Infrastructure Investment as a Real Options Game: The Case of European Airport Expansion

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This article analyzes the optional and strategic features of infrastructure investment. Infrastructure investments generate other investment opportunities, and in so doing change the strategic position of the enterprise. A combination of real options theory and game theory can capture the elusive value of a strategic modification of a firm's position in its industry. My model focuses in particular on an analysis of European airport expansion. Airports with infrastructures that are less constrained by growth regulations capture more value, because they are in a better position to exercise growth options available in the airport industry.

For a firm with growth opportunities, infrastructure sets the stage and creates the strategic context in which the firm can flourish. Although the nature of infrastructure development—investment in land, distribution, communication, human capital, or technology—depends on the type of business, its defining characteristic is that it generates other investment opportunities. By setting the path for investments to follow, infrastructure development helps create the necessary platform for the firm's growth potential and thus shapes the strategic position of the enterprise.

Few investment opportunities, whether they strengthen core capabilities or access new geographical locations, exist in a vacuum, and they should therefore be considered in their strategic and competitive context. Because such opportunities are often contingent on follow-on investments, they can be viewed as a bundle of real options. By integrating real options valuation with game theory principles, we can make a more complete assessment of strategic growth option value in an interactive competitive setting.

I focus on European airport expansion, taking a detailed look at a specific application and validating the more general option games approach. I explain developments in the European airport industry by considering the infrastructure of each airport as a firm-specific asset (platform) that generates a set of sequential expansion options in a context of competitive responses and changing market conditions. Such investments in land, terminals or runways are typically indivisible or "lumpy" which introduces an important tradeoff between flexibility and commitment in an airport's growth strategy.[1] However, limited overall growth or local growth restrictions might foreclose exercising certain expansion options in the chain of sequential investments. When local growth becomes restricted for large airports, it is still possible to invest in regional

[1]Pindyck (1988) shows that the future growth value of the firm can be considered as a chain of sequential capacity expansion options.

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airports or international strategic network acquisitions that can create value by jointly exploiting economies of scale or other core competencies.

Although I apply the option games approach to the airport industry, it can be generalized to infrastructure investment in other industries. For instance, it can be applied in the context of corporate infrastructure, platform, or R&D investment in volatile industries such as information technology, electronics, and pharmaceuticals.

Models combining game theory and options are typically based in continuous time and are developed from a theoretical perspective. Often, researchers assume that firms have the same costs or produce only one unit forever (if they are active in the market), and that the inverse demand curve is generic. Although interesting theoretical issues are investigated through these continuous-time models, the models are not readily applicable for practical valuation purposes. In practice, firms are not generally homogeneous. The underlying stochastic variables are seldom likely to follow a geometric Brownian motion, in particular for applications other than in natural resources. The firm must choose not only the optimal timing of an expansion but also the optimal capacity to install. It is much easier to handle asymmetries between competitors and to define alternative stochastic processes with a discrete time approach. Such an approach is thus better suited for the practical application of the options-game approach to investments in real markets. The resulting analysis is also more accessible for corporate managers, since it does not require in-depth knowledge of stochastic calculus and differential equations. Therefore, for simplicity and accessibility, I present my application of a sequential exercise game in discrete time.

The paper is organized as follows. Section I describes the relevant literature. Section II examines infrastructure investment and developments in European air traffic. Section III presents the valuation model for infrastructure investment strategies. Section IV applies the model to the expansion possibilities of European airports. The final section summarizes the insights gained and discusses relevant implications.

I. The Real Options Game Literature

An important contribution of real options theory to the valuation literature is that it shows that the optimal trigger value at which a firm should invest must be well above the investment cost (i.e., there should be a large positive NPV) due to the option value inherent in a "wait-and-see" approach (McDonald and Siegel, 1986; Dixit and Pindyck, 1994). In the early literature on real options, researchers either ignored competitive entry or assumed that it was exogenous.[2] However, if there is (the threat of) competition, whereby each firm's payoff is

[2]In the development financial literature on real option valuation in the last decades, Baldwin (1982) finds that optimal sequential investment may require a positive premium over net present value (NPV) to compensate for the loss of future investment opportunities. Kester (1984) discusses concepts of the strategic and competitive aspects of growth opportunities. Baldwin (1987) and Trigeorgis (1991) show that a firm anticipating future competitive entry at a specified time will invest earlier for preemptive reasons. Other studies, e.g., Aguerrevere (2003), Brennan and Schwartz (1985), Childs, Ott, and Triantis (1998), Ingersoll and Ross (1992), Kemna (1988), Majd and Pindyck (1987), McDonald and Siegel (1986), Myers (1987), Titman (1985), Trigeorgis (1993), and Trigeorgis and Mason (1987), examine various valuation models for real options. There are several books on real options valuation. Dixit and Pindyck (1994) provide an excellent study on the economic foundations for investment under uncertainty. The books of Amram and Kulatilaka (1999), Baldwin and Clark (2000), Copeland and Antikarov (2001), Schwartz and Trigeorgis (2001), and Trigeorgis (1986, 1996) present good overviews of the real options literature and its various applications. Smit (1996) and Smit and Trigeorgis (2004) focus on the integration of strategy and valuation and discuss applications of real options and games. The books of Grenadier (2000a) and Huisman (2001) cover continuous-time models from a theoretical perspective.

affected by the actions of other players, competitive interaction can again change the optimal investment criterion.[3] Only recently have strategic considerations, particularly with regard to imperfect competition, been treated in a formal and rigorous fashion in the financial economics literature.[4]

Competitive strategies using option and game-theory principles are discussed in Smit and Ankum (1993). Dixit and Pindyck (1994) consider two competitors who can strategically time their investment decisions (for given output choices) and show that the first firm enters earlier (and the second firm later) when there is no threat of competition. Kulatilaka and Perotti (1998) show that in a Cournot duopoly setting, the first to invest can gain a strategic advantage, since market share and the value of early investment increase more with higher demand uncertainty than does the value of waiting. Perotti and Kulatilaka (1999) consider a Stackelberg growth option when a firm has a first-mover advantage and also conclude that higher demand uncertainty justifies earlier exercise of the growth option.

Grenadier (2002) shows that the Nash equilibrium exercise strategies are the same as those obtained in an artificial, perfectly competitive equilibrium with a modified demand function, and provides a general solution for equilibrium investment strategies in a Cournot-Nash oligopolistic setting. Thus, one can leverage on the continuous-time results under perfect competition to obtain results for an imperfectly competitive setting. Pawlina and Kort (2001) examine the impact of investment cost asymmetry on the value and exercise strategies of firms under imperfect competition. If the cost asymmetry is small, the firms invest jointly, but if it is high the lower-cost firm preempts its competitor. If the cost asymmetry is sufficiently large, the firms will enter sequentially. In Spencer and Brander (1992), a firm makes a tradeoff between a Stackelberg leadership approach vs. a wait-and-see strategy that results in a simultaneous output game with its rival. They deal with rivalry and the timing of output decisions as a consequence of the degree of idiosyncratic uncertainty for each firm.

Smit and Trigeorgis (2001) analyze two-stage games where the investment strategy depends on the type of competition (Cournot or Bertrand competition). The authors study the situations in which a firm that can optimally choose its timing and output decisions may be justified in hastening a strategic investment (e.g., R&D or an advertising investment), and when it should wait or abandon. In Perotti and Rosetto (2002), a firm may pursue different competitive entry strategies, depending on the degree of strategic advantage that investing in the growth opportunity provides. If the strategic advantage acquired via the investment is small, the firm becomes a leader, but is induced to invest prematurely to preempt its competitor. If the advantage is high, the firm can enter at the optimal time without fear of preemption, as if it were a monopolist.

In many real-world situations, agents must formulate option exercise strategies under imperfect information. In such a setting, agents may infer the private signals of other agents through their observed exercise strategies. The building of an office building, the drilling of an exploratory oil well, and the commitment of a pharmaceutical company to the research of a new drug all convey information to other market participants. McGahan (1993a) shows the

[3]The tradeoff between flexibility and commitment of irreversible investment is well documented in the early IO literature. Dixit (1979, 1980, 1989) and Spence (1977, 1979) provide in-depth treatments of investments (such as building excess capacity) designed to preempt competitive entry. Anderson and Engers (1994), Caballero and Pindyck (1996), Dixit (1999), Spencer and Brander (1992), Green and Sadanand (1991), and Sadanand and Sadanand (1996) model an incumbent firm facing the tradeoff between firm scale and preemptive investing against the option and information value of waiting.

[4]The competitive exercise of options has been the subject of several articles in the financial-economic literature. Constantinides (1984), Emanuel (1983) and Spatt and Sterbenz (1988) analyze the competitive exercise of warrants and convertible bonds.

effects of incomplete information about demand on preemption. Grenadier (1999) develops an equilibrium framework for option exercise games with asymmetric private information. This framework allows many interesting aspects of the patterns of equilibrium exercise to be analyzed. In particular, informational cascades, where agents ignore their private information and jump on the exercise bandwagon, may arise endogenously. Lambrecht and Perraudin (2003) consider entry exercise strategies with preemption effects under incomplete information about the competitor's entry threshold and investment amount. Incomplete information prevents investors from "marginally" preempting their competitors (as may usually be the case in complete information models), and consequently a greater portion of the option value of waiting is preserved. Incomplete information can help explain why firms in practice may delay their entry beyond the breakeven trigger.

The combined option and game approach is particularly appropriate for R&D valuation[5] due to the "winner-takes-all" nature of the patent system. Milterson and Schwartz (2003) study an *optimal stopping time* problem of R&D investment where firms learn investing in competitive markets in the sense that investments take time and information is revealed while investing, so that it becomes optimal to prematurely abandon the investment even before completion. Weeds (2002) derives optimal investment strategies for two firms that compete for a patent that may help explain strategic delay in patent races and shed some light on the role of first vs. second movers. Lambrecht (2000) and Weeds (2000) consider innovation with uncertainty over completion and time delays, which can explain phenomena like faster exit ("reverse hysteresis") and delayed commercialization ("sleeping" patents). Although innovation is perhaps an obvious context in which completion uncertainty arises, many physical investments also take time to build and there is often uncertainty over exactly when the project will be completed. Building a factory, opening a mine, sinking telephone cables—all take time to complete and the completion date is likely to be uncertain. Mason and Weeds (2002) consider more general strategic interactions with externalities that may justify why investment might sometimes be speeded up under uncertainty.

Williams (1991, 1993) and Grenadier (1996) develop continuous-time models for exercise strategies in real estate development.[6] Grenadier's (1996) analysis of the timing of real estate development can help provide an explanation for why some markets may experience building booms in the face of declining demand and property values. Developers, fearing preemption by a competitor's exercise, may proceed into a "panic" equilibrium in which all development occurs during a market downturn.

Applications described in Lambrecht (2004) explain takeover activity.[7] Unlike financial options, the exercise of merger options is also influenced by strategic considerations since the payoff to each merged firm ultimately depends on the post-merger ownership share it obtains in the new firm. Lambrecht (2004) presents a real options model for the timing and terms of mergers and takeovers motivated by economies of scale, providing an explanation for the procyclicality of merger waves. Smit (2001) describes a real options game framework for Pan-European consolidation strategies through a series of synergistic deals in fragmented industries.

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[5]Smit and Trigeorgis (1997) analyze two-stage R&D games in which the investment opportunity value depends on endogenous competitive interactions. The modification of the strategic position of the firm is related to the degree of incomplete information, the existence of learning effects, and the willingness to compete or form joint research alliances. Garlappi (2002) analyzes the impact of competition on the risk premia of ownership claims to R&D ventures engaged in a multiple-stage patent race.

[6]See Burlan, Mayer, and Somerville (2002) for evidence from real estate development of the strategic exercise of real options.

[7]The idea of an acquisition as a real option is introduced by Smith and Triantis (1995).

In other applications, Lambrecht (2001) describes debt restructuring under product market competition.[8] The author examines the impact of capital structure on the investment and foreclosure decisions of firms. Financially distressed firms may choose to reduce their debt repayments through a one-off "take-it-or-leave-it" debt exchange offer made by the equityholder. Firms with higher bankruptcy costs, or with higher incremental monopoly benefits, can get bigger reductions on their debt repayments. Allowing for debt exchange offers can therefore reverse the order in which firms go bankrupt.

Practical valuation studies of real options and games can be found in Kemna (1993), Nichols (1994), Smit (1997; 2001), and McGahan (1993b). In an interview with the CFO of Merck, Nichols (1994) sheds light on the use of real options and games in practice. McGahan (1993b) studies the tradeoff between commitment and flexibility in the case of the compact disk introduction. By building a large plant, Philips could preempt Sony and other potential competitors from building their own CD plants. McGahan derives a threshold probability of market acceptance that would justify pursuing a wait-and-see strategy.

Although infrastructure investment is an area of general interest, its valuation is not well understood. A key difference between the practical valuation model in this paper and other models in the new options-game literature is that this paper explicitly values the growth opportunities generated by the infrastructure of the firm as a sequential exercise game, instead of focusing on a single project. I estimate the value of a firm's growth opportunities as the sum of the outcomes of repeated expansion subgames along an equilibrium path in the overall game.

II. Infrastructure Investments and Air Traffic Developments

To understand the growth and strategic option value of infrastructure investment, we must first consider the investor's ability to appropriate the value of growth opportunities.[9] By nature, benefits that result from infrastructure are dispersed across operating divisions and, possibly, external players. For instance, there are corporate, network, and regional benefits associated with infrastructure. Corporate growth opportunities result from the fact that infrastructure is a firm-specific asset, in the sense that it can create an advantaged strategic position to expand. Examples of infrastructure investment with corporate benefits are projects in physical infrastructure, such as distribution, service, information technology, communication, and transportation systems; and human capital infrastructure. In short, corporate infrastructure can be viewed as a platform for creating future growth for the enterprise.[10]

Infrastructure investment in new markets and network investments among firms cannot be considered in isolation. Firms must seek out opportunities to complete the investments collaboratively and utilize complementary competencies. Network infrastructure investment is obviously important for airports, but can also be particularly important in industries where innovation entails novel connections between previously unconnected industries, markets, or technologies. For instance, transport and distribution operations can gain cost efficiencies

[8]Grenadier (2000b, 2000c), Huisman and Kort (1999), Joaquin and Butler (2000), Shackleton, Tsekrekos, and Wojakovski (2004), and Smit and Trigeorgis (1998, 2004) provide various treatments of the intersection between real options and game theory.

[9]See Munnell (1992) for a more general discussion of infrastructure investment and economic growth.

[10]See Kulatilaka, Balasubramanian, and Stork (1996), Zhu (1999), and Schwartz and Zozaya-Gorostiza (2000) for an analysis of IT infrastructure investments. See Kogut and Kulatilaka (1994), McGrath (1997), and Perotti and Rosetto (2002) for real option models of strategic platform investments.

by creating more efficient network connections between firms. The same is true in high-tech industries, where alliances often make value-increasing "pre-investments" to develop and position a common technology standard.

In addition to creating corporate or network opportunities, infrastructure investments can induce growth in a region. Infrastructure investments that generate regional benefits include investments in marine ports, airports, railroads, or electricity networks. Governments play a key role here, both because they establish the regulatory framework and because they often play a role in providing the infrastructure. Thus, part of the growth option value of these investments does not flow to the investor, but is shared with other players in the region where the investment is made.

The shareholder value of an airport may differ from its societal value. Shareholders, who play a value-maximizing game, are particularly interested in the value of corporate and international network growth opportunities for the airport. The value of the airport for society is much broader, however, and includes the induced and dispersed regional growth as well as any negative side effects of noise and pollution.

My model focuses on the shareholder value of associated corporate and network benefits of airport infrastructure. In the model, infrastructure is idiosyncratic for each airport. Growth opportunities arise from the interplay of infrastructure, uncertain development of demand, and environmental restrictions. When future demand is uncertain, it is sensible not to commit to a static scenario of expansion investment, but to follow a more flexible investment strategy in which the timing of investment in the next "module" of capacity depends on the evolution of demand (Pindyck, 1988) and the strategy of the competitor. Many airport expansion investments, such as runways or terminals, are large and lumpy, so that investment decisions require an important tradeoff between flexibility and pre-commitment.

In providing a rationale for its capacity expansion with the proposed Terminal 5, for example, Heathrow (London) alludes to the competitive interaction (commitment value) associated with their corporate and regional growth opportunities: "Without a fifth terminal (Terminal 5) at Heathrow, the world's busiest international airport, many travelers will be forced to use rival continental airports to connect between flights. Transfers account for a third of Heathrow's business, and losing this could have a damaging effect not only on BAA [British Airports Authority], but also on the national and local economies. If airlines are denied the opportunity to grow at Heathrow many of them will choose Paris, Frankfurt, or Amsterdam to expand their business—not other UK airports" (Terminal 5 BAA, 1999).

Several new developments in air traffic have affected the positions and expansion strategies of European airports, and will continue to do so in the coming decades. These developments will necessitate a new, more dynamic approach to long-term planning and valuation of airports. First, governments in some countries are already limiting their roles as airport owners.[11] Several European airports, e.g., Aéroports de Paris (ADP) (which includes Orly and Roissy-Charles de Gaulle), are still fully government-owned, but others, like British Airports Authority, which went public in July 1987 (and which includes Heathrow, Gatwick, and Stanstead in the greater London area, among other airports), or Fraport (Frankfurt), are already public companies. Local regulations can prevent some airports from further local expansion and can severely limit the profit stream from airport growth opportunities. Some restricted airports are forced to go public to seek international growth through networks and cooperation. For instance, Schiphol in Amsterdam has plans to go public in the near future.

Second, global growth in air traffic has resulted in more passenger demand. The number of

[11]Kay and Thompson (1986) examine the sale of government industrial assets and stress the importance of competition in the privatization process.

flights within Europe is expected to continue to grow during the coming decades despite the development of new and efficient transportation alternatives, such as the expansion of the TGV (Train à Grande Vitesse, or high-speed train) network and the Channel tunnel. Airports face uncertainty in demand growth due to changes in the overall economy. Growth or bankruptcy of the home carrier, and various other factors have great impact on demand in flights for an airport. An unexpected decline in the level of growth could motivate airports to defer their expansion plans.[12]

Third, a small number of European mainports (as the main airports are called) and many smaller airports characterize the industry structure. As a result, European airports are starting to form efficient, star-shaped, "hub-and-spoke" networks, where a central or "hub" airport connects many "spoke" destinations. These networks are expected to influence the relative competitive positions of European airports. A hub-and-spoke system in Europe makes it possible to increase the frequency and variety of destinations relative to the "point-to-point" system, and uses capacity more efficiently.[13] A potential new alliance or merger of the home carrier with a larger partner at a nearby hub can have great impact on the strategic position of an airport. For instance, the merger of KLM, the home carrier of Schiphol, with the larger Air France, the home carrier of Roissy-Charles de Gaulle, could affect the future position of Schiphol airport as a hub, in particular because Roissy-Charles de Gaulle has considerable opportunities to expand.[14]

Finally, there has been a strong tendency recently to deregulate air travel. Deregulation will create new connection opportunities, while increased competition will support efficiency and concentration.[15]

III. Infrastructure Valuation as an Options Game

I value airport expansion in a competitive context as an options game, using a two-step procedure. First, I value the existing base-scale operation without any of the expansion opportunities by using traditional valuation. I then determine the "value added" of the infrastructure-related future expansion opportunities, or the present value of the growth opportunities (PVGO), in a competitive setting. I estimate the PVGO as the present value of the expansion values of the subgames along the equilibrium growth path. The strategic position of the airport and its growth option value will depend on the infrastructure and the timing of the expansion investments under competition.

A. The Value of Assets in Place

I begin the analysis with a "catchment area," which I define as a "local market" for flights.

[12]See Daniel (1995) for a rigorous analysis of congestion pricing and capacity of large hub airports.

[13]Hendricks, Piccione, and Tan (1997) analyze the competition between a hub operator and regional carriers. In Hendricks et al. (1995), the authors study an optimization problem of an unregulated air carrier that chooses a network of connections and a set of prices to maximize profits.

[14]See Borenstein (1990) for an analysis of the influence of airline mergers on airport dominance and the market power of airlines.

[15]Marin (1995) analyzes the impact of liberal bilateral agreements on some European air routes in terms of price competition and market structure. The author suggests that after the liberalization, firms exploit their cost advantages and differentiate their products more, but market structure still depends on access to airport facilities and other ancillary services controlled by the flag carriers. Good, Roller, and Sickles (1993) analyze the implications of US airline deregulation for European transport.

For instance, adjacent airports (Airport A and Airport B) can compete for local or transfer passengers in a certain area, forming a duopoly. Q_A and Q_B are the yearly demands (measured in flights) for Airports A and B, respectively, with total demand $Q_M = Q_A + Q_B$. Current demand for Airport i (i = A or B) equals the current market share, s_i, times total demand Q_M: $Q_i = s_i Q_M$.[16] Demand for Airport i at time t, $Q_{i,t}$ is uncertain. I assume it follows a binomial process.

