European Industrial Policy:

The Airbus Case

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Abstract

This paper estimates the impact that Airbus's presence has had on the market for large commercial airliners. Our model reproduces (in a multi-stage) game a stylised characterisation of six main stages in the development of the large commercial airliner market, allowing for three players (Boeing, Airbus and McDonnell Douglas) and four market segments. The model is then used to ask a number of counterfactual questions about what would have happened in a variety of circumstances (notably ones in which Airbus did not enter the market). Besides capacity and product developments, we also model the level of expenditures on research an development in order to see whether Airbus's presence has had an impact on the type and technological specification of aircrafts produced. We find that given the prior presence of McDonnell Douglas in this market, Airbus has had only a modest impact on the prices of commercial airlines (an average of 3.5%). The reasons are twofold : first, although the Airbus presence constraints the actions of Boeing, it weakens the incentive for McDonnell Douglas to compete vigorously with Boeing. Secondly, by reducing Boeing's market share, it prevents the realisation of the substantial economies of scale and scope that are believed to exist in this technology. Overall, this means that the consumer surplus argument for government subsidy to Airbus is only weakly supported by the model. Consumer surplus benefits from a challenge to Boeing have certainly been substantial but most of them could have been achieved by McDonnell Douglas on its own. In terms of product development, we find that although Airbus may have deterred McDonnell Douglas from producing an aircraft in the same category of the A 300 (medium range, medium-bodied), it may in contrast have actually made it easier

for McDonnell Douglas to produce the MD-11 in competition with the A 330/340 and the Boeing 777. This is because the loss of scale and scope economies by Boeing as a result of the Airbus entry has substantially raised the cost to Boeing of producing the 777, making entry more attractive for McDonnell Douglas even when Airbus's presence is taken into account. Finally, we find that the presence of Airbus reduces Boeing's profits by at least $ 100 bn and McDonnell Douglas's by two-thirds. Airbus itself makes profits which are difficult to estimate with confidence, but which may lie somewhere between $49bn and $52bn, of the order of a billion dollars per annum and equivalent to a rate of return over the whole period of between 6% and 11%. If we give the same weight to profits and consumer surplus, this implies that Airbus has had a large negative impact on world welfare but a comfortably positive impact on European welfare.

1. Introduction

When should governments intervene to promote specific types of productive activity in the economy? Answers to this question have been subject to periodic swings of fashion, but a consensus has gradually emerged that intervention needs to be based on a sound account of why unaided markets will fail to encourage adequately efficient levels of the activities concerned, as well as a reasonable optimism that government failures will not lead to distortions as significant as those market failures it is sought to correct. The application of this consensus to actual cases, however, has generated substantial discord, particularly when the activities under discussion are not public goods, but private goods which for one reason or another are claimed to be supplied in inadequate quantity or quality. That the state should be a vigilant referee of the competitive process is a view that would command widespread assent; that it should be an active player in the competitive game is a much more debated and debatable claim.

In no specific field of economic activity has the debate been more vigorous than in commercial aerospace, where production has been supported and encouraged in covert or overt ways by friendly governments around the world. Many reasons can be imagined for the favoured status of aerospace, from the cynical ("politicians like shiny toys") to those more firmly grounded in an analysis of market failure. There are persuasive grounds for thinking that aerospace is likely to be subject to market failures, notably because of large scale economies in production and the importance of research and development. Furthermore, these market failures are often difficult for individual countries to overcome on their own, so aerospace has given rise to significant international co-operation, the success or failure of which has sometimes been seen as an important indicator of the prospects for co-operation in other fields.

The most celebrated instance of such cooperation is the European Airbus consortium, which was formed in the late 1960s to challenge the dominance of the Boeing Corporation in world markets; in 1994 for the first time, the former sold more commercial aircraft than the latter. Its rivalry with Boeing and McDonnell-Douglas (MDD, also of the United States) has led to fierce claims, in the GATT and other fora, about the role of public funding in generating "unfair" competition.

The question what benefits flow from government support for commercial aerospace is particularly pertinent to Airbus because the consortium owes its very existence to explicit decisions by collaborating governments. Broadly speaking, three kinds of benefit have been thought to flow from the Airbus presence in the market for large commercial jet airframes. The first consists of lower prices to consumers resulting from a challenge to a dominant producer (Boeing), benefits that could not be supposed to motivate a purely commercial competitor. The second consists in various kinds of economic spillover from the advanced technology embodied in the Airbus models; these might consist in the adaptability of technological advances to other industries, or simply in the spur to technological improvement by Airbus's own rivals. The third kind of benefit consists in whatever profits accrue to the consortium as a result of its activities. However, such profits, if they exist, do not necessarily constitute a case for government support, since profits are the reward for any normal unsubsidized commercial activity.

Two kinds of argument have typically been advanced to show why governments may be justified in subsidising activities that can be expected to be profitable. The first, which was doubtless an important motivation for the original launch of the Airbus consortium, is a belief that private capital markets often fail to fund activities that have a genuine expectation of being profitable but happen to have a long investment horizon. This may be because private investors are more averse to risk than governments ought to be, or because of institutional failures (such as those due to internal agency problems) biasing decision-making towards projects with early repayment profiles - for example, managers may inflate current profits at the expense of long-term profits to persuade shareholders of their competence, and this may be rational even if shareholders know they are doing so (Stein, 1989). Even if correct, such an argument also requires confidence that government "short-termism" is a less serious problem, a confidence that can falter in the face of such facts as the date of the British Government's announcement of launch aid for the Airbus A-330/340 programme, just a few weeks before the general election of 1987. The second argument, however, is more subtle, and appeals to the possibility that certain activities may paradoxically be profitable (before subsidies) only because it is known they enjoy government support. This is because the knowledge of government support may add vital credibility to a producer's presence in the market, and may deter either predation by an established rival or entry by a new one.

This idea that governments can affect the credibility and success of entry enjoyed something of a vogue in the mid-1980s due to interest in so-called Strategic Trade Policy. Governments will typically add to the credibility of entry by committing to absorb whatever losses will occur and the provision of finance for fixed development cost (with repayment linked to performance) will signal this intention. Such schemes have indeed been the most important element of public support to the Airbus. Face with guaranteed entry, Airbus competitors will presumably alter their competitive strategies (including pricing and product developments). In particular, government support for the A-320 programme is often thought to have induced Boeing to produce a new version of the 737 in the segment for narrow bodied, small range aircrafts. In the absence of guaranteed competition, Boeing may have instead opted for the development of a completely new aircraft in that market. Similarly, government support for the A330/340 programme was thought likely not only to deter a very aggressive response to Airbus from Boeing, but also perhaps to deter McDonnell-Douglas from developing a long-range medium-bodied aircraft at all, especially given its highly visible hesitation about whether to continue in the civil side of the aerospace business at all. In the event, in spite of Airbus and its government support, McDonnell-Douglas went ahead with the development of the MD-11, a model which is now in production.

Government can also affect the success of entry, if they do not affect the credibility of the venture. By subsidizing production, government can affect the outcome of the competitive game in such a way as to shift rents in favour of the domestic firms (see Brander and Spencer, 1985). As indicated above, public support to Airbus has taken mostly the form of a reduction in fixed, development cost and has not affected variable production costs to an appreciable extent. This aspect will thus be neglected in the present analysis.

This paper reports the results of a model whose purpose is to estimate the impact that Airbus's presence has had on the market for large commercial airliners. In doing so we want to ask what have been the costs and benefits of the decision to set up the consortium. This exercise highlights the consequences of European public support to Airbus only to the extent that in the absence of government support, the Airbus project would not have flown at all. Indeed we do not model the way in which government support has added to the credibility of the project and what would have happened without support (the Airbus project might have survived, but in a very different form). The implicit assumption behind our policy conclusions is therefore that government support has been decisive for the very existence of the project.

Besides addressing specific question about industrial policy in the airframe industry, this paper also tries to draw some more general lessons about the appropriate conduct of industrial policy by governments. Although it is only proper to be cautious about drawing general lessons from a very particular case that has been analyzed according to an even more particular model, the aerospace industry has been used in the past to make a number of general claims about industrial policy[2], and it is helpful at the very least to see whether we have learned anything that casts light on these more general claims.

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[2] For example, Baldwin & Krugman argue that "for those who work on the "new" trade theory that emphasize increasing returns, dynamics and imperfect competition, these economic

The model of the paper has a number of important features. First, it is a model of a sequence of production decisions taken over a forty year period since the 1950s and affecting output and sales over six decades. The aim has been to reproduce a stylized characterisation of six main stages in the development of the large commercial airliner market (including a stage that has not yet taken place, namely the development of replacements for the Boeing 747). Then the model is used to ask a number of counterfactual questions about what would have happened in a variety of circumstances (notably ones in which Airbus did not enter the market). Secondly, we explicitly model (albeit in a highly simplified way) decisions about the development of new models and the level of expenditure on research and development, in order to see whether Airbus's presence has had an impact on the type and technological specification of aircraft produced as well as on their quantity and price. Thirdly, the model is a linear one, which means that it uses a simplified (and therefore tractable) approximation to underlying technologies and market conditions that may be very far from linear. The reliability of the approximation is higher for small changes around observed historical outcomes, but is more suspect the more radical the counterfactual simulations that are run. Fourthly, reliable data are available for only some of the parameters of the model; for others we have had to rely on informed guesses, or calibrations that are consistent with observed history. Some of our

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characteristics would in and of themselves make aircraft a natural target for study" (1988); and that "the presence of dynamic factors....[makes the industry] a uniquely rewarding subject for a trial run (of new trade theories and policies)" (1987).

simulation outcomes (those concerning outputs and, to a lesser extent, prices) are more robust to uncertainties about these parameters than others (probably the least robust, unfortunately, are our estimates of profits).

A number of striking conclusions nevertheless emerge from the simulations. First, given the prior presence of McDonnell-Douglas in this market, Airbus has had only a modest impact on the prices of commercial airliners (an average of 3.5%). The reasons are twofold: first, although the Airbus presence constrains the actions of Boeing, it weakens the incentive for MDD to compete vigorously with Boeing. Secondly, by reducing Boeing's market share it prevents the realisation of the substantial economies of scale and scope (including learning effects) that are believed to exist in this technology. Overall this means that the consumer surplus argument for government subsidy to Airbus is only weakly supported by the model. However, Airbus is nevertheless a more effective competitor to Boeing than is MDD, in the sense that prices in a market with only Boeing and MDD would on average be 2% higher than in a market with only Boeing and Airbus. This is principally because MDD produces aircraft that have significantly higher running costs than those of Airbus. Furthermore, if MDD had not been present in this market, a Boeing monopoly would have had dramatically higher prices (by 15% on average). So consumer surplus benefits from a challenge to Boeing have certainly been substantial - but most of them could have been achieved by MDD on its own[3].

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[3] Although MDD is a less effective competitor to Boeing than Airbus, it should not be thought that under plausible alternative specifications of our model it might turn out to be a negligible competitor to Boeing although still present in the market. This is because scale economies are

Secondly, the impact of Airbus on technological innovation by other producers has been negative[4]. This is because Airbus entry has lowered their expected production runs and thereby reduced the profitability of investment in fuel- and maintenance-efficiency. Aggregate research and development in the industry has risen, but there has been greater duplication.

Thirdly, the Airbus presence reduces Boeing's profits by at least \$100 bn. and MDD's (which would anyway be low) by about two-thirds. Airbus itself makes profits which are difficult to estimate with confidence, but which may lie somewhere between \$40bn and \$52bn, of the order of a billion dollars per annum and equivalent to a rate of return over the whole period of between 6% and 11%. If we give the same weight to profits and consumer surplus this implies that Airbus has had a large negative impact on world social welfare but a comfortably positive impact on European welfare.

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so important in this technology that, if a producer enters the market at all, it will always do so at a scale of production that makes a significant difference to its competitors' sales.

[4] Airbus itself has of course contributed to technological progress via its own investments, but the benefits of this should be fully reflected in the prices of its aircraft and consequently in its profits. The externalities (which provide the rationale for public support) consist solely in the impact on innovation by other producers. This model does not, however, measure pure technological spillovers (such as any ability by Boeing to innovate more chaeply by copying Airbus technology); it looks merely at the impact of competition on incentives to innovate.

Fourthly, the simulations shed an intriguing light on the rent-stealing argument. Although the model does not enable us to model predation (since within each production stage producers play a static game in production capacities), it does allow us to examine the impact of guaranteed entry by Airbus on the entry decisions of other producers. Although Airbus may have deterred MDD from producing aircraft in the same category as the A-300 (medium range, medium-bodied), it may in contrast have actually made it easier for MDD to produce the MD-11 in competition with the A330/340 and the Boeing 777. This is because the loss of scale and scope economies by Boeing as a result of the Airbus entry has substantially raised the cost to Boeing of producing the 777, making entry more attractive for MDD even when Airbus's presence is taken into account.

This last point has potentially important implications in a wide range of contexts outside the particular circumstances of commercial aerospace. In simple models of entry deterrence it is often assumed that a firm faces symmetric rivals: actions that weaken or deter one will weaken or deter them all. When a firm's rivals are significantly asymmetric, however, this reasoning may be importantly flawed. Actions by firm A that weaken its rival firm B may reduce the threat it poses to firm C by enough to more than offset any threat to firm C from firm A. Interestingly, this phenomenon has important analogies in evolutionary biology, where the introduction of predator species into an ecosystem has been shown in certain circumstances to increase rather than reduce the number of other species the ecosystem can support[5]; in recognition of these analogies we can even christen it the Starfish Effect.

It is important to note that the very circumstances which give rise to the Starfish Effect - namely the presence of large economies of scale and scope - are precisely the circumstances which have typically been thought propitious for the rent-stealing argument. For example, Baldwin & Flam (1989) say that "the market for 30-40 seat commercial aircraft seems to be the near ideal real world counterpart to the Brander-Spencer model [of rent-shifting]", because "the industry is marked by very strong static as well as dynamic economies of scale; to enter requires a large initial investment, and marginal costs are falling substantially due to learning by doing. Policies that can affect capacity choices and output therefore have important effects on costs and profits and on the distribution of profits and welfare between countries". The model of this paper, however, suggests a more cautionary message: economies of scale and

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[5] Wilson (1993), p.164 reports an experiment by Robert Paine: "The starfish Pisaster ochraceus is a key-stone predator of mollusks living in rock-bound tidal waters, including mussels, limpets and chitons. It also attacks barnacles...Where the Pisaster strfish occurred in Paine's study area, fifteen... of the mollusk and barnacle species coexisted. When Paine removed the starfish by hand, the number of species declined to eight. What occurred was unexpected but in hindsight logical. Free of the depredations of Pisaster, mussels and barnacles increased to abnormally high densities and crowded out seven of the other species". See the discussion of this and related phenomena in Sigmund (1993).

scope indeed increase the extent to which entry decisions can redistribute rents. But in the presence of asymmetric rivals they also make it more likely that entry decisions of at least some firms are strategic complements rather than strategic substitutes, and therefore make the task of selective government intervention harder rather than easier.

Overall, the results of the model suggest that the external benefits from the entry of Airbus into the market, though positive, have been modest. This suggests that government support for the Airbus consortium will have been justified primarily if it proves to have been profitable, and there is at least a reasonable chance that it will so prove.

2. The Market for Jet Airframes: a historical sketch

The commercial aircraft industry is characterised by unusually large static and dynamic scale economies as well scope economies and it has been subject to significant demand and technological shocks since the second world war.

To start with, development cost give rise to significant scale economies and these costs are rising : development costs for the Boeing 777, which is now entering service, could be as much as 4.3 (according to Tyson, 1992). On a cost per seat basis, development costs for this aircraft have increased substantially relative to those incurred for the 747 in the early 70s. With such initial outlays, fixed cost per unit are about halved when output is doubled from an initial level of 200 units. Even at the scale of 500 units, a 50 % increase in output still leads to a drop in average development costs of about 33 %. However large, fixed cost do however play a relatively minor role by comparison with variable cost in generating scale economies (for instance, at a production level of 500 units, average fixed cost do not typically account for more 10 % of overall (fixed and variable average costs).

Indeed, most of the dynamics of costs is associated with variable costs (as much as 90 % according to Klepper, 1990) ; the production of aircafts involves the coordination of thousands of tasks and this process can be improved as experience accumulates. Such learning by doing leads to important dynamic scale economies. The basic rule of thumb used in the industry is that production costs decrease by 20% when output doubles (within realistic production ranges).

Basic aircraft design can also sometimes be shared across a number of different models; experience gained in production processes can also to some extent be applied to different production lines. As a result, significant economies of scope can arise, and the more so, the closer are the aircafts in terms of basic characteristics (fuselage size, wing span, type of fitted engines). For instance, there is much commonality between the Airbus A330 and A 340. The Airbus A 330 is shorter than the A 340 but their fuselage has a common central section and they share the same wings (except for engine pots - as the A430 has four engines and A330 has only two). By contrast, the importance of scope economies between the A 330/340 family and the A320 (a much smaller aircraft) is much reduced. It is basically associated with some avionics initially developed for the A320 which has been further developed and adapted for the A330/340 family.

Overall, these costs characteristics are such that if the industry is analysed purely in terms of static productive efficiency, it is at best a natural oligopoly (allowing for managerial diseconomies), and possibly a natural monopoly (as claimed, for instance by Tyson, 1992). According to Sutton (1995), the characteristics of technological improvements in this industry provide a second additional reason behind high concentration. He suggests that research and development on existing models is sometimes such that advanced versions can effectively dominate particular segments. According to his analysis, a successful aircraft design is therefore one that can be developed later in the lifetime of the aircraft into a product that vertically dominates competitors. Such successful design experience two large peaks in sales, one when the aircraft is launched and one when the advanced version comes on sales. By contrast, unsuccessful design experience only one peak in sales (when it is launched) and the market becomes eventually dominates by the successful design.

The first major development in the industry was triggered by the invention of the jet engine and its application to civil aircraft. The first civil jet aircraft, the Comet (designed and produced in Britain), flew in 1949 and entered service in 1952. Relative to previous piston engines, jet engines allowed for much superior performance (in terms of speed and range) but involved much larger fixed development costs. This change in cost structure inevitably led to consolidation in an industry characterised by a larger number of independent producers. The European industry was fragmented (including Hawker Siddely, Vickers, de Havilland, Sud aviation, British Aircraft Corporation and Fokker) and its first mover, de Havilland with the Comet, was grounded for several years because of technical problems. In the meantime, both Douglas and Boeing developed their commercial aircrafts (the DC 8 and 707, respectively) and managed, because of a larger domestic market, to establish themselves quickly and reap the necessary scale economies[6]. By the early sixties, the European industry, victim of small national market and fragmented supply had all but disappeared.

The basic design for the 707 and DC8 were soon developed to meet the diversified domestic need of American airlines; first, the 727 was developed as a three engine version of the 707, which could fly across the US. In order to meet the demand for short inter-city links, Douglas produced the DC 9 by scaling down the DC8 and the 707 was further reduced by Boeing, to produce the 737 (with two engines). This is the first important product development in the industry, after the basic jet design were produced and it is modelled as stage A in our simulation. Because of financial difficulties, Douglas also merged with Mc Donnell (a company specialising in military procurement) at this time.

By the end of the 60s, the industry was affected by a new development in engine technology. The turbo-fan technology, invented by Rolls-Royce, had the potential for much greater thrust than the traditional turbo-jet technology. Such increase in power meant that much larger aircraft could be flown and that the number of engines could be reduced for existing

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[6] Both the DC8 and 707 were derived from military projects (the (in)famous B47/B52 in the case of Boeing) financed by the pentagon.

any aircraft sizes. This, in turn, could allow for significant savings in fuel[7]. The US government then financed competing developments for a large scale transport aircraft by Boeing and Mc Donnell Douglas and Lockheed. All three decided to develop commercial applications. Mac Donnell Douglas and Lockheed designed tri-jets aircrafts (respectively the DC 10 and the L1011 with similar range and capacity (350 passengers over 5 500 nautical miles). Boeing decided to leapfrog competition and designed a significantly larger aeroplane (more than 400 passengers and more than 6000 nautical miles) with four engines. This is the second major product development in the industry (modelled as stage B). Lockheed eventually won the contract for the military transport aircraft and retreated from the commercial market (after having incurred substantial losses).

By producing tri-jets with a capacity of 350 passengers, Lockheed and Mc Donnell Douglas had however left what became known in the industry as a "hole in the sky". American airlines wanted a 250 seat (wide body) aircraft that could fly across the US and save on fuel. European airlines wanted an aircraft of similar size and range for some of their dense intra-European routes. The Airbus first responded by designing the A300 and its derivatives the A310, with an extended range and smaller capacity. Soon after, Boeing proposed the 757, an extended version of the 737 as a stopgap measure[8]. However, as narrow body jet, the 757

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[7] In addition, turbo fans are much quieter than turbo jets as the core of the engine is surrounded by a large flow of air.

[8] According to industry analysts, the aircraft was designed to meet the particular needs of British Airways in order to ensure that it would not defect to Airbus.

had insufficient capacity and could not be extended further. Boeing then developed the 767, an entirely new design, which competed head on with the A300/A310. This is the third major product development in the industry (modelled as stage C).

The deregulation of the American airlines industry and the development of air transport in Europe gave rise to a new development; a short to medium range aircraft with a seating capacity of about 150 was needed to support feeding into hubs in the US and to connect capitals in Europe. Airbus moved first by developing the A320, fitted with many advanced technological features like the fly by wire technology. This strategy was meant to differentiate Airbus offering from that of Boeing and Mc Donnell Douglas, which both developed new versions of existing aircrafts. Boeing developed the 737-300 (and later the 737-400) arguing that a much superior aircraft could soon be designed after new developments in engine technology (the prop-fan) would materialise[9]. Mc Donnell Douglas produced the MD 80, a derivative of the DC9. This is the fourth major product development in the industry (stage D).

By the mid eighties, it became apparent that the DC 10 was becoming technologically obsolete and that the 747 was used sometimes inefficiently. It was used on short term / high density routes for which it had inadequate aerodynamic characteristics and long but medium density flights (where the load factor was not inefficiently low). In addition, some very long distances (Europe-Australia) could not be covered (at full load) without a stop-

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[9] Despite high intial hopes, this technology has been abandonned.

over.   Airbus responded by producing the A330/A340 family. The A330 has two engines and seats about 370 over 5000 miles, whereas the A340 has four engines and can cover more than 7 000 miles (with a slightly reduced capacity). Boeing waited two years longer than Airbus before designing a competing aircraft, the 777, which is somewhere in between the A330 and A340. This delay may however prove crucial to the extent that the 777 incorporates the latest advances in engine technology such that it can come close the performance of the A340 with only two engines.   This stage of competition is currently taking place and it is modelled as stage E.

Despite major improvements over the last twenty years, the 747 is now ageing and industry analysts anticipate that the next major product introduction will occur in that segment. Airbus is already talking about a potential A350 (600 seats ?) and Boeing has unveiled plans for a 800 seat aircraft (a double decker over the whole length of the aircraft). Is it unclear however whether the market for such large aircrafts will materialise (see FT, April 3, 1995); at this point, there are few interested airlines (British Airways and Singapore Airlines) but much will depend on the development of airport facilities (restrictions to further airport construction tend to favour mega aircrafts) and air traffic control (the safety distance between large aircrafts is significantly shorter than that between small ones).   This is the last stage of competition in our model (stage F).

The main characteristics (in terms of range and single class seating) of the aircrafts produced at these various stages of competition are presented in figure 1.   The various market segments associated with these product designed are also broadly presented; in the course of the 35 years of history that we model, two decisions will be taken in the short range-narrow body segment (DC9/737-100 and later the MD80, 737-300 and A320), one decision in the medium range-medium body segment (the 757/767 and A300/310), one decision in the long range-medium body (the A330/340, MD11 and 777) and two decisions in the long range-wide body (747, DC10 and 747 replacement).

In order to illustrate further the developments that our basic model will account for, table 1 also presents the cumulated sales of the various aircrafts produced at these various stages of competition.

Table 1. Cumulated deliveries - 1952-1993

Short range-narrow body	
737 (all versions)	2 507
DC9	918
MD80	1 087
A320	431
Medium range-medium body	
757	537
767	519
A300	399
A310	240
Long range-medium body	
MD11	93
A340	21
A330	1

777	0
Long range-wide body	
747	920
DC10	372

3. Previous studies of Airbus

Our model examines the impact of the entry of a third producer into the market for large civilian passenger aircraft. Two items of previous research have modelled competition purely as a duopoly between Boeing and Airbus. Both have claimed that the presence of Airbus in this market has had overall negative consequences, both from the point of view of the world as a whole and from the narrower point of view of European shareholders, consumers and taxpayers. Baldwin & Krugman (1988) model competition in one market segment, between the Airbus A300 and the Boeing 767. They estimate that the entry of Airbus resulted in substantial consumer gains, but large losses of profits to Boeing and smaller but still substantial costs to European taxpayers. The United States suffered as a whole from the policy, and Europe suffered in aggregate for all but discount rates of 3% or less. The negative impact of Airbus entry is due to the presence of substantial learning economies[10] which are diluted by the presence of competition.

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[10] By learning economies are meant reductions in marginal costs of production as production runs increase.

Klepper (1990) extends this analysis by modelling competition between two producers in three segments: short-range narrow body aircraft, medium-range medium body aircraft and long-range wide body aircraft. His main conclusion confirms that of Baldwin & Krugman, namely that the competitive benefits of Airbus entry are swamped by the loss of learning economies; the effect is even stronger in his model due to the presence of significant scope economies[11] between segments. Klepper (1994) also considers the impact that production subsidies for Airbus would have on the outcome of competition and welfare. He finds that a 20 % subsidy would increase Airbus's market share in all segments to 50-60%, while leaving consumers relatively unaffected. The main effect of production subsidies is to transfer learning (and profits) from Boeing to Airbus. As indicated above, we neglect production subsidies in the present analysis as they account for small share of the overall public support to Airbus.

The present model differs from the previous work in two main ways:

1) We include three producers in the model. Our results indicate that the impact of a third producer is qualitatively and quantitatively very different from that of a second.

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[11] Scope economies occur when marginal costs of production in one segment fall as production runs in a different segment increase. This is due to the transferability of some production methods between different models in a manufacturer's range.

2) We model the decision to develop new products rather than treating manufacturers' product ranges as given. This enables us to ask whether Airbus entry had an effect on its rivals' product range and quality as well as on the prices and output of given products. In addition we divide the market into four main segments.

The price of complicating the model in this way has been our adoption of a linear specification for demand and production technology, as well as the assumption that producers act as Cournot competitors (taking each others' capacity as given); together these simplifications enable analytical solutions to be found to the game between producers at each stage.

4. The model: a brief description

Our model (details of which are given in Appendix 1) describes a stylised history of the market for large passenger aircraft since the 1960s as a sequence of six stages in the development of four market segments. These four segments are:

1) Short-range, narrow bodied (SRNB)
2) Medium range, medium bodied (MRMB)
3) Long-range, medium bodied (LRMB)
4) Long-range wide bodied (LRWB)

The six stages of competition are:

A) (early 1960s):	The players decide whether to enter SRNB [this corresponds to the decision by Boeing to produce the 727 and 737, and by MDD to produce the DC-9]
B) (late 1960s):	LRWB [Boeing 747, MDD DC-10]
C) (1970s):	MRMB [Airbus 300,310, B 757,767]
D) (early 1980s):	SRNB [Airbus 320, B 737, MD-80]
E) (late 1980s):	LRMB [A-330,340, B 777, MD-11]
F) (late 1990s):	LRWB [replacements for the 747?]

The order in which these six decision stages occur is a given feature of the model; we do not claim to show why they occur in this order. At each stage we model the three manufacturers (Airbus, Boeing and MDD) as taking simultaneous decisions whether or not to enter the relevant market segment, and if so what level of development costs to incur, in the knowledge that they will subsequently compete in production capacities with whichever other producers also enter. In taking its decision each manufacturer knows what has occurred at previous stages and foresees what will happen in future stages; it decides its production capacity for the lifetime of the aircraft taking as given the production capacity installed by its rivals and its own past and future production capacity in other market segments. Development takes five years and production continues for a further twenty-five. All producers are assumed to maximise profits, both in their development decisions and in deciding how much production capacity to install.

These assumptions about taking capacity as fixed require further comment. They fall into three categories. First, there is the assumption that a single producer's capacity, once installed, cannot be changed. This is clearly very unrealistic when we consider that production in practice continues for 20-25 years for most aircraft models. It may, however, be an adequate approximation to a more realistic situation in which changing production capacity is sufficiently expensive to outweigh any likely strategic advantage of changing it once it has been installed. A producer will not wish to make a unilateral change in installed capacity unless this would induce some favourable reaction from a competitor (otherwise this level of capacity would not have been optimal in the first place); our assumption implies that the prospects of any such reaction are not great enough to outweigh the costs of a change. We have made this assumption because to do otherwise would greatly complicate the model, which in its six-stage form is already complicated enough at least for our taste. However, one extension seems to us potentially well worth exploring, though we cannot do so in this paper. This would be to take seriously the idea that aircraft sales at a given production stage typically follow a twin-peaked pattern. One way to model this would be to suppose that capacity can be changed half-way through a production run, and an aircraft's technical specifications can be upgraded, in response to new information that has been revealed about market conditions. To model this would involve, in addition to a doubling of the number of decisions about production capacity, a satisfactory modelling of uncertainty and its resolution.

The second assumption worth commenting upon is the assumption that intertemporal pricing issues (within segments) can be ignored. A number of different constraints will affect the intertemporal pricing of aircrafts. To the extent that airlines prefer to homogenous fleets to reduce maintenance costs and the training of the crew, manufacturers may have an incentive to undertake some "penetration" pricing. The incentive to price aggressively in the early stages of sales because of such network effect among consumers will also be exacerbated by competition (see Matutes and Regibeau (1995) on competing standards).

To the extent that aircrafts are durable, the manufacturers may also have an incentive to discriminate across buyers over time (initially selling to those airlines with a high willingness to pay and progressively reducing price along the demand curve). As is well know, such price discrimination is difficult when buyers anticipate the strategy and decide to wait. As conjectured by Coase (and shown by Stokey, 1981), a monopolist trying to discriminate across discrete time periods would lose all market power as the time periods become arbitrarily shorter. There are however several ways in which the monopolist can mitigate his loss of market power; any device that will commit him not flood the market at later stages will give buyer the appropriate incentive to buy early. As emphasized by Bulow (1982), if the monopolist can rent the services of the durables rather than sell them, he will be better off. Indeed, by renting the durables the monopolist will have an incentive to maintain the value of the existing stock of goods and hence will avoid flooding the market. A commitment to a fixed capacity will be equally effective. As suggested by Bulow (1982, p 326), in the presence of repeat buying, firms will have an incentive to establish a reputation for protecting the assets of their customers and hence should be able to commit to pricing strategies which do not involve sharply decreasing prices over time.

These various commitment devices seem to be present in the commercial aircraft industry; both Boeing and Airbus undertake some leasing (even thought the largest share of leasing in undertaken by third agents), changes in capacity are very costly and the game is repeated. Aircraft manufacturers are therefore likely to retain substantial market power and should be able to undertake some intertemporal discrimination. Given the other constraints mentioned above (involving network effects), it is unclear however what will be the shape of the intertemporal price structure. An indeed, there is some evidence (Klepper, 1990) that aircraft remain constant over time. For the sake of this analysis, we thus simply assume that prices are kept constant (in real terms) over the life time of the aircraft.

The third assumption worth commenting upon is the assumption that producers take their own and others' future capacity at other stages as given when choosing their level of capacity today. What this rules out is the possibility that producers may choose their capacity today in order to influence decisions made by themselves or other producers in the future (as we explain below, we do indeed take into account the strategic motive for entry decisions, but not the strategic motive for capacity decisions conditional upon entry). Our justification for treating the impact of strategic motives as small enough to ignore is based on two types of consideration. First, regarding producers own decisions in the future, we can appeal to the envelope theorem. A marginal increase in output today in order to influence the marginal calculations determining the level of a producer's own output in a future period is small enough to ignore[12]. We cannot however appeal to the envelope theorem to ignore the impact of producers decisions on those of competitors in the future. However, ignoring the impact on a competitor's output relies more on what might be called the « back-of-the-envelope theorem », according to which strategic effect can be ignored when they are likely to be very small, and when the cost of taking them explicitly into account is large ; there are two strategic effects of output decisions that would add enormously to the current model's complexity. One is that an increase in output beyond the level that would otherwise be profit-maximising changes a rival's optimal choice of output in other market segments in ways that make a non-marginal difference to the decision-maker's profits. Making this explicit would require us to solve an 18 by 18 system of equations rather than a series of 3 by 3 systems, a great increase in complication for what our ad hoc sensitivity analysis (as we report in section 6 below) suggests is likely to be a small increase in accuracy. Secondly, a large increase in output beyond the non-strategic level might induce a discontinuous change (such as the exit of a competitor) whose effect would be to raise profits of the decision-maker above the non-strategic profit-maximising level. By their very nature such effects cannot be taken into account by finding the first-order conditions for profit-maximisation (which is what enables us to find analytic solutions to the capacity game at each stage). Instead they must be discovered by a simulation methodology that searches over all possible capacity levels (taking into account all competitors'

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[12] Of course, there may be a significant inducement to increase output today in order to benefit from reductions (via scope or learning economies) in the costs of producing the intra-marginal units of output which it is expected will be produced in the future, but this is fully taken into account in our model.

best responses to these output levels) to see whether any discontinuous future entry decisions may be influenced by them in a manner favourable to the decision-maker. This would make solving the model very considerably more complicated than it is at present, so we have not undertaken this task. Our model is best described as representing a fully strategic game in entry decisions, given that producers know that if they enter a market they will be setting capacity non-strategically[13]. However, after presenting the simulation results we discuss whether and to what extent our findings may be sensitive to this assumption.

The model's specification of both demand and technology is linear, enabling us to find analytical solutions to the system of equations describing the choice of production capacity at each stage.

Demand for aircraft in one segment is a function not just of the prices of aircraft in that segment but also of prices of those in neighbouring segments. Within each segment aircraft are assumed to be differentiated solely by fuel and maintenance costs; that is, aircraft within each segment are deemed perfect substitutes if they have the same fuel and maintenance costs (adjusted for numbers of seats). Accordingly, we do not allow for national biases in demand, which would also require modelling regional markets. This assumption may be questionable, in particular for the US. As indicated in 1, which reports on regional markets shares, it appears

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[13] Technically, therefore, we are solving for a sub-game perfect equilibrium of an entry game whose payoffs are determined at each stage by the Nash equilibrium of a one-shot game in capacities.

that US producers have a relatively high market shares in their domestic markets, relative to that obtained outside US and Europe (the ROW). By contrast, Airbus obtains market shares in Europe which are closer to those observed in the ROW. Such distribution of sales is consistent with the view that European airlines buy aircraft mostly on merits whereas US airlines may be biased towards their domestic suppliers.

Table 1. Regional market shares of airbus products

	Europe	US	ROW
Narrow body-short range	31 %	22%	29%
Medium body-long range	53%	33%	46%
Medium body-medium range	44%	15%	48%

The costs of production embody scale economies both in the form of fixed development costs and in the form of marginal costs that decline with the level of output. There is also a learning effect embodied in the fact that a producer's marginal costs are lower for a given market segment if it has produced an earlier model within that segment[14]. Finally,

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[14] Our calculation of the profit-maximising capacity decisions at each stage do not take account of the effect that a marginal increase in output today in a given market segment may have on the marginal costs of producing output in the same market segment when this generation's aircraft are replaced in twenty-five years' time. This is partly because of the length

there are economies of scope in the form of marginal costs that decline with the level of output produced in neighbouring segments.

The model is solved backwards. This means basically that the solution at each stage is constrained by the requirement that predictions about the future must be consistent with rational behaviour by all parties when those predictions are realised. What this implies is that the model must not assume that producers were incapable of foreseeing developments which the model itself predicts.

The steps involved in finding a solution are as follows. They consist of finding the Nash equilibria consistent with a set of historical production data, and then checking to see which of these Nash equilibria are sub-game perfect:

1) Parameter values are chosen for the whole model.

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of time ahead (the average impact on the next generation's marginal costs takes place 37.5 years from the present, which becomes negligible with even mild discounting). It is also because to do so would introduce an arbitrary asymmetry between the calculation for our first two stages of competition (A and B) where replacements are foreseen within our finite-horizon model, and the remaining stages where it is not, although such replacement will almost certainly take place.

2) Using historical data about production in previous stages, the model calculates the profit-maximising output in stage F under each combination of decisions by the three players to enter the market or to stay out.

3) For each such combination it determines whether each of the parties would make more profits by changing its entry decision[15]. If so, the combination is rejected as a non-equilibrium. Any combinations that survive this test are listed as solutions. In principle there might be multiple solutions: for instance, it might turn out to be profitable for only one producer to enter a particular market segment, but for any of the three to able to do so as long as the others stayed out. However, for our base run and all simulations only a single combination of decisions has turned out to constitute a solution at each stage of the model.

4) The output values predicted for each producer by the solution to stage F are used as parameters for the solution to stage E (stage E involves entry into a neighbouring segment to that entered at stage F, so there are economies of scope as well as cross-elasticity

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[15] In the results we report producers do not discount future profits in making these entry decisions. The reason for this is that under no reasonable calibration is MDD making a comnmercial rate of return in the base run, so that to model the entry decisions as properly discounted would make it difficult to calibrate the model consistently with MDD's presence in the market. We have, nevertheless, compared our results with what would occur if proper discounting were used and MDD were assumed to face counterfactually low fixed costs in the base run; the qualitative results are very similar.

effects to take into consideration). We solve for an equilibrium at stage E taking as given the predicted result at stage F as well as the historical values of output in stages A to D.

5) The procedure is repeated analogously for the other stages back to stage A.

6) We then check whether, at any stage, the equilibrium entry decision of any producer would be different if, instead of historical output data, the equilibrium were calculated using the outputs that would have been chosen if some producer X at an earlier stage had made a non-equilibrium entry decision[16]. If so, we compare the total profits for producer X under the two historical sequences and choose as the solution to the model the one that yields the highest total profits.

We use the term "run" of the model to refer to a carrying out of steps 1) to 6) for a given set of parameter values.

Each run of the model takes the characteristics (namely development and operating costs) of aircraft types as given. However, it also calculates the optimal investment by each manufacturer in product characteristics. For the base run the parameters of the function determining investment levels are chosen so that manufacturers' historical investment levels are the optimal ones given the output levels they produced. When running simulations under

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[16] Technically this amounts to ensuring that entry decisions at later stages are defined as functions of earlier decisions.

alternative hypotheses, changes in outputs by the manufacturers are likely to alter the return to investment in product characteristics and so change both the optimal level of investment and the aircraft running costs that would result. Ensuring complete consistency between the parameters of a run and their optimal values would require prohibitive computational resources for comparatively little benefit. So in order to ensure approximate consistency the procedure we have adopted is as follows. A simulation is run using the same parameters as the base case. This generates a number of results including output levels and optimal investment levels, which may be significantly different from historical levels of these variables that have been used as parameters for the simulations. We therefore run a second simulation using among its parameters the relevant variables generated by the first run. In the simulations we have reported, the results of the second run are very similar to those of the first run, suggesting that further attempts at convergence are unnecessary. This means that our results can be interpreted as showing the impact of various alternative scenarios not just on physical volumes of output produced but also on the quality of aircraft developed.

At two points in the model (stages D and F) at least one manufacturer is faced with a choice between continuing to produce an existing model and producing a new or upgraded model. Here our procedure has been to run a simulation under each of the two alternatives and to compare the profits to the manufacturer in each outcome, reporting the more profitable solution.

4. Results

In this section we report a comparison between prices and outputs at each stage of development under various alternative hypotheses. First we report a "base run", which attempts to reproduce fairly closely the history of the passenger aircraft market since the 1960s, and reasonable current estimates of future demand. According to this base run, both Boeing and MDD enter the SRNB and LRWB segments; Airbus and Boeing both produce MRMB aircraft though MDD stays out; and all three producers enter the LRMB segment. We have also conjectured that Airbus and Boeing (though not MDD) will decide to produce new LRWB aircraft in the late 1990s. One important feature to note about the base case is that both Boeing and MDD are assumed to foresee the later entry of Airbus even when making their initial decision at stage A. This has the effect of making them produce slightly lower output since they foresee that Airbus's presence will make it harder in the future to exploit economies of scope between different models.

Appendix 2 reports the procedure we have used in calibrating those parameters of the model about which we do not have direct data. To give some idea of the sensitivity of the results to alternative values of the parameters, Table 3 shows two alternative base runs which differ in respect of perhaps the hardest parameters to calibrate with confidence, namely elasticities of demand. In principle elasticities are determined jointly by three variables: price, output and the ratio of marginal cost to price at the equilibrium output. The former two are given by historical data or forecasts, and the last is thought to lie somewhat below 60% (this is a kind of stylised fact about which there is a rough industry consensus). However, because of uncertainty about this last value we have calibrated a second base run with elasticities about

20% (in absolute value) higher than those given in the first. Subsequent tables will report the figures based on the lower elasticities, because these are the ones that approximate better to the consensus value of the price-marginal cost ratio; but the sensitivity of results to alternative assumptions should be borne in mind. The most immediate impact of higher elasticities is to lower the profitability of all producers: that of Airbus falls from 8% to 6%, and MDD barely makes a positive rate of return. But in addition the effect of Airbus is weaker under high elasticities; the percentage change in prices is roughly halved, and if induced quality changes are taken into account the consumer surplus benefits of Airbus entry become negligibly small.

Table 3

Comparison of two base runs: high and low demand elasticities

Elasticities of demand	High	Low
Airbus rate of return	6%	8%
Boeing rate of return	23%	27%
MDD rate of return	1.1%	2.8%
Simulation without Airbus; effect on:		
Prices unadjusted for quality	1.9%	3.8%
Prices adjusted for quality	0.1%	2.1%
Prices unadjusted (last 4 stages)	3.2%	5.8%
Prices adjusted (last 4 stages)	0.7%	3.5%
Consumer surplus unadjusted ($bn.)	-18	-36
Consumer surplus adjusted ($bn.)	-0.5	-20
Consumer surplus unadj. (last 4)	-22	-39
Consumer surplus adj. (last 4)	-5	-23
Boeing profits ($bn.)	151.5	103.3
MDD profits ($bn.)	8.5	23.9

A number of comments about the profitability calculations are in order. First, by "rate of return" we mean the internal rate of return of the stream of revenues and costs accruing to developing and manufacturing airframes in the four segments of the model; this is not the same as the rate of return of the manufacturer on its capital employed, since the manufacturer will typically have pre-existing overhead capital investments in addition to the development expenditures incurred in respect of particular airliners. Secondly, with respect to Airbus we have nevertheless sought to impute an capital cost to the development of its first aircraft which can be thought of as the cost of setting up an aerospace operation over and above the cost to an established operation of developing a new model. We have been extremely conservative in this; a lower imputed capital cost, allied to lower elasticities, might raise Airbus's rate of return to something like 11%, while lower capital costs in the presence of higher elasticities imply a rate of return around 9%. Thirdly, we have assumed that manufacturers' revenues accrue at a constant rate throughout the lifetime of each model; in practice this may overstate rates of return since it does not allow for slow initial sales of new models. Finally, all of these estimates are dependent on the forecasts of future demand and prices that have been used. More pessimistic forecasts might significantly lower the rate of return to all producers including Airbus. This is particularly important to bear in mind in the case of Airbus since most of its profits in the base run occur after the mid-1990s. Figure 2 illustrates; it is worth noting for comparison that the internal rate of return of Airbus's profit stream up to the mid-1990s is only 0.7%, even under the low elasticities assumption. Overall, we must stress that rates of return are purely illustrative and should not be considered as forecasts.

Table 4 reports aircraft prices under different alternative assumptions in addition to those of the (low elasticity) base run. We have chosen to report the low elasticity simulations because the overall findings of the paper (that the impact of Airbus on prices is small but its effect on industry profits is large) emerges even more strongly from the high elasticity simulations, and we have preferred not to allow the mere choice of simulations to give added strength to conclusions that are already quite striking. First we report the result of a simulation in which Airbus never enters the market, then one in which MDD never enters, and finally one in which Boeing remains a monopoly throughout the period. All prices are in millions of 1994 dollars, rounded to the nearest million. They do not take into account the fact that aircraft may have different operating costs in the simulations from those in the base run, a qualification that is explored more fully in Table 7.

Table 4

Aircraft prices $m

Stage/segment	Base Run	No Airbus	No MDD	Boeing Monopoly
A SRNB (1960s)	33	32	36	35
B LRWB (1960s)	127	127	138	138
C MRMB (1970s)	66	69	65	74
D SRNB	29	32	32	40

(1980s)				
E LRMB (1980s)	102	113	106	114
F LRWB (1990s)	125	126	125	143

Table 5 shows total aircraft deliveries at each stage of the model under the same set of alternative assumptions:

Table 5

Aircraft deliveries

Stage/segment	Base Run	No Airbus	No MDD	Boeing Monopoly
A SRNB (1960s)	3627	3806	3265	3540
B LRWB (1960s)	1296	1308	1152	1161
C MRMB (1970s)	2841	2709	2947	2586
D SRNB (1980s)	6021	5675	5594	4499
E LRMB (1980s)	1236	1086	1189	1101
F LRWB	1507	1507	1512	1280

(1990s)

Table 6 overleaf shows the percentage changes in prices under the different simulations, unadjusted for quality differences (which are shown in Table 7). Note that the absence of Airbus actually lowers prices in Stage A, even though Airbus does not enter in Stage A in the base run. This is because Boeing anticipates a higher output in a neighbouring segment (the medium body, medium range segment at stage C); because of larger spillovers across segments, Boeing has therefore a stronger incentive to expand output at stage A. However, once Airbus actually enters the market (from Stage C onwards) it has an unambiguously downward impact on prices.

Note also that the absence of MDD lowers prices in the MRMB segment (in which MDD has no presence in the base run). This is because MDD's absence from the two neighbouring segments enables the other producers to realise more economies of scope and so lower prices.

The absence of Airbus in almost all cases results in the other manufacturers making higher investments in operating efficiency. This is because the return to such investments rises as the manufacturers are able to realise savings in operating costs over a higher level of output. However, Airbus's absence also deprives consumers of access to Airbus's aircraft, which have lower fuel and maintenance costs than MDD's, so not all customers purchase more fuel-efficient aircraft in the absence of Airbus.

Table 6

Changes in Aircraft prices compared to Base Run

Unadjusted for quality

Stage/segment	No Airbus	No MDD	Boeing Monopoly
A SRNB (1960s)	- 3%	+ 7%	+ 4%
B LRWB (1960s)	0	+ 9%	+ 9%
C MRMB (1970s)	+ 5%	- 2%	+ 12%
D SRNB (1980s)	+ 8%	+ 9%	+ 36%
E LRMB (1980s)	+ 11%	+ 3%	+ 11%
F LRWB (1990s)	+ 1%	0	+ 15%

Table 7

Changes in Aircraft prices compared to Base Run

Adjusted for quality

Stage/segment	No Airbus	No MDD	Boeing Monopoly
A SRNB (1960s)	- 3%	+ 7%	+ 3%
B LRWB (1960s)	0	+ 7%	+ 7%
C MRMB (1970s)	+ 3%	- 2%	+ 10%
D SRNB (1980s)	+ 8%	+ 9%	+ 35%
E LRMB (1980s)	+ 3%	+ 1%	+ 3%
F LRWB (1990s)	+ 1%	0	+ 11%

Full details (including results and parameter values) of the base run and No Airbus simulation are given in Appendix 4. Three features of the simulation in particular are worth noting:

1) The absence of Airbus encourages MDD to enter segment 2 with a direct competitor to the Boeing 737.

2) The absence of Airbus discourages MDD from producing the MD-11. This is because Boeing can now reap sufficient scale economies to be able to price the 777 at a level against which MDD is unable to compete. Note that this is the contrary to the view expressed in the mid-1980s that entry by Airbus would discourage entry by MDD (see Vickers, 1985, and the various arguments in Dixit & Kyle, 1985 and Geroski & Jacquemin, 1985). This view proved to be mistaken, and the current model suggest why. Airbus's entry actually made life easier for MDD because its sales reduced Boeing's economies of scale.

3) The base run has Airbus deciding in the late 1990s to produce a direct competitor to the 747. Obviously this is dependent on precise demand projections. Given the ones we have used, Airbus entry would keep MDD out of this segment.

5. Implications for benefits to consumers and producers

The prices and outputs reported in the simulations can be used to calculated changes in aggregate consumer surplus[17] (this means overall benefits to airlines, and it is a further question to what extent such benefits might be passed on to passengers). For the No Airbus case these amount to approximately a reduction of $36 bn, or a reduction of $20 bn if quality differences are taken into account[18]. For the Boeing monopoly case they amount to a reduction of just over $118 bn (quality-adjusted). For comparison, without Airbus total profits in the industry would be some $68 billion higher over the whole 60-year period, and under a Boeing monopoly they would be $290 billion higher.

The reason why Airbus does not have a larger impact on prices is that the pro-competitive effects of entry are offset by a weakening of the competitive pressure from MDD, and reduced learning economies for both existing manufacturers (especially Boeing). Our

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[17] These are measured as the area of the trapezium in a demand-supply diagram bounded by the demand curve and the two price lines (before and after the change). Since demand curves are linear in this model this area can be measured precisely.

[18] If one includes only the impact on consumer benefits in those segments in which Airbus has a presence, the figure for the consumer benefits due to Airbus entry is $26 bn instead of $20 bn. This is because the model assumes that other producers produced less at stages A and B in anticipation of Airbus's entry. This assumption may be thought unrealistically strong, in which case the figure of $26 bn may be a more appropriate one. However, it should be noted that under the high elasticities assumption this could fall to as low as $5 bn.

estimates of these effects are obviously dependent on the parameter values chosen, but we have endeavoured to use a realistic value in the light of the industry consensus.

One final question we can use to model to answer is what would have been the consequences of a "wrong" decision by Airbus. In the base run entry by Airbus in the late 1960s with a rival to the Boeing 747 would be unprofitable. But suppose European governments had picked a loser? How bad would it have been? The answer is that the decision would have resulted in losses of about $3.5 billion, sufficient to bring Airbus's overall rate of return over the whole period down from 8% to 6%. The impact on the overall market would have been negligible, since in that event (according to our simulations) MDD would not have developed the DC-10, and the two events would to all intents and purposes have cancelled each other out. So it would have been regrettable but scarcely a disaster. This is worth bearing in mind in the light of claims that failed government support can be very costly. For example, Helpman & Krugman (1989) write: "It is possible to believe that imperfect competition is pervasive while at the same time believing that the imperfections associated with it are fairly modest and the gains from optimal deviations from free trade small. Again, the quantitative work reported in chapter 8 seems to confirm this. One can always do better than free trade, but the optimal tariff or subsidies seem to be small, the potential gains tiny, and there is plenty of room for policy errors that may lead to eventual losses rather than gains". What the present model suggests is that losses resulting from failures of strategic trade policy, while certainly counting as losses, may also be quite small. Strategic trade policy may sometimes be both less effective than its friends would hope and less dangerous (from a narrow nationalistic perspective) than its enemies fear. In this model the entry of Airbus is bad for the world as a whole, but not particularly dangerous for its backers in Europe.

6. How robust are the findings?

Two qualitative findings emerge very clearly from our model under any reasonable variation or re-calibration that respects its fundamental structure. First, the impact of Airbus entry on consumer surplus is modest; and secondly, its impact on Boeing's profits is large.

The particular reaction of MDD to Airbus entry is quite sensitive to the details of model specification. For example, it would take only a small change in the parameters to ensure that MDD did not produce a rival to the Boeing 737 even if Airbus had never produced the A-300. Likewise, a small change in parameters (a reduction in the scope parameter, for example) would mean that MDD still continued to produce the MD-11 even in the absence of Airbus. However, a more general qualitative result is highly robust. The reaction of MDD (the weaker rival) to Airbus's entry is the net outcome of two factors that tend in opposite directions: the direct effect of the Airbus presence in lowering aircraft prices, and the indirect effect in weakening Boeing and thereby raising aircraft prices. This second effect, which if sufficiently large can give rise to the Starfish phenomenon, is an important factor in all reasonable specifications of the model even if it is not always the determinant one.

The Starfish effect continues to be observed in the high elasticities simulation as well as that reported using low elasticities (that is, MDD does not produce the MD-11 in the absence of Airbus). In general the impact of Airbus on prices is weaker when elasticities are high. This is what one would expect since under these conditions a monopoly or duopoly is less able to exploit market power. This increases the risk that the pro-competitive effect of Airbus entry might be outweighed by its adverse impact on the ability of other producers to exploit scale economies and on their incentive to make R&D investments. Indeed our simulations with high elasticities reveal a slight negative impact of Airbus entry on (quality-adjusted) prices in the two medium-range segments (occupied by the A-300 and the A-330/A-340). While we should not put undue weight on these findings, they do indicate that even the weak impact of Airbus on prices in our main simulations may be overstated.

The model's qualitative findings are certainly sensitive to assumptions about the likely course of future demand. This is in contrast to the conjecture that has sometimes been made about this industry that increased investment in product development would outweigh any effect of demand expansion and thereby ensure that the market was always likely to be dominated by one or two producers (see Sutton, 1987). Our results indicate that the indirect effect of demand expansion on fixed investment is nothing like enough to outweigh the direct effect of demand expansion. In consequence, how many manufacturers the market can profitably support will always be sensitive to demand projections.

There are four respects in which the model's findings may be sensitive to the model's structure rather than to its specific parameters. First, the model assumes that the only impact of competition on production costs is by affecting manufacturers' output levels and thus their ability to reap scale and learning economies. We have not allowed for the possibility that competition may act as a direct spur to increased efficiency in production methods. There is no professional consensus about how to model such effects, but there is evidence that they may be important in some industries. It is likely that taking such phenomena into account would increase the effect of Airbus entry in lowering aircraft prices.

Secondly, our modelling of production decisions assumes that production capacity is decided once and for all at the start of a model's production cycle and cannot be subsequently changed. While this assumption is clearly unrealistic, it is not clear what effect a more realistic assumption would have on the model's results.

Thirdly, the fact that we ignore the possible strategic motivation for capacity choices (unlike that for entry decisions) may slightly affect both the calibration of the base run and the nature of the simulations. The only plausible strategic motivations we have ignored are ones in early stages that affect subsequent marginal entry decisions by MDD at either stage E or Stage C, or ones that affect output decisions at stage D. Ignoring these last may mean we have slightly underestimated the marginal cost of producing the Boeing 737 (because we have treated actual output as equal to the Cournot output, instead of as exceeding the Cournot output by an amount designed to induce output reductions by rivals at a later stage); ad hoc simulation suggests this would make a very small difference to the overall results, and that the linear specification of our model may even exaggerate this difference.

Alternatively, the base run may underestimate the marginal cost of producing the DC-10, since additional output of the DC-10 beyond the static profit-maximising level might have contributed to the learning economies that made the decision to develop the MD-11 at stage E just profitable. It is conceivable also that Boeing may have produced larger numbers of SRNB aircraft at Stage A than would otherwise have been profitable, in order to deter entry by MDD at Stage C (where MDD did not in fact enter). Either effect would imply that the presence of Airbus encourages strategic increases in output at earlier stages because of Airbus's tendency to weaken MDD and make its entry decisions more marginal; this effect would counteract that already noticed, in which the knowledge of Airbus's subsequent entry restrains output by Boeing and MDD at stages A and B because of the anticipated loss of scale and scope economies. Ignoring the strategic motive for capacity-setting in the simulations, however, would only really matter as far as MDD's predicted entry at Stage C (with a rival to the Boeing 737) is concerned. It is possible that, in the anticipated absence of Airbus, Boeing might have wished to produce more SRNB aircraft to deter entry by MDD. This effect works in the opposite direction from the previous two. And all these effects concern the impact of Airbus on output at Stages A or B - that is, before Airbus's actual entry. Since there is some doubt in any case to what extent Boeing and MDD really foresaw so early the subsequent development of the consortium, it seems to us that the quantitative impact of our ignoring strategic motivations for capacity-setting is most unlikely to be important.

Finally, our modelling of investment in aircraft quality is undoubtedly simplistic. Producers are supposed to maximise profits by choosing a point on a differentiable technology production function that yields aircraft operating costs as a function of fixed development costs. This overlooks the possibility that investment may be subject to indivisibilities, and more profoundly ignores the possibility of R&D expenditures' arising partly out of non-maximising managerial behaviour: if incentives for R&D expenditure arise more out of threats to existing profits than out of the prospect of making more, then Airbus may have had a more beneficial effect on innovation in the industry than our model implies. Furthermore, since aircraft in a given segment are identical except with regard to operating costs this implies that all development expenditures by different producers within a segment represent pure duplication. Given the fact that there is still some differentiation of aircraft even within segments, once again our methodology may paint an unwarrantedly negative picture of the impact of Airbus on this market. Quantifying the extent of any bias is, however, a much more difficult task.

8. Concluding remarks

This paper has modelled the impact of Airbus on the market for large jet aircraft. What have we learned? Most importantly we have learned that an entrant facing two asymmetric rivals is in a quite different situation from an entrant facing a single incumbent. Airbus has had a much less significant effect on prices and outputs in this market than earlier duopoly models had led us to expect. We have also learned that entry deterrence involves delicate calculations; when rivals are asymmetric there is a serious danger of the Starfish effect.

In the light of these sober lessons it is encouraging and perhaps surprising that Airbus is not Concorde: it has a reasonable chance of making a good if not spectacular profit. This profit has been bought at the considerable expense of the shareholders of the Boeing Corporation and (perhaps) the taxpayers of the United States. It is not surprising that they have objected; given the sums of money at stake it is perhaps more surprising that there have not been more determined efforts to sponsor transatlantic collusion.

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Appendix 1: The Structure of the Model

A.1.1 Definitions and Equations

There are 4 market segments, indexed i=1,..,4:

1) Short-range, narrow bodied (A 320, B 737, MD-80)

2) Medium range, medium bodied (A 300/310, B 757, B 767)

3) Long-range, medium bodied (A 330/340, B 777, MD-11))

4) Long-range wide bodied (B 747)

Producers are Airbus, Boeing and McDonnell-Douglas, indexed j=1,2,3.

Demand is linear, and chain linked, i.e. there is substitution between products in one segment and those in neighbouring segments:

(1) $k_{ij} + m_{ij} = a_i + b_i q_i + c_i(q_{i+1} + q_{i-1})$

where:

k_{ij} represents the annual capital cost to the airline of running the aircraft;

m_{ij} represents other costs (basically fuel and maintenance);

q_i is total output in segment i.

Note that for segments 1 and 4, one of the two neighbouring segments has demand identically equal to zero.

k_{ij} is in turn a function of the price of the aircraft:

(2) $k_{ij} = p_{ij}(r + D)$

where:

p_{ij} is the price of the aircraft;
r is the real interest rate;
D is the depreciation rate;

Equations (1) and (2) together yield an expression for the price of the aircraft:

$$p_{ij} = [a_i + b_i q_i + c_i(q_{i+1} + q_{i-1}) - m_{ij}]/(r + D) \tag{3}$$

Costs are likewise linear, and display scale, learning, chain-linked scope and vintage effects:

$$\begin{aligned} C_j = F_j &+ (\alpha_{1j} - \Gamma(Q_{2j}+q_{2j}))q_{1j} + (\beta_1 - \delta Q_{1j})(q_{1j})^2 \\ &+ (\alpha_{2j} - \Gamma(Q_{1j}+q_{1j}+Q_{3j}+q_{3j}))q_{2j} + (\beta_2 - \delta Q_{2j})(q_{2j})^2 \\ &+ (\alpha_{3j} - \Gamma(Q_{2j}+q_{2j}+Q_{4j}+q_{4j}))q_{3j} + (\beta_3 - \delta Q_{3j})(q_{3j})^2 \\ &+ (\alpha_{4j} - \Gamma(Q_{3j}+q_{3j}))q_{4j} + (\beta_4 - \delta Q_{4j})(q_{4j})^2 \end{aligned} \tag{4}$$

where:

C_j is the total cost of production by producer j.

F_j is the fixed cost of production by producer j (which is a function of the segments in which it operates).

α_{ij} is a vintage-specific cost parameter for the model produced in segment i by producer j (capturing the idea that the cost of production of a model may depend on factors peculiar to its vintage).

Q_{ij} represents cumulative output in segment i by producer j (to capture learning effects).

Γ and δ represent respectively scope and learning parameters.

A.1.2 Solving the Model

We can use equations (3) and (4) to formulate a profit function which will then be differentiated with respect to output. In principle, since output in one segment affects prices (and therefore profit) in neighbouring segments, we should differentiate the global profit function for all segments considered together. In practice, to simplify notation we can define the incremental profit function for producer j in segment i as those components of profit in segments i-1, i and i+1 considered together that are affected by output in segment i:

$$\begin{aligned}(5)\qquad \pi_{ij} = {} & q_{ij}\,[a_i + b_i q_i + c_i(q_{i+1} + q_{i-1}) - m_{ij}]/(r + D)\\ & + q_{i-1,j}\,[a_{i-1} + b_{i-1}q_{i-1} + c_{i-1}(q_i + q_{i-2}) - m_{i-1,j}]/(r + D)\\ & + q_{i+1,j}\,[a_{i+1} + b_{i+1}q_{i+1} + c_{i+1}(q_{i+2} + q_i) - m_{i+1,j}]/(r + D)\\ & - F_{ij} - (\alpha_{ij} - \Gamma(Q_{i-1,j}+q_{i-1,j}+Q_{i+1,j}+q_{i+1,j}))q_{ij} + (\beta_i-\delta Q_{ij})(q_{ij})^2\\ & - (\alpha_{i-1,j} - \Gamma(Q_{i-2,j}+q_{i-2,j}+Q_{ij}+q_{ij}))q_{i-1,j}\\ & - (\alpha_{i+1,j} - \Gamma(Q_{i+2,j}+q_{i+2,j}+Q_{ij}+q_{ij}))q_{i+1,j}\end{aligned}$$

where F_{ij} is the incremental fixed cost associated with entry by producer j into segment i.

Differentiating (5) with respect to q_{ij} yields:

$$\begin{aligned}(6)\qquad d\pi_{ij}/dq_{ij} = {} & [a_i + b_i q_i + c_i(q_{i+1} + q_{i-1}) - m_{ij}]/(r + D)\\ & + [b_i q_{ij} + c_{i-1}q_{i-1,j} + c_{i+1}q_{i+1,j}]/(r + D)\\ & - (\alpha_{ij} - \Gamma(Q_{i-1,j}+q_{i-1,j}+Q_{i+1,j}+q_{i+1,j}))\\ & - 2q_{ij}(\beta_i-\delta Q_{ij})\\ & + \Gamma(q_{i-1,j}+q_{i+1,j})\end{aligned}$$

Setting equation (6) equal to zero for j=1,2,3 and substituting $q_i=q_{i1}+q_{i2}+q_{i3}$ yields a system of simultaneous equations in the three variables q_{i1},q_{i2} and q_{i3}. This system is very lengthy to solve by hand, so we have used a Mathematica programme to do so. The solutions are described in Appendix 3.

Essentially this solution technique involves assuming that the output decision in each segment is taken simultaneously by the three producers, with each one treating as parametric its own (historically given) past and (rationally anticipated) future output in other segments, as well as the output of its competitors in all segments. This latter is the Cournot assumption, which Kreps and Scheinkman (1983) have shown is a reasonable approximation to a form of competition in which producers first choose production capacity and then compete in prices.

There are six stages of the model, which correspond to a stylised account of the history of the civil airliner market from the mid-1960s to the late 1990s. At each stage producers choose once and for all the level of production capacity (i.e. output) over the 25-year life of the model produced:

A (early 1960s): The players decide whether to enter segment 1 [this corresponds to the decision by Boeing to produce the 727 and 737, and by MDD to produce the DC-9]

B (late 1960s): Segment 4 [Boeing 747, MDD DC-10]

C (1970s): Segment 2 [Airbus 300,310, B 757,767]

D (early 1980s): Segment 1 [Airbus 320, B 737, MD-80]

E (late 1980s): Segment 3 [A-330,340, B 777, MD-11]

F (late 1990s): Segment 4 [replacements for the 747?]

The model is solved backwards, in the following way. First stage F is solved, taking as parametric the (historically given) value of output in the other segments. Then stage E is solved, taking the historical value of output in stages A-D and the equilibrium value of output in stage F (and so on analogously for other stages). We then check whether, at any stage, the equilibrium entry decision of any producer would be different if, instead of historical output data, the equilibrium were calculated using the outputs that would have been chosen if some producer X at an earlier stage had made a non-equilibrium entry decision. If so, we compare the total profits for producer X under the two historical sequences and choose as the solution to the model the one that yields the highest total profits.

For the base run, which attempts to reproduce history, there is by definition a fairly close correspondence between historical and equilibrium values of output. For counterfactual simulations, we have undertaken a first run from which we extract equilibrium output values that are then entered as historical values in the second run; the results of the two runs are usually very similar, indicating that the model converges rapidly.

There are two small qualifications to the temporal structure of the model. One is that production in the different market segments is not simultaneous, so that cross-elasticities are not strictly valied for the whole production run of a model. The solution we have adopted is the following. Stages C and E (corresponding to segments 2 and 3) overlap with both an earlier and a later stage in which productions are made in a neighbouring segment (decisions in Stage C overlap with production in stages A and D; decisions in stage E overlap with production in stages B and F). Prices in these segments are determined as the weighted average of the prices that would obtain if there were full overlap with either of the two relevant stages. The weights are parameters lambda2 and lambda3, which can be interpreted as the proportion of its life that aircraft in segments 2 and 3 respectively will be competing against the earlier model in a neighbouring segment as opposed to competing against the replacement models. At other stages we have assumed full overlap, but have chosen relatively modest cross-elasticities to relfect the fact that in practice there will be competition from neighbouring segments only for some of a model's lifetime.

The second temporal qualification is that we have treated the introduction of the DC-10 as belonging to segment 4 (instead of segment 3 where it would more naturally belong). This is to avoid introducing an additional decision in segment 3 earlier in the model, which would considerably increase the computational complexity of the model while yielding little new insight. However, we have assumed that learning economies were utilised by McDonnell-Douglas in building the MD-11.

A.1.3 Endogenising Product Development

The model can also be used to endogenise expenditure on research and development, by making operating costs of the aircraft a function of fixed development costs, and examining the way in which different hypotheses about market structure affect the incentives of manufacturers to invest in reducing these costs. To do this we differentiate equation (5) with respect to F_{ij}. Setting the derivative equal to zero, we can appeal to the envelope theorem to ignore any effect of changing fixed costs on the optimal value of q_{ij} when small changes are considered. This procedure yields:

$$(7) \qquad d\pi_{ij}/dF_{ij} = -q_{ij}[dm_{ij}/dF_{ij}]/(r+D) - 1 = 0$$

Multiplying by F_{ij}/m_{ij} gives the equilibrium level of fixed costs:

$$(8) \qquad F_{ij} = q_{ij}.m_{ij}.h_{ij}/(r+D)$$

where h_{ij} is the (absolute value of the) elasticity of aircraft operating costs with respect to fixed costs.

Solving (8), which has two unknowns, requires choosing a function relating F_{ij} to m_{ij}. We have chosen for simplicity a constant elasticity cost function:

$$(9) \qquad m = k(F)^{-h}$$

where subscripts are omitted for notational convenience. Substituting (9) in (8) yields an expression for F*, the optimal value of F:

(10) $F^* = (kqh/(r+D))^H$,

where $H = 1/(1-h)$.

It is worth noting that the choice of a constant elasticity form (coupled with the calibration methods we discuss below) probably somewhat exaggerates the incentive for manufacturers to make investments in reducing operating costs; it has been suggested to us that the elasticity probably falls as development costs rise. However, since the qualitative results we report do not differ according to whether or not we endogenise development costs, the fact that the true value of endogenous development costs may lie somewhere between the two cases suggests the model's findings are fairly robust to this modification.

We have used the same method for incorporating cost endogeneity in our counterfactual simulations as for incorporating output variation. That is, we run a simulation with changed parameters, observe the endogenous costs and then run a second simulation with those costs entered as new parameters and report the results of the second run; again the difference between first and second runs is usually small.

Appendix 2: Data and Calibration Methods

The model just described has 23 industry parameters and 32 manufacturer-specific parameters, making 119 (= 32 X 3 + 23) parameter values to be chosen in total. Some of these parameters represent historical values of variables (such as output or operating costs) that the model also generates endogenously. Actual parameter values are supplied with the results of each model run. We have chosen them in the following way:

Non-capital operating costs (18 values: i.e. 3 per stage):

Data supplied by the DTI for actual models, plausible guesses used where a manufacturer has no model in the relevant segment. All costs and prices are in millions of US dollars. We have standardised for size where competing models differ.

Fixed costs per stage (18 values):

DTI estimates of average fixed costs, tempered by own guesswork as to variations in such costs between producers and via sharing between programmes in different segments. Note that fixed costs affect only entry decisions, not outputs conditional on entry. They do, however, affect estimates of rates of return, which is another reason for treating such estimates with caution.

Historical outputs (12 values):

DTI records and projections, tempered by own guesswork. Only 12 values are needed because historical values of stages D and F do not enter into solutions of other stages.

Accumulated learning (18 values):

These are just historical outputs of models relevant to production at a given stage. Only four values are non-zero, corresponding in segment D to prior production of the 727, 737 and DC-9, in segment E to prior production of the DC-10 and in segment F to prior production of the 747.

Interest and depreciation (1 value):

We have chosen a long run value of 0.15, based on 6% real interest plus 9% depreciation, which is consistent with the operating cost data supplied us by DTI. Higher values would tend to damage Boeing and Airbus and help McDonnell-Douglas, since the latter's aircraft tend to have lower capital and higher non-capital operating costs. Coversely, lower values in the simulations would weaken McDonnell-Douglas.

Economies of scale (4 values):

In each segment we have chosen a parameter that gives, at the mean value of output, an approximation to the view, widely accepted in the industry, that a doubling of output would be expected to yield a 20% fall in marginal costs of production.

Economies of scope (1 value):

Here there is no comparable industry consensus that we have been able to ascertain. We have chosen a linear approximation to the two values of the scope parameter of Klepper (1990), using his higher value of 0.0033 for our base case.

Economies of learning (1 value):

The parameter here is chosen to approximate the view that a 100% increase in accumulated production leads to a 20% saving in variable cost. The main effect of alternative values is on prices in segment D, where lower values lead to slightly higher prices in the alternative simulations but leave the base run unaffected.

Marginal production costs (12 values):

The intercept of the marginal cost curve is specific to each segment and each producer (changes in marginal costs between different stages of segments 1 and 4 are in effect captured by changes in the values of m). We have chosen these values so that, at equilibrium outputs, variable costs are approximately equal to 60% of historical revenues, in line with the industry consensus on the division of costs into fixed and variable components. However, after calibration of the demand function (see below) we have then adjusted the relative values of α_{ij} within each stage so as to reproduce approximately the historical market shares. The values of α_{ij} can then be interpreted as embodying not only marginal costs of production as such but also any differences in manufacturers' ability to produce to customers' specifications (such as differences in perceived reliability, convenience etc.).

Own-price demand coefficients (4 values):

Once the marginal cost curve is determined, calibration to historical output levels determines the point of intersection of the marginal cost and marginal revenue curves, and calibration to historical prices determines the slope of the marginal revenue curve (and hence, in a linear model, the demand curve).

Demand intercepts (6 values):

These are determined by the same process that determines the own-price elasticities. Note, however, that intercepts may differ between stages A and D, and between B and F, since historical outputs differ, but we have constrained price coefficients to be the same.

Cross-price demand coefficients (4 values):

Lacking either data on these or an effective means of calibration we have chose them to lie at between 10% and 5% of the own-price values. This reflects a view that aircraft in neighbouring segments are a fairly poor substitute for one another, at least over the range of price variation under consideration here. This does not mean, however, that cross-price effects are unimportant, since they may affect the profitability of an entry decision. Setting all cross-price effects to zero in our base run induces entry by McDonