12].

5. Conclusion: a new economic roadmap for airport capacity expansion

This paper has outlined the different available interventions for airport demand and capacity management, focusing on infrastructure interventions. We have appraised the economic implications of each possibility, highlighting the factors that may support the underlying policy, managerial, and operational decisions. We have obtained several insights into the problem of capacity expansion. First, airport capacity is rather difficult to define due to its multi-faceted and dynamic nature, and it depends both on the available infrastructure and on operating procedures. In addition, airport throughput is highly conditioned by factors that shape capacity and delay and shows significant variability when these factors are modified. Second, a marginal change in capacity at congested airports may have a great impact on demand distribution, airline competition, operating revenues and costs, and other characteristics of a given airport. Third, on-time performance is clearly non-linear, and thus sensitive to variations in demand and capacity. Last, airport expansion management involves a trade-off between mitigating congestion and maximizing capacity utilization, so decision-making tools are required to support and improve policy and managerial choices. Considering the discussion provided in this paper, we can draw several recommendations to provide a new approach to the problem of airport capacity expansions:

- Identify the sources and extents of uncertainty surrounding the planning process, and locate which uncertainties might be alleviated through increased flexibility in the design process.
- Move towards a stochastic approach that considers those uncertainties, particularly the varying nature of traffic demand.
- Characterise the capacity of the different elements of the airport (including the related economic factors) and identify the development objectives of the infrastructure system.
- Include the cost of delay, the cost of congestion, and the economic value of additional airport capacity as part of the decision framework.
- Evaluate the effects of economies of density, scale, and scope in infrastructure extension.
- Consider the problem of risk and loss aversion of airport managers as well as the issue of how expectations are framed as to the potential investment return.
- Appraise the effects of a marginal change in capacity, particularly at congested airports.
- Develop decision-making tools that improve policy and managerial choices, and involve all relevant stakeholders.
References

[1] Ashford N J, Mumayiz S and Wright P H 2011 *Airport Engineering: Planning, Design, and Development of 21st Century Airports: Fourth Edition* (New York: Wiley & Sons).

[2] Rodríguez-Sanz Á, Comendador F G, Valdés R A and Pérez-Castán J A 2018 Characterization and prediction of the airport operational saturation *J. Air Transp. Manag.* 69 147–72.

[3] Gillen D, Jacquillat A and Odoni A R 2016 Airport demand management: The operations research and economics perspectives and potential synergies *Transp. Res. Part A Policy Pract.* 94 495–513.

[4] Jacquillat A and Odoni A R 2017 A roadmap toward airport demand and capacity management *Transp. Res. Part A Policy Pract.* 114 168–85.

[5] EUROCONTROL 2019 *CODA (Central Office for Delay Analysis) Digest: All-Causes Delay and Cancellations to Air Transport in Europe - 2018* (Brussels: European Organisation for the Safety of Air Navigation (EUROCONTROL)).

[6] Performance Review Commission 2019 *Performance Review Report—An Assessment of Air Traffic Management in Europe during the Calendar Year 2018* (Brussels: European Organisation for the Safety of Air Navigation (EUROCONTROL)).

[7] Neufville R de, Odoni A R, Belobaba P and Reynolds T 2013 *Airport Systems: Planning, Design, and Management* (New York: McGraw-Hill).

[8] Barnhart C, Fearing D, Odoni A and Vaze V 2012 Demand and capacity management in air transportation *EURO J. Transp. Logist.* 1 135–55.

[9] Gurtner G, Cook A, Graham A and Cristóbal S 2018 The economic value of additional airport departure capacity *J. Air Transp. Manag.* 69 1–14.

[10] Kwakkel J H, Walker W E and Marchau V 2012 Assessing the efficacy of adaptive airport strategic planning: results from computational experiments *Environ. Plann. B Plann. Des.* 39 533–50.

[11] Horomjeff R M, McKelvey F X, Sproule W J and Young S 2010 *Planning and Design of Airports* (New York: McGraw-Hill).

[12] Adler N and Yakhemsky E 2018 The value of a marginal change in capacity at congested airports *Transp. Res. Part A Policy Pract.* 114 154–67.

[13] Zografos K G, Salouras Y and Madas M A 2012 Dealing with the efficient allocation of scarce resources at congested airports *Transp. Res. Part C Emerg. Technol.* 21 244–56.

[14] Vaze V and Barnhart C 2012 An assessment of the impact of demand management strategies for efficient allocation of airport capacity *Int. J. Revenue Manag.* 6 5–27.

[15] Ryerson M S and Woodburn A 2014 Build Airport Capacity or Manage Flight Demand? How Regional Planners Can Lead American Aviation Into a New Frontier of Demand Management *J. Am. Plan. Assoc.* 80 138–52.

[16] Fukui H 2012 Do carriers abuse the slot system to inhibit airport capacity usage? Evidence from the US experience *J. Air Transp. Manag.* 24 1–6.

[17] Jorge J D and de Rus G 2004 Cost-benefit analysis of investments in airport infrastructure: A practical approach *J. Air Transp. Manag.* 10 311–26.

[18] Xiao Y, Fu X and Zhang A 2013 Demand uncertainty and airport capacity choice *Transp. Res. Part B Methodol.* 57 91–104.

[19] Desart B, Gillingwater D and Janic M 2010 Capacity dynamics and the formulation of the airport capacity/stability paradox: A European perspective *J. Air Transp. Manag.* 16 81–5.

[20] Kincaid I, Tretheway M, Gros S and Lewis D 2012 *ACRP Report 76: Addressing Uncertainty About Future Airport Activity Levels in Airport Decision Making*. Transportation Research Board of the National Academies, Washington, DC. http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_076.pdf.

[21] Leucci G 2016 Infrastructure development/investment (why airports invest) *J. Airpt. Manag.* 10 266–72.

[22] Sun Y and Schonfeld P M 2017 Coordinated airport facility development under uncertainty *Transp. Res. Rec.* 2603 78–88.

[23] Young S Y and Wells A T 2019 *Airport planning and management* (New York: McGraw-Hill).

[24] Wu C L 2012 *Airline operations and delay management: Insights from airline economics, networks and strategic schedule planning* (Routledge: Oxon).

[25] Ashford N J, Stanton H P M, Moore C A, Coutu P and Beasley J R 2013 *Airport Operations* (New York: McGraw-Hill).

[26] Shone R, Glazebrook K and Zografos K G 2019 Resource allocation in congested queueing systems with time-varying demand: An application to airport operations *Eur. J. Oper. Res.* 276 566–81.

[27] Wang J and Sparrow F T 1999 The cost of uncertainty in capacity expansion problems *Int. J. Energy Res.* 23 1187–1198.