To determine the value of assets in place, I first consider the value dynamics event tree of Airport i (i = A or B), $V_{i,t}$, without any expansion opportunities, government restrictions, or competitive interactions. The total operating free cash flow at time t for airport i, $TCF_{i,t}$, equals (uncertain) demand, $Q_{i,t}$, multiplied by the average operating free cash flow per air transport movement, $CF_{i,t}$: $TCF_{i,t} = Q_{i,t} CF_{i,t}$. Uncertainty in the quantity $Q_{i,t}$ results in an event tree of potential total operating free cash flows for each airport. Using a binomial framework, I first calculate the risk-neutral probability, *p*, from the tree values (of TCFs), without any options or competitive interactions (see Cox, Ross, and Rubinstein, 1979).[17]

$$p \equiv \frac{(1+r)TCF_t - TCF^-_{t+1}}{TCF^+_{t+1} - TCF^-_{t+1}} \tag{1}$$

Here, TCF^+_{t+1} and TCF^-_{t+1} are the next-period total operating free cash flows for Airport i under uncertain demand in the up (+) or down (–) states, and r is the risk-free interest rate. Backward valuation with the above probabilities in an event tree (without options, restrictions, and competitive interactions) can result in the same value as a discounted cash flow calculation. However, using real option valuation facilitates the correct valuation in each branch (state) of the tree when expansion options, competitive interactions, or other factors change the risk along the branches in the tree. This valuation uses the traditional "as if traded" argument for valuing real options discussed in Mason and Merton (1985).

At the end nodes (time T), I obtain the terminal value of Airport i without any competitive interactions or restrictions, $V_{i,T}$, assuming a perpetuity of annual operating free cash flows of assets in place growing (without expansion) at a constant rate $g_{i,T}$, discounted at a constant risk-adjusted rate (weighted average cost of capital), k_i:

$$V_{i,T} = \frac{TCF_{i,T+1}}{k_i - g_{i,T}} \tag{2}$$

The assets in place at most European airports allow for only limited growth. Therefore, the number of unrestricted flights $Q_{i,t}$ (and free cash flow $TCF_{i,t}$) can be cut off at high levels of demand due to full capacity or environmental restrictions, $Q^{max}_{i,t}$. The restricted demand for airport i, $Q^*_{i,t}$, is equal to:

$$Q^*_{i,t} = \min [\, Q^{max}_{i,t}, Q_{i,t} \,] \tag{3}$$

[16]This model can easily be adjusted to incorporate different demand functions. For instance, prices could be set according to the linear demand function: $P(Q, \theta_t) = \theta_t - Q_M$, where θ_t is the demand shift parameter, P is the market price, and Q_M the total capacity.

[17]Since the value, $V_{i,t}$, is a constant function of the cash flows $TCF_{i,t}$ with $V_{i,t} = \frac{TCF_{i,t+1}}{k_i - g}$, the risk-neutral probability p can also be estimated from event-tree values: $p \equiv \frac{(1+r)V_t - V^-_{t+1}}{V^+_{t+1} - V^-_{t+1}}$.

The terminal value is equal to the value estimated in Equation 2 minus a perpetual call option reflecting $Q_{i,t}^{max}$ in the strike price. Of course, both the growth rate and the opportunity cost of capital may change along the end nodes in the tree if there are restrictions and interactions. In the backward valuation, I can then consistently discount the resulting certainty-equivalent values at the risk-free rate, r, to determine the value of assets in place when there is a capacity restriction. When I step backward in time to the current state, I calculate the value by taking the discounted expectation of the future up and down values using the risk-neutral probabilities *p* (i.e., $(pV^{+}+(1-p)V^{-})/(1+r)^{\Delta t}$), and adding this to the present value of these expected net total cash inflows for the period between the nodes.

B. Competitive Equilibrium Expansion

For expansion, the players face a value-capture game for flights under exogenous stochastic demand. In each period, the airport management has an option to invest in the next module of expansion if demand is high or to defer investment if demand is low. I assume that investment creates additional capacity $\Delta Q_{i,t}$, measured in flights per year. The cash-flow value of expansion, $\Delta V_{i,t}$, is the present value of the incremental cash flow ($\Delta TCF_{i,t}$) from the additional capacity. In standard real option theory, such an option to expand would be analogous to a call option, C_i, on this added cash-flow value ΔV_i. The exercise price would be equal to the extra investment outlay, I_i, required to build additional capacity. In the absence of competitive interaction this results in a (non-linear) call option payoff: $C_i = Max[\Delta V_i - I_i, 0]$.

However, in an option-game valuation, the incremental value of a lumpy (or indivisible) expansion investment involves competitive interactions. Such interactions introduce a discontinuity in this non-linear option payoff, due to preemptive investment. The capacity depends not only on the evolution of yearly demands in flights (with $Q_M = Q_A + Q_B$), but also on the investment of the competitor. Investment in additional capacity $\Delta Q_{i,t}$ can be temporarily underutilized until demand has grown sufficiently.

I simplify the analysis by assuming that there are only two rivals. The two airports play a repeated expansion game, where in each period they may expand simultaneously by making a lumpy investment (building on the opportunities generated by their infrastructure).

Figure 1 shows a (two-period) example of the repeated capacity expansion game in an extensive form. The alternative actions by the two airports to make the expansion investment (I) or to defer (D) are shown by squares (□) along the tree branches.

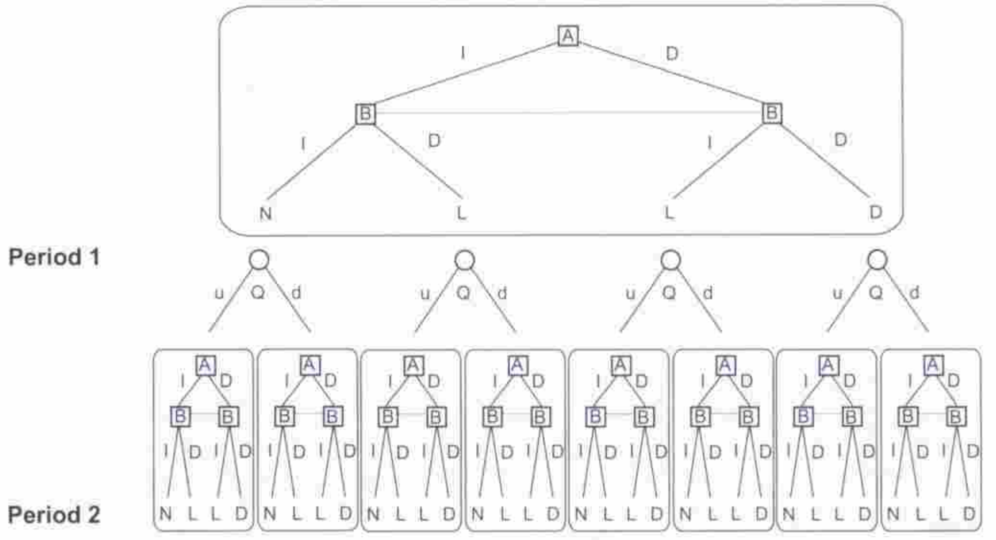
I examine the total value creation of an expansion opportunity, $C_{i,t}$, at the end of each tree branch in the subgame of Figure 1, under four investment-timing scenarios: *i*) when both airports invest simultaneously (N), sharing the additional aircraft traffic, ΔQ_M, resulting in an equal payoff for capacity expansion for each firm in a symmetrical game ($C_N = \Delta V_N - I_i$); *ii*) and *iii*), when one airport (A or B) invests first and the other waits, with the first mover (L) preempting some of the market growth in flights from its competitor; the value creation for the leader equals $C_i = \Delta V_{iL} - I_i$, the follower foregoes exercising the expansion option in this subgame ($C_j = 0$) but faces again the option to expand when the game is repeated; and (*iv*) when both airports decide not to invest in a period (D) they face an option to invest when the game is repeated.

The circles (o) in Figure 1 show the resolution of market demand (traffic) uncertainty in this two-period example. After the first expansion game, demand (Q_A) moves again and the game is repeated. I note that earlier decisions to expand can affect the value in the second expansion subgame. Although Figure 1 presents a two-period example, the tree can be expanded to include more periods and nodes, thus increasing the complexity and accuracy

Figure 1. Two-Period Example of the Expansion Game (in Extensive Form)

The firm may gain an advantageous strategic position as a result of a better infrastructure (or create such a position by making a strategic infrastructure modification). The market structure is assumed to result in a duopoly, where either of two competing firms (A or B) may invest (I) in additional capacity (using their infrastructure) or defer investment (D). The incremental value of an additional lumpy unit of capacity, $\Delta V - I$, depends on the development of demand (Q_t) (u or d) and the investment decision in the previous period by the firm and its competitor (D or I). Starting at the terminal nodes, the valuation of growth opportunities (PVGO) works backwards in time to the top summing the state value creation and taking expectations over the future investment opportunity values. The value of the investment opportunity, C, in each "state of the world", is the outcome of an investment subgame:

Simultaneous Expansion, N: If both firms decide to invest in expansion (I) in the same period (simultaneously), the value creation of the expansion for firm A or B equals $C = \Delta V_N - I$.
Sequential Expansion, L: If the firm invests first in an expansion project and its competitor invests in a later period. The value of the expansion for the leader equals $C = \Delta V_L - I$ (with $\Delta V_L > \Delta V_N$); the value for the follower at that state equals 0.
Do Not Invest/Defer, D: Management has the option to defer its decision to invest if market demand (Q_t) is low and undertaking the project would result in a negative value.



of the model.

In solving for equilibria in the overall (super)game, the valuation process of the strategic choices uses game theory analysis. The solution concept for predicting player behavior requires that I first find the optimal decisions in each subgame. The investment opportunity value at the end of each branch in the binomial option tree would equal the Nash equilibrium outcome of each simultaneous investment subgame.

To estimate the present value of the series of expansion options for each airport, $PVGO_i$, I sum the equilibrium values, C_i, of the repeated expansion option subgames. The process moves backward over random demand moves, using the associated risk-neutral probabilities to calculate the present value of the growth options at the beginning of the tree. Backward induction using these subgames results in a subgame-perfect equilibrium trajectory. Thus, I calculate the present value of growth opportunities in equilibrium for Airport i at time t ($PVGO_{i,t}$) by adding the expectation of expansion option values of the following period's growth value (using risk-neutral probabilities) to the cash-flow value creation at the current expansion subgame, $C_{i,t}$:

$$PVGO_{i,t} = \left[\frac{pC^{+}_{i,t+1} + (1-p)C^{-}_{i,t+1}}{(1+r)^{\Delta T}}\right] + C_{i,t} \tag{4}$$

However, an additional complication in the valuation arises when the growth option value is path-dependent. Then, the growth option value at any point in time depends not only on the current level of demand, but also on historical demand patterns for the firm and the firm's competitors. A growth strategy is typically path-dependent if projects are irreversible and require time to build, or when the infrastructure development process involves mutually exclusive projects of considerable scale that make it difficult to switch between strategic paths without costs.

One could also extend the analysis to the case in which there is uncertainty about the type of competition and the payoff. An important aspect of sequential games with incomplete information is that firms can extract information from their opponents' prior moves, resulting in a Bayesian equilibrium.

C. Simplified Numerical Example of Valuing Growth Opportunities

To illustrate the valuation of growth opportunities, I consider the hypothetical example of the two-stage game in Figure 2. The growth opportunities (PVGO) consist of sequential local expansion (in stage 1) and further geographical growth (in stage 2). I assume that competitors have the same relative competitive position. Depending on subsequent random demand moves, either Airport A or Airport B can invest in a sequential capacity expansion. In this setting, I assume that the players have complete information about the competitor's investment, capacity, and cash flows. (In many applications, this strategic symmetry under complete information may not be the case.)

The local expansion stage of Figure 2 involves two expansion subgames. The additional value of this incremental capacity, C_A or C_B, depends on the timing of capacity installation by the airport relative to its competitor. If both invest simultaneously, each airport captures 30,000 of the additional flights with the expansion, the cost of capital equals 8%, and the growth rate in cash flows of €600 per flight equals 3%. The investment outlay equals €200 million or €250 million depending on the capacity. Thus, $C_N = \Delta V_N - I_N = (30{,}000 \times 600) / 0.05 - 200$ million = €160 million. A leader will capture 45,000 flights of additional demand, so $C_L = \Delta V_L - I_L = (45{,}000 \times 600) / 0.05 - 250$ million = €290 million. Deferment will result in no additional value creation, $C_F = C_D = 0$.

In the next period, demand may remain at a level of 430,000 flights (dQ_0) for each airport or increase to 460,000 flights (uQ_0). The additional value of the next module of incremental capacity, C_A or C_B, depends on the timing of capacity installation by the airport relative to its competitor and the level of demand. For example, if demand increases to 460,000 flights, the

Figure 2. Numerical Example of the Expansion Game (in Extensive Form)

The growth opportunities (PVGO) of Airport A or Airport B consist of sequential local expansion (boxes) and further geographical growth (end node). The competitors have the same relative competitive position and complete information. Depending on subsequent random demand moves, either Airport A or Airport B can invest in a sequential capacity expansion.

The value creation of the local expansion subgame for firm A or B equals:

$$C_N = \frac{\Delta Q_N CF}{k-g} - I = \frac{30{,}000 \times 600}{0.08-0.03} - 200\text{m} = 160\text{m under simultaneous expansion;}$$

$$C_L = \frac{45{,}000 \times 600}{0.08-0.03} - 250\text{m} = 290\text{m under sequential expansion (leader);}$$

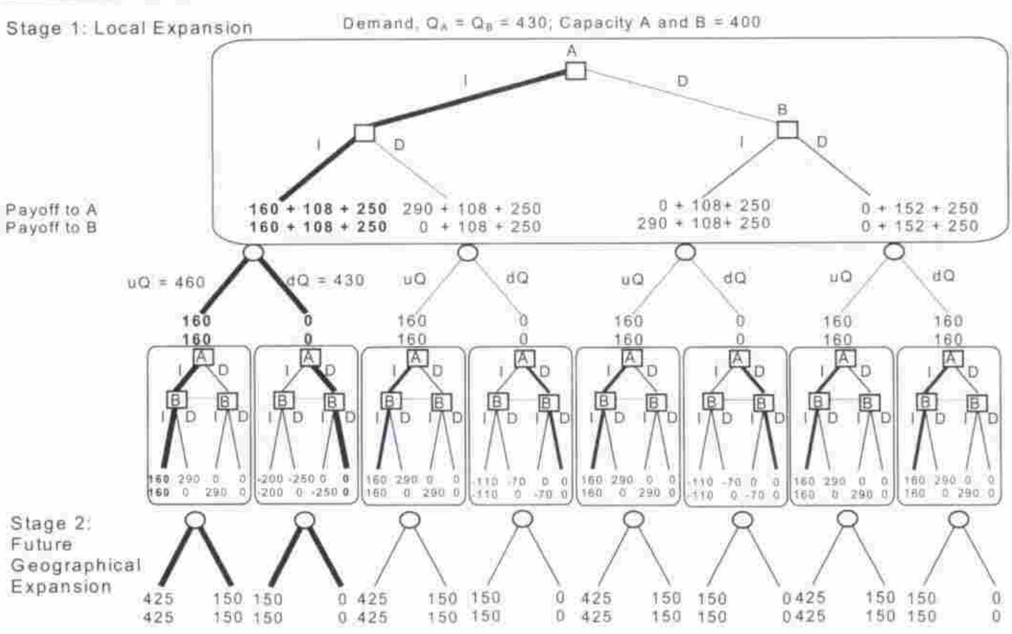
$$C_F = \frac{p\,C_{t+1} + (1\text{-}p)C_{t+1}}{1+r} = \frac{0.71 \times 160 + 0.29 \times 0}{1+r} = 108\text{m (follower);}$$

$$C_D = \frac{p\,C_{t+1} + (1\text{-}p)C_{t+1}}{1+r} = \frac{0.71 \times 160 + 0.29 \times 160}{1+r} = 152\text{m when both defer.}$$

The value of the investment opportunity, in each state of the word, is the outcome of an investment subgame. Starting at the terminal nodes, the valuation works backwards in time to the top summing the state value creation and taking expectations over the future growth option values.

That is, $$PVGO_A^* = \left[160 + \frac{0.71(160) + 0.29(0)}{1.05}\right] + \frac{0.71^2(425) + 2 \times 0.29 \times 0.71(150) + 0.29^2(0)}{1.05^2} = 518\text{m}$$

Parameter Values (for Airport A and B): additional handling under shared investment $\Delta Q_N = 30{,}000$; additional handling when leader, $\Delta Q_L = 45{,}000$; Investment, $I_N = 200$ million $I_L = 250$ million; Cash Flow per flight CF = 600; cost of capital, k = 8%; growth rate, g = 3%; risk free interest rate, r = 5%; upward movement, u = 1.07; downward movement, d = 1; risk neutral probability, p = 0.71.



additional value equals C_N = €160 million, C_L = €290 million, C_F equals zero, and C_D also equals zero. The corresponding values of additional investment are much lower if demand remains at 430,000 flights.

The end node of the game involves geographical expansion. When an airport faces growth restrictions in future periods, the option of further investment at complementary regional or international airports becomes more significant. Although harder to estimate, the incremental values of international expansion shown in the second stage of Figure 2 can be derived in the same way as the incremental value of the local expansion subgames. The additional value of these growth opportunities also depends on the development of demand and the investment decisions by the competitor (equal to zero, €150 million, and €425 million after two periods).

For simplicity, I do not include any interaction of geographical expansion with the value of local expansion in the game and value local expansion therefore independently from geographical expansion. The backward valuation process of sequential local expansion starts at the various subgames in the second period. This process values the second capacity expansion and then works backward in time to value the first module of investment. For example, a path of investment for both firms starts in the first subgame of local capacity (left branches in the first box in Figure 2) tracing an upward and downward market demand realization to the two subgames in the second module of capacity (two boxes on the left side in Figure 2).

The optimal competitive strategies in these subgames are derived by utilizing the project payoff values. For example, in the subgame on the left in Figure 2 (the second module of capacity and demand moves up, or $Q = 460$) each airport has a dominating strategy to invest in capacity (I) regardless of the other's actions (for each airport, $290 > 0$ if the competitor defers and $160 > 0$ if it invests), resulting in a (symmetric) Nash equilibrium outcome of a €160 million incremental value of expansion at the airport.

However, as shown in the subgame on the right in Figure 2, if demand moves down (so that Q remains 430), the total market demand would not justify investment. Each airport now has a dominant strategy to defer regardless of the other's actions. This results in an equilibrium outcome with values of (0, 0) for airport (A, B), respectively.

If the risk-free rate equals 5% per year, then the implied risk-neutral probability, p, estimated from the event tree of values, equals 0.71. From backward binomial valuation, using Equation 4, the option to invest in this trajectory equals $(0.71 \times 160 + 0.29 \times 0) / 1.05$ = €108 million.

After solving the second subgames[18], I can now value the four competitive scenarios in the first subgame of Figure 2. For example, the value of incremental capacity when both firms invest equals $C_N = (30{,}000 \times 600) / 0.05 - 200$ million = €160 million plus the option value of future local expansion equal to €108 million (in addition to the expected value of future geographical expansion equal to €250 million).

The other competitive scenario's can be solved in the same way. In the first subgame of Figure 2, each airport has a dominant strategy to invest in production capacity regardless of the other airport's actions (for each airport $290 + 108 > 0 + 152$ if the competitor defers and $160 + 108 > 0 + 108$ if it invests), resulting in a (symmetric) Nash equilibrium outcome of a €160 + €108 million incremental value of local expansion at the airport.

[18]For instance, when tracing the paths where only one of the airports invests in the first subgame (increasing total capacity to 845,000) and total demand remains at 860,000 (dQ), the incremental total demand in the second subgame is 15,000 flights. When they both would expand they share demand, resulting in a value destruction of €110 million, when only one of the airports invests the value destruction equals €70 million, and when both defer the value creation equals 0. I use the Nash equilibrium outcome (0,0) where both airports defer in the backward valuation process.

The highlighted (bold) branches along each tree in Figure 2 indicate the optimal actions along the subgame-perfect equilibrium path. To estimate the present value of growth opportunities, PVGO, I sum the option value of the expansion subgames along the (subgame-perfect) equilibrium path. In this hypothetical example, the first local capacity addition generates €160 million, while the option value of the second addition equals €108 million and further geographical growth opportunities may create additional value of €250 million. From the backward binomial risk-neutral valuation of Equation 4, I see that the expected equilibrium growth option value then equals:

PVGO = local expansion + option value of future geographical expansions

$$= \left[160 + \frac{0.71(160) + 0.29(0)}{1.05}\right] + \frac{0.71^2(425) + 2 \times 0.29 \times 0.71(150) + 0.29^2(0)}{1.05^2} = 518 \text{ million}$$

If the value of assets in place equals €2.8 billion, the breakdown of total value into the two components in the symmetrical game equals €2.8 billion + €518 million = €3.3 billion of total asset value. Although this hypothetical example is oversimplified, it shows the structure for the valuation of a more detailed and accurate case.

D. The Subgame Equilibrium Growth Paths

Figure 3 shows the combined options and games analysis for a three-period game in normal form. Panel A shows that the investment opportunity value at the end of each branch in the binomial options tree now equals the equilibrium outcome of a simultaneous investment subgame.

To solve each expansion subgame, I must first identify pure dominant strategies, i.e., those actions that always give a higher payoff to a player than does any other action, whatever the other player does. In a Nash equilibrium of pure strategies, neither firm can improve by making a unilateral move.

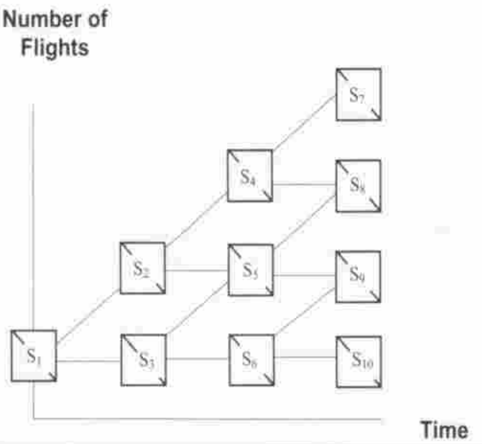
First, I consider the equilibria in a symmetrical subgame, in which the airports have an equal strategic position to expand. The equilibria in pure strategies of a symmetrical subgame appear in the left column of Figure 3. At paths with high demand, expansion investment has a positive expected payoff regardless of the expansion strategy of the competitor. With a pure, dominant strategy to invest, the payoff of Airport A's expansion strategy (payoff of lower row) exceeds its payoff from a regular investment strategy (payoff of upper row), regardless of which strategy Airport B chooses (left-hand "not invest" column or right-hand "expansion" column). That is, $\Delta V_L - I_A > 0$ and $\Delta V_N - I_A > 0$ (without sequential interactions). A Nash equilibrium in pure strategies for this investment rivalry subgame results in the lower right-hand cell, with a value creation equal to $C_A = C_B = \Delta V_N - I_i$.

At low-demand paths (e.g., following the path $S_1 \Rightarrow S_3 \Rightarrow S_6 \Rightarrow S_{10}$ in Figure 3), expansion is likely to result in a negative value regardless of the competitor's strategy. That is, $\Delta V_L - I_i < 0$ and $\Delta V_N - I_i < 0$, which may convince management not to invest (with $C_A = C_B = 0$). The payoff from pursuing a regular strategy in the total of the upper row (and left-hand column for Airport B) exceeds the airport's payoff from an expansion strategy in the total lower row (and right-hand column for Airport B). A pure Nash equilibrium for this subgame results in the values in the upper left-hand cell, which show that both airports would follow a regular (defer) strategy with no value creation from current expansion. However, an intermediate level of demand cannot justify expansion in both airports. In this unpredictable zone, a mixed

Figure 3. The 2 × 2 Simultaneous Subgame in each State and the Nash Equilibria for Different Demand Regions

In Panel A, S represents the state of nature in the binomial option tree and (C_A, C_B) represents the value creation of an additional module of expansion by firm A and firm B in each investment subgame, where C_i equals $V_{L,i} - I_i$, $V_{N,i} - I_i$, or 0 (with i = A or B) depending on the strategies of the competitors. The investment opportunity value at the end of each branch in the binomial option tree equals the Nash equilibrium outcome of a simultaneous investment subgame. Backward induction of the Nash equilibrium outcome of the subgames results in a subgame-perfect equilibrium. Panel B presents the subgame equilibria along the (subgame-perfect) equilibrium trajectory. A symmetrical game is likely to have equilibria in pure strategies for very low and very high demand growth paths. In low demand, no one builds, but at high levels of demand, everyone builds. For intermediate-demand growth trajectories, lumpy investment means that there will be no Nash equilibria in pure strategies. Asymmetry between firms alters the subgame-perfect equilibrium demand regions, particularly the intermediate region of demand growth trajectories where the airport with a sufficiently better infrastructure would have an equilibrium region where it is able to preempt growth.

Panel A. Repeated Investment Subgame Embedded in a Dynamic Option Analysis



		Airport B: Don't Invest	Airport B: Expand
Airport A	Don't Invest	(0, 0)	$(0, \Delta V_L - I_B)$
	Expand	$(\Delta V_L - I_A, 0)$	$(\Delta V_N - I_A, \Delta V_N - I_B)$

Panel B. Subgame Equilibrium for Different Demand Trajectories

Trajectories of Demand	Symmetrical Game		Asymmetrical Capture Game	
	Payoff Structure (for both)	Nash Equilibrium	Payoff Structure	Nash Equilibrium
High	$\Delta V_L - I > 0$ and $\Delta V_N - I > 0$	Both build	$\Delta V_L - I_i > 0$ and $\Delta V_N - I_i > 0$ for both	Both build (better infrastructure allows earlier expansion)
Intermediate	$\Delta V_L - I > 0$ and $\Delta V_N - I < 0$	Dis-equilibrium	$\Delta V_L - I_i > 0$ and $\Delta V_N - I_i > 0$ while $\Delta V_N - I_j < 0$ for the other	Better infrastructure pre-empts growth
Low	$\Delta V_L - I < 0$ and $\Delta V_N - I < 0$	Neither builds	$\Delta V_L - I_i < 0$ and $\Delta V_N - I_i < 0$	Neither builds

equilibrium results, and it is probable that the competitive roles of each airport will be decided by discussions and negotiations.[19]

The value payoff of the numerical example in Panel A of Figure 4 confirms that the value of the option subgame of investing in additional capacity, C, is a nonlinear function of the evolution of exogenous market demand, and shows discontinuities due to competitive interactions. For very low and very high demand growth paths, the subgame has a Nash equilibrium in pure strategies. In low demand, no one builds, but at high levels of demand, everyone builds. I note that for intermediate-demand growth trajectories, lumpy investment means that there will be no Nash equilibria in pure strategies.

The basic example is, by construction, symmetric for both airports. As noted, infrastructure investment can modify the position of the enterprise and enhance the scale and value of the airport's growth opportunities relative to its competitor. I consider the case in which Airport A has a modified infrastructure that results from a better competitive position vis-à-vis Airport B. The equilibria in pure strategies for the asymmetric subgame appear in the right columns of Figure 3. This modification will in turn alter the subgame-perfect equilibrium demand regions, particularly the intermediate region of demand growth trajectories where the airport with the better infrastructure would have the ability to preempt growth. In this intermediate demand region, Airport A, which has a superior infrastructure, may have a pure dominant expansion strategy; the lower row exceeds its payoff from a wait-and-see strategy (upper row), regardless of the actions of the competitor: $\Delta V_L - I_A > 0$ and $\Delta V_N - I_A > 0$. The NPV of the competitor can turn negative, making it optimal for Airport B to defer. A new pure Nash equilibrium for this investment rivalry subgame results in the lower left-hand cell, which shows that the airport with the better infrastructure absorbs growth with a value creation of $\Delta V_L - I_A$ for Airport A and a value creation of zero for Airport B.

Panel B of Figure 4 illustrates the nonlinear value payoff of such an asymmetric option game. For high levels of demand, the airport with the better infrastructure captures a greater market share than does its competitor. At intermediate levels of demand, the leader may choose an early preemptive action that would make it unprofitable for the follower to expand at a high scale. For very low levels of demand, neither airport finds it profitable to build.

IV. Implementation in the Case of Schiphol Airport

To highlight important application features of the option game approach, I present the case of a European airport expansion. I consider the growth options and restrictions that have been implemented at Schiphol airport in The Netherlands.

A. Valuation Results

Industry experts believe that liberalization in European air traffic will result in competitive capacity expansion in the next decades. The horizon (end nodes) in the expansion game for airport growth is the year 2020. After 2020, I assume that "the hand will have been played" in Europe, and that operational cash flows at Schiphol will grow at a constant (low) rate.

[19]One can employ a random mechanism (e.g., a flip of a coin) to decide which of the two identical firms will enter first in an equilibrium with sequential entry. In our practical context, it is probable that actions will be decided by negotiation. See also Eriv and Roth (1998) for the outcomes games of mixed strategy equilibria based on experiments.

Figure 4. Non-linear Payoff of an Expansion Option Compared to Exogenous Demand (Q), Illustrating the Equilibrium Demand Zones for the Symmetrical Game (Panel A) or when One Airport Has a Better Infrastructure (Panel B)

The number of flights Q_M, is uncertain and increases by u or declines by d in each period. Investment, I_i, creates additional capacity for Airport i, measured in flights per year. The value of the investment and quantity depends on development of demand (u or d) and the timing of investment by its competitor, where ΔQ_N is the quantity when they both invest simultaneously, ΔQ_L is the quantity of the leader and ΔQ_F the quantity of the follower. The value of an expansion option, C, is the option value of the incremental cash flow ($\Delta TCF_{i,t}$) from the additional capacity when each of these timing scenarios occur. The sensitivity of subgame equilibrium value, C, to demand shows an option-like payoff with competitive interactions. The symmetrical game shown in Panel A has a Nash equilibrium in pure strategies at low demand (neither builds) and high demand (both build). For intermediate growth trajectories, there is no Nash equilibrium in pure strategies. A maximum capacity restriction limits the upside potential. Panel B shows that differences in existing infrastructure and expansion opportunities change the relative strategic positions of the airports, causing the game to become asymmetrical. The airport with a better infrastructure can preempt growth at intermediate and high-growth trajectories. Parameter values in Panel A: $\Delta Q_N = \frac{1}{2}\Delta Q_M$; $\Delta Q_L = \frac{2}{3}\Delta Q_M$; $\Delta Q^{max} = 30{,}000$; CF = 600; k = 8%; growth in cash flows = 3% (in CF); risk free rate, r = 5%; u = 1.07; d = 1; p = 0.71; $I_A = I_B = 200$ million. Parameter values in Panel B: $I_A = 150$ million; $I_B = 200$ million.

Panel A. Payoff of Expansion in a Symmetrical Subgame (Equal Infrastructure)

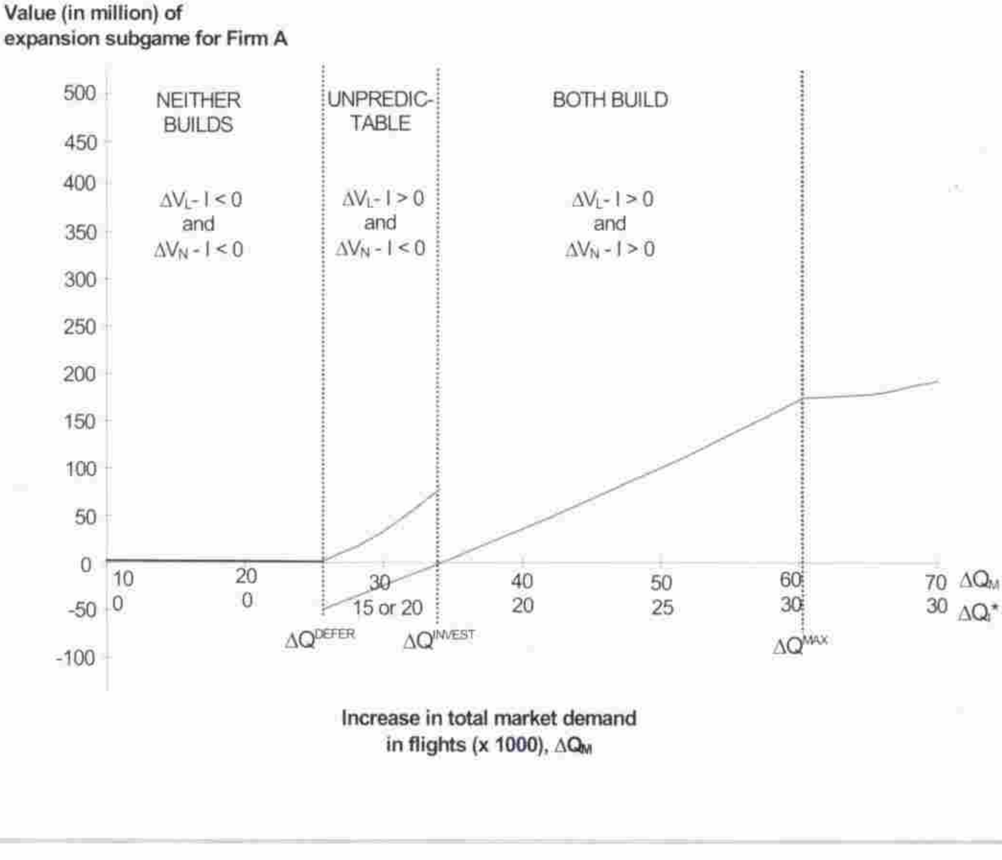
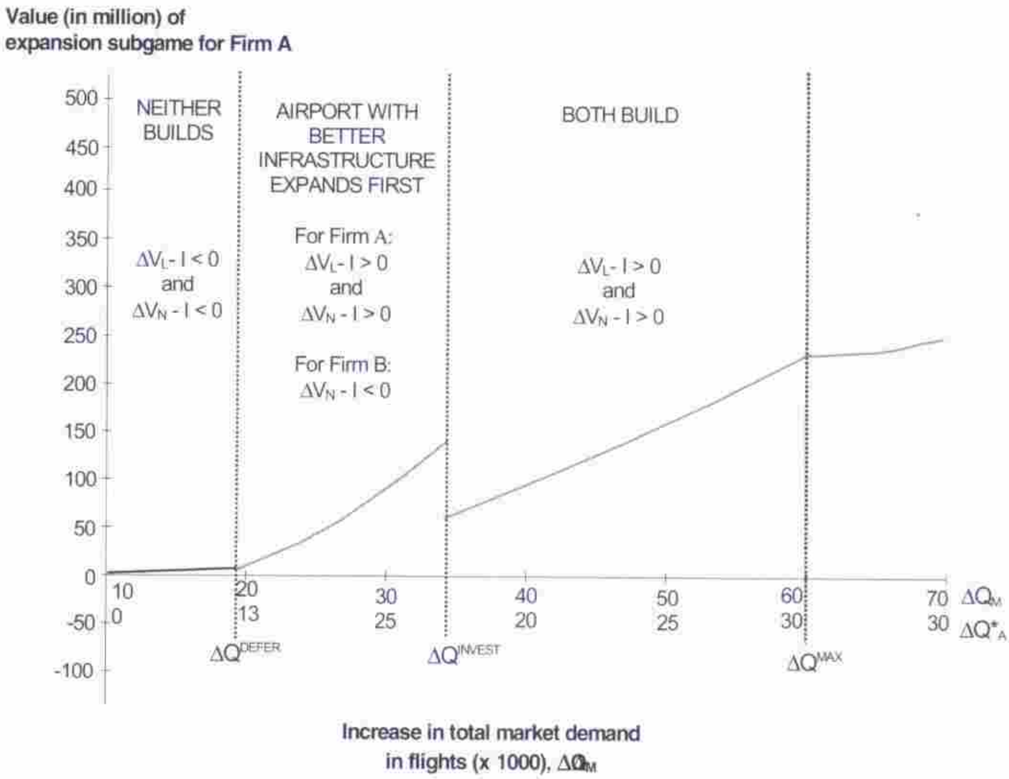


Figure 4. Non-linear Payoff of an Expansion Option Compared to Exogenous Demand (Q), Illustrating the Equilibrium Demand Zones for the Symmetrical Game (Panel A) or when One Airport Has a Better Infrastructure (Panel B) (*Continued*)

Panel B. Payoff of Expansion in an Asymmetrical Subgame (Airport A has a Better Infrastructure)



In Panel A of Figure 5, I map the projection of demand into the future by using a binomial forward process. This projection is based on the historical pattern of demand for Schiphol Airport from 1960 to 2000, extrapolated by modeling growth and uncertainty until the year 2020.[20] In the figure, I limit the number of nodes so as to link up with the schematic option game tree presented in Panel A of Figure 3 and to preserve the intuition of scenario analysis. To estimate the uncertainty of flights, I project a set of trajectories or scenarios in the future, and back out the implied uncertainty embedded in the various growth trajectories.

For greater accuracy in the valuation I can convert the projection to shorter subperiods. In this valuation, I use subperiods of one year with constant binomial up and down parameters. The uncertainty in demand growth implied in the event tree results in (average) binomial parameters $u = 1.07$ and $d = 1$ for yearly subperiods. (Alternatively, I could trace the value dynamics from the event tree and back out implied binomial parameters for each subperiod.)

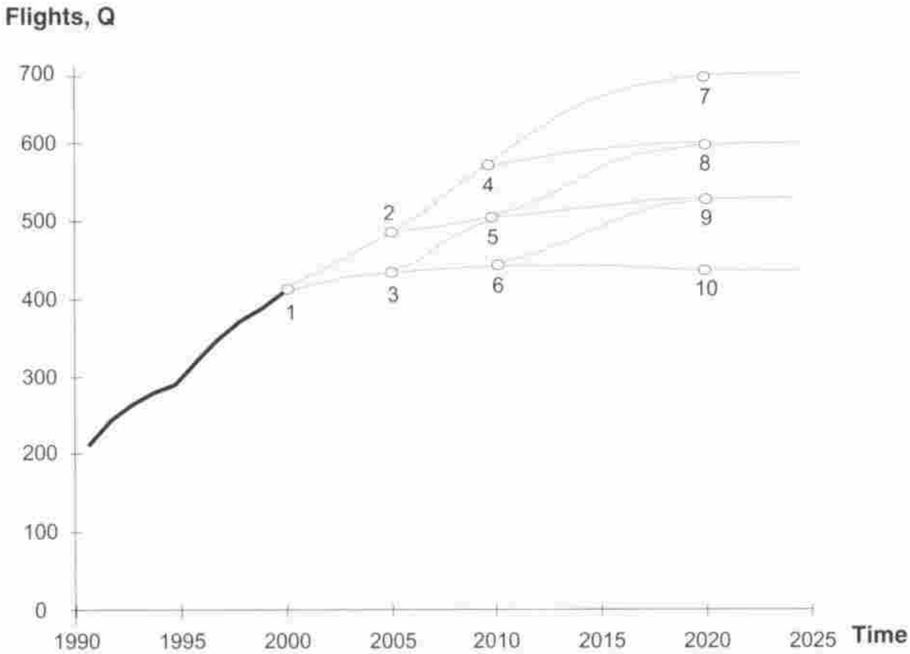
I use the historical volatility of growth in flights for a reality check on the average growth and volatility that is implied in the projection. I obtained a dataset of flights from the Central

[20]*Source:* Schiphol Masterplan, 2003, Chapter 1.

Figure 5. Projections of Demand and Expansion Strategy (2000-2025)

I use a binomial process for the valuation of flexible growth. Panel A shows the extrapolation of demand is a series of potential "states of the world" for Schiphol airport until the year 2020, expressed in air transport movements (further divided into local and transfer passengers, and freight). After 2020, projections are that demand will grow at a constant rate. These projections are used to estimate volatility in demand. Panel B presents the strategy results for capital allocation decisions. The lower line represents the threshold for the expansion of runway and area capacity. The middle line presents the restriction for growth. The upper line represents the growth option for investment in a network of complement airports under the assumption that the noise restriction is not imposed on regional airports.

Panel A. Extrapolation of Flights (in thousands) Including Network Expansion Strategy



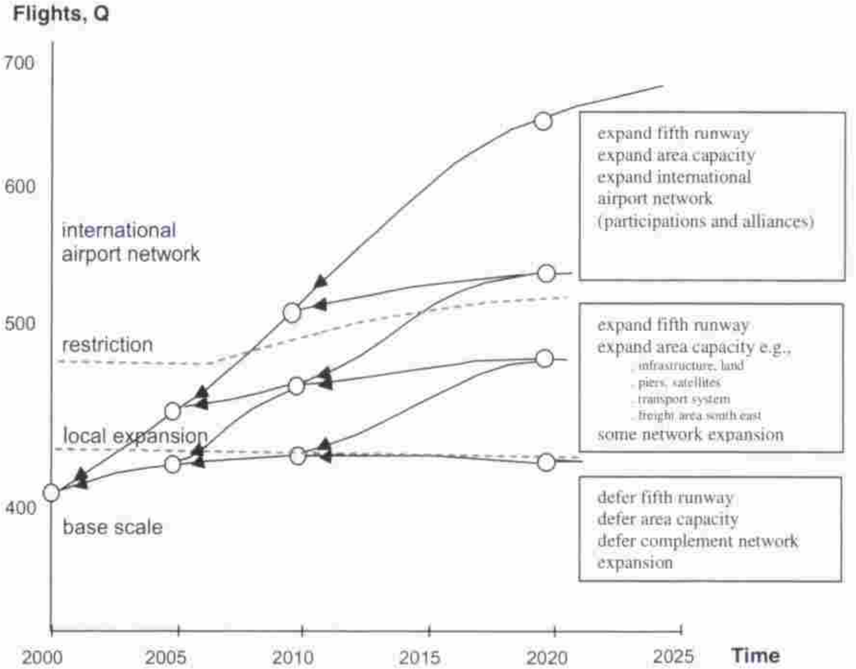
Bureau of Statistics of the Netherlands that covers the period 1960–1997. During the period 1960–1999, there is only one year of negative growth (1981), which justifies the non-lognormal parameters of u and d (with $d \neq 1/u$).[21]

The estimated after-tax operational cash flow per flight, CF_t, equals €550 in 2001. CF_t is both directly and indirectly related to air transport traffic $Q_{1,t}$. The direct component of CF_t results from (the average) amount of local passenger traffic, transfer passenger traffic, and freight, multiplied by the appropriate tariffs, plus payments for landing rights minus operating costs. The indirect portion of cash inflow per flight results from landside activities, such as real estate leases for retail businesses and their customers, and is estimated as a proportion of the direct cash inflow. I note that the cash flows per flight are likely to be time- and state-dependent. Transfer passengers and freight follow a closely related pattern in which, at a higher level of demand, the proportion of transfer passengers increases compared to the number of local passengers. For network expansion opportunities, i.e., at high trajectories of

[21]Assuming that d = 1, I calibrated the binomial tree resulting in an upward movement u = 1.07 and a true (actual) probability, q of 0.7.

Figure 5. Projections of Demand and Expansion Strategy (2000-2025) (*Continued*)

Panel B. Rollback Procedure for a Flexible Expansion



demand, the proportion of landside activities relatively increases. To estimate the total free cash flows for assets in place, $TCF_{i,t}$, I multiply the operating cash flows per flight by the number of flights (the state variable), and subtract the replacement investment. Of the total investment of €300 million per year, I assume that €100 million is used to sustain assets in place and €200 million is for growth opportunities.

Once I determine the volatility of demand in air transport movements and the operating cash flows, I can then construct the event tree of values; I note that $Q_0 = 423{,}000$ and can move up or down with binomial parameters $u = 1.07$ and $d = 1$ per year. The risk-free interest rate, r, is 5%. The weighted average cost of capital, k, applied at the end nodes, equals 8.5% and declines with excess demand. The risk-neutral probability, p, equals 0.71.

Starting with values at the terminal nodes of the tree and using the constant growth model in Equation 2, the valuation of assets in place works recursively in time. The value dynamics of assets in place requires an estimation of the maximum capacity. For higher demand states, Equation 3 indicates that maximum capacity (without expansion) is reached when growth exceeds 425,000 flights ($Q^{max} = 425{,}000$). For this set of input variables, the backward binomial valuation of assets currently in place results in an estimated value of €2.7 billion (in the year 2000).

Sequential lumpy (or indivisible) expansion investments can increase capacity to 460,000 flights per year by the year 2003 (Q^{max}), and may continue to increase capacity, but at a lower rate. Such regulatory restrictions can severely limit the upside potential of Schiphol airport, causing the subgames for local expansion to become asymmetric at intermediate and higher states of demand. In addition to the restricted local expansion, the valuation of growth opportunities requires an estimation of any regional growth opportunities as well as the international network potential.[22]

Although hard to estimate, the incremental value of international expansion derives from the leverage of Schiphol's core competencies (e.g., the "Airport City" concept) on follow-on acquisitions, and causes favorable asymmetries in the expansion subgames at higher trajectories of demand. The total sum of the estimated values for (restricted) local, regional, and international expansion subgames equals €720 million (as of 2000).

Including local, regional, and international expansion options, the total company (asset) value estimated as the value of assets in place plus the present value of growth opportunities equals €2.7 billion plus €720 million, for a total of €3.4 billion. Subtracting the (market) value of debt (€0.9 billion), the value of equity is €2.5 billion. Again, this estimation is as of the year 2000. I also note that this valuation should be recalculated with updated input parameters if Schiphol were to go public in the future. This is the total equity value, and only a proportion of the total equity capital would be traded if Schiphol went public.

It is important to note that the value of growth opportunities is very sensitive to changes in the input parameters, since the implicit option leverage makes growth option value sensitive to changes in its underlying value. Since several of the input parameters are hard to estimate (e.g., future international acquisition opportunities are unknown) it is important to perform an extensive sensitivity analysis for the expansion subgames.

B. Strategy Results[23]

In the valuation procedure above, the pattern of expansion-related outlays is contingent on the level of growth. Panel B of Figure 5 provides a schematic summary of the strategy implications for capital allocation that emerge from this valuation procedure.

In 2000, air transport movements totaled 423,000 flights per year. Without expansion, demand would have reached full capacity immediately and the cash flows would have been truncated. The lower line in Figure 5, Panel B, shows the "local expansion" threshold above which the local expansion options would be exercised. Continuous growth from S_1 to S_2 triggers sequential investment until Schiphol's expansion reaches the limits of environmental restrictions (460,000 flights by 2003), as shown by the restriction line in Figure 5, Panel B.[24] Examples of important local expansion projects involve infrastructure investments in land, the five-runway system, and the expansion of Terminal West, which should help to preempt growth in the capture game for transfer passengers in the same catchment area. However when growth in demand in flights is limited (which can be the result of the acquisition of the home carrier KLM by Air France, declining economy or various other factors), the airport management might find it better to defer several investment decisions. At lower paths, e.g., from S_1 to S_3, the dominant strategy would be to defer expansion.

To reach higher levels of growth, the airport group should become less dependent on location. It should avoid capacity restrictions by setting up strategic alliances and forming joint ventures with both regional and international airports. Examples of investment in regional

[22] See Lambrecht (2004), Smith and Triantis (1995), and Smit (2001) for models and applications of option valuation for acquisition strategies.

[23] See Myers (1987) for a discussion of the gap between corporate finance and strategy. Camerer (1991), Thakor (1991), and Nichols (1994) discuss the advantages and limitations of applying real option and game theory in strategy and finance.

[24] After 2003, the regulations will change and the number of flights may increase. (Information based on the Source: NV Schiphol, 2001, Facts & Numbers 2000.)

airports include real estate investment in Rotterdam Airport and Lelystad, and terminal expansion at Eindhoven airport. In international acquisition strategies, large high-quality airports may function as a platform and leverage core competencies and capabilities (again, the Airport City concept) to follow-on acquisitions or alliances on a broadened international base. Examples of international growth opportunities include the new Terminal 4 of John F. Kennedy International Airport in New York, a participation in Brisbane Airport, and the cooperation agreement with Fraport (Pantares).

In Figure 5, Panel B, the upper, or "network growth options," line represents further growth opportunities that can be realized by expansion at regional and international airport networks.

C. Industry Implications

The valuation of Schiphol airport can be subjected to a "reality test" by comparing it with the value of assets and growth options of other competing airports. Table I shows the implied value of the growth opportunities embedded in the stock prices of traded competing airports, such as BAA (which includes a network of airports), Fraport (Frankfurt), UZAZ (Zurich), VIA (Vienna), and CPH (Copenhagen), as of December 2000.[25] The table confirms that the market clearly values the growth opportunities of publicly traded airports. The implied growth option value as a proportion of the stock price (PVGO/Equity) ranges from 30% to 40% for large airports such as (London) and Frankfurt.

The estimated PVGO-to-equity ratio for Schiphol is about €720million/2.5 billion, or 29%. The valuation of assets in place embedded in the equity of €1.8 billion (total value of assets in place – debt = 2.7 – 0.9 = €1.8 billion) and the present value of growth opportunities of €720 million for Schiphol airport thus appear consistent with the value components of public airport stocks shown in Table I.

We can gain several insights from examining competitive strategies for the development of the European airport industry. Location, relative size, prior infrastructure, the quality and strategic position of the home carrier, and complementary assets can make exercising the expansion option more valuable for a mainport than for a smaller player. These differences also introduce asymmetries into the expansion game. The market share of the European airports seems to be affected by a concentration trend that arises from the value asymmetries that enable larger airports to grow more rapidly than smaller airports. The airports of London and Paris (not traded) seem to sustain their positions as mainports in Europe. London has the largest airports, but Paris' Roissy-Charles de Gaulle has the advantage of considerable growth options attributable to its infrastructure. Heathrow and Schiphol may reach their boundaries for growth in the next two decades. Frankfurt is also restricted. The Frankfurt and Amsterdam airports aspired to first become Eurohubs and then grow into mainport status. This concentration trend, if continued, should result in a limited number of European mainports and many smaller airports.

Figure 6 shows that the larger airports have experienced a particularly significant increase in aircraft movements, passengers, and freight, as illustrated by the steeper slope of the higher curves (compared to the lower curves) in Figure 6. In the coming decades, most intercontinental and European flights will be concentrated at the largest airports. Following this concentration trend, many of the smaller airports will adopt a market niche strategy of feeding the hubs at the end of a spoke. A few airports will emerge as mainports (big), some as Eurohubs (medium), while most of them will be spokes (small).

Idiosyncratic growth restrictions may also prompt airports to seek cooperation with other

[25] As is well known, recent economic convulsions made airport stock prices drop thereafter.

Table I. Stock Prices, Earnings, and Values of Current Operations Compared to Growth Opportunities for the Airports of BAA, Frankfurt, Copenhagen, Zurich, and Vienna (Estimated December 2000)

The table presents the implicit market valuation of the growth prospects for a number of European airports. I adjust the stock price for the value generated by continued current operations of assets in place under a no-growth policy (Kester, 1984). The market equity value prices the firm's "bundle of growth options". Column 1 presents the average stock price as of December 2000 (Fraport as of 31 December 2001, since it went public in 2001). In Column 2, the earnings per share shows the average analyst forecast next period. Column 3 presents the market value of equity (in Euro). In Column 4, the earnings are discounted under a no-growth and full-payout policy (as an annuity) using various discount rates. Column 5 shows the proportion of growth opportunities in the stock price of European traded airports (Equity Value-Asset Value)/ Equity Value.

Airport	Value per Share		Total Value of Traded Shares				PVGO/P
	1. Share Price	2. Earnings per Share	3. Market Value of Equity (Million €)	4. Capitalized Value of Earnings using Various Discount Rates (9%	10%	11%)	5. Growth Options to Equity ((3-4) / 3)
BAA (London a.o.)	£6.18	£0.40	€10,951	€7915	€7124	€6476	28% - 41%
FRAG (Frankfurt)	€26.5	€1.69	€2,391	€1694	€1525	€1386	29% - 42%
UZAZ (Zurich)	SF269	SF16.1	€870	€579	€521	€474	33% - 46%
VIEV (Vienna)	€40.3	€3.33	€846	€777	€699	€636	8% -25%
CPH (Copenhagen)	DK680	DK49	€831	€660	€594	€540	21% - 35%

airports. A cooperation strategy might involve strengthening the position of domestic regional airports that are part of a group, or it might mean becoming part of an international network. For instance, BAA has a network of regional airports in the UK, i.e., Heathrow, Gatwick, Stansted, Southampton, Glasgow, Edinburgh, and Aberdeen, and has equity stakes in airports outside the UK.

V. Conclusions and Implications

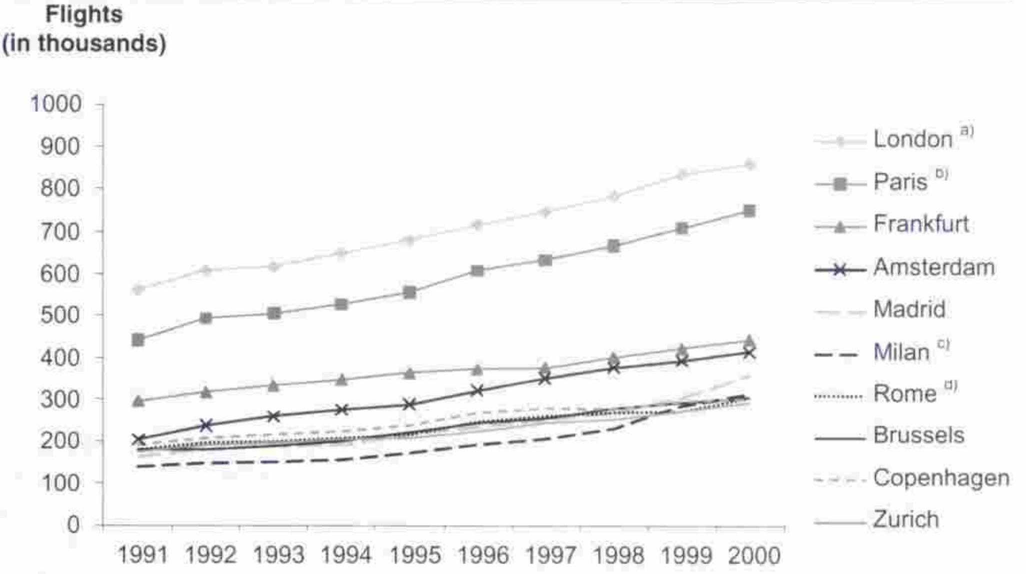
The value of airport infrastructure derives from potential enhancement of the airport's strategic position. Infrastructure investments increase an airport's ability to capture growth opportunities in the industry. Therefore, infrastructure and network investments require careful scrutiny and more sophisticated competitive analysis than suggested by standard DCF analysis. Compared to traditional valuation, the combined real options games method can not only accurately evaluate an individual investment, but can also shape the strategic thinking process by providing deeper insights into the tradeoff between flexibility and competitive pressures to invest for different types of investment strategies.

However, implementing an infrastructure valuation and estimating the boundaries of some input parameters also shows a potential limitation in evaluating the worth of both existing infrastructure and an expansion strategy. Whether obtained by a traditional approach or by

Figure 6. Growth of Large European Airports (1991-2000)

Development of Flights (Panel A), Passengers (Panel B), and Freight (Panel C) of the largest European airports in the period 1991 until 2000. The airports of London and Paris sustain their position as mainports; the airports of Frankfurt and Amsterdam emerge as Eurohubs and have captured a relatively strong position in freight due to their location in an industrial area. Most of the smaller European airports have an important niche function as spokes. The steeper slopes of the higher curves (compared to the lower curves) show that the larger airports have benefited more from the total growth in flights. The market share of the European airports seems to be affected by a concentration trend that arises from the value of asymmetries that enable larger airports to grow more rapidly than smaller airports. This concentration continues until the airports reach their environmental boundaries. Roissy-Charles de Gaulle in Paris has the advantage of considerable growth options attributable to its infrastructure. Heathrow and Schiphol may reach their boundaries for growth in the next two decades. Frankfurt is also restricted.

Panel A. Development of Flights (in thousands) of Largest European Airports



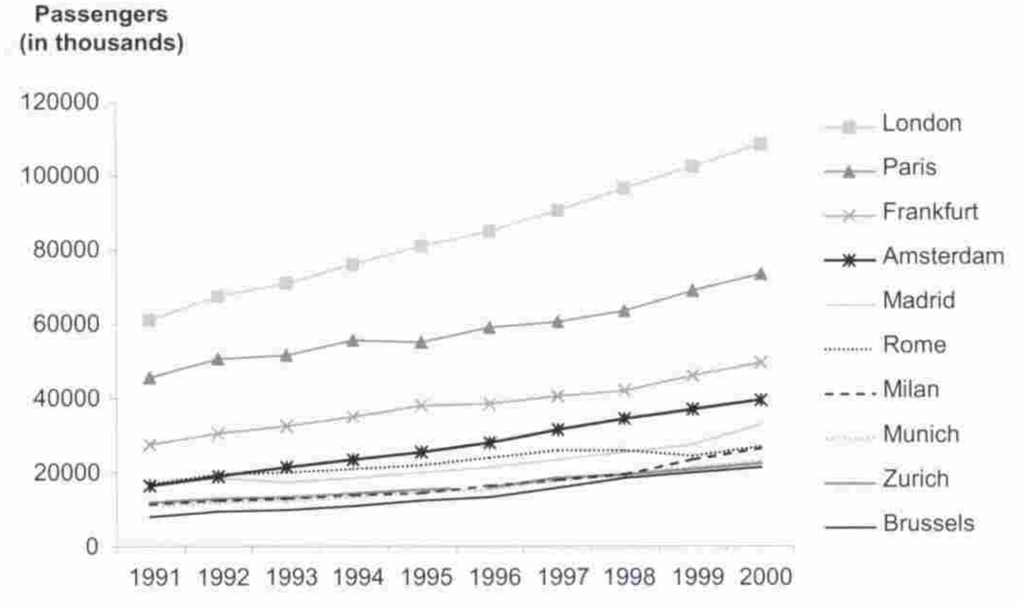
[a]Heathrow, Gatwick, Stansted; [b]Orly, Charles de Gaulle; [c]Linate Malpensa; [d]Fiumicino, Ciampino

an option-game approach, the valuation results are sensitive to hard-to-estimate parameters, such as investment in future acquisition opportunities. Therefore, valuation and strategic planning should interactively complement each other. Indeed, we can best view the real options-game approach to evaluate a growth strategy generally as an attempt to subject such strategic intuition to the discipline of a more rigorous analytical process.

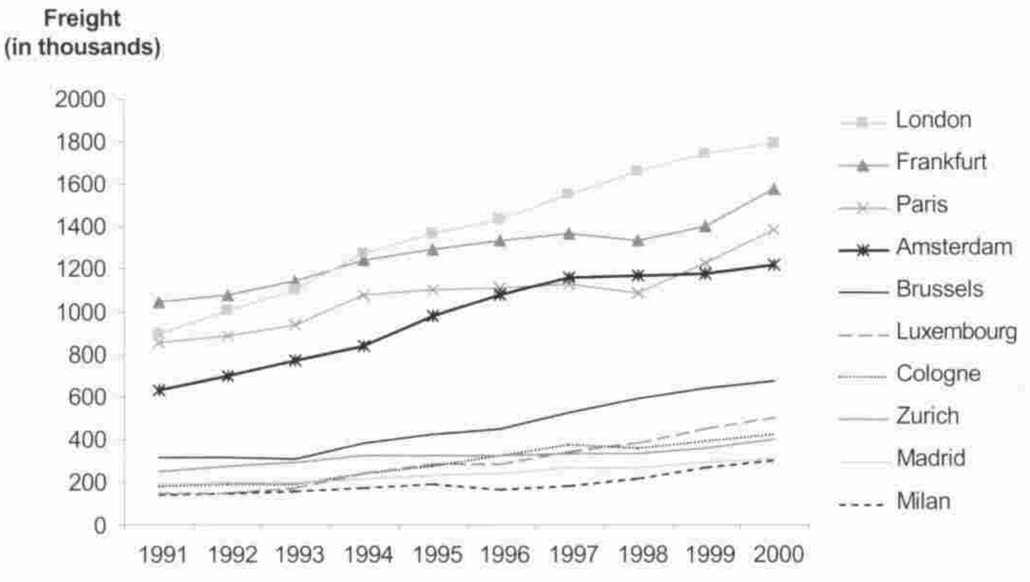
For example, when Schiphol's management was contemplating a complement airport in the North Sea as an expansion option, BAA officially expressed its concerns that the large scale of this project would affect its own growth opportunities in London. The enormous up-front investment of this alternative growth strategy for Schiphol would generate strategic commitment value (might preempt future growth in the industry), but at the same time it would sacrifice flexibility value and once made it would be very hard to recover. Schiphol management's current strategy seems to be to take a more flexible route under which management may adjust sequential investments according to the level of growth.

Figure 6. Growth of Large European Airports (1991-2000) (*Continued*)

Panel B. Development of Passengers (in thousands) of Largest European Airports



Panel C. Development of Freight (in thousands of tons) of Largest European Airports



For this kind of application, a discrete-time binomial analysis is the most appropriate approach, because it does not make the model overly complex. Thus, it preserves important features such as the tractability of values in the model, the modularity to embed the many strategic features necessary for a realistic setting, and the accessibility of the methodology. The number of nodes can be limited to preserve the intuition of a scenario analysis where an equilibrium trajectory connects the valuation with the intuitive strategic logic underlying the infrastructure investing. But, in contrast to a standard good/fair/bad scenario, this analysis allows for varying growth possibilities along various paths, thus making it possible to value flexible expansion. Of course, in a discrete-time approach the number of nodes can easily be expanded to obtain increased accuracy in the valuation results.

The combined real options and game theory framework not only values the growth opportunities of a firm in a competitive context, but can also help guide managerial judgment in deciding whether and when it is appropriate to grow at the current location, and when participation in a network or strategic alliance is the preferred route. Thus, the valuation results of an infrastructure expansion strategy should be consistent with that strategy's underlying logic and design. In the case of capacity expansion, an airport's prior infrastructure, size, governmental growth restrictions, and home carrier are idiosyncratic to each airport, generating significant competitive asymmetries that can help explain differences in the valuation, exercise, and timing of expansion options.

The larger airports or mainports, which have infrastructures that enable them to absorb high growth, are expected to solidify or enhance their positions. The result will be a structure in which many smaller airports will support a limited number of European mainports. At the same time, to achieve higher growth, local expansion limitations and the influence of globalization may motivate some airports to devise network strategies that can more fully utilize economies of scale and which can then generate network benefits. The options and games analysis helps us better understand such competitive developments in the European airport industry.■

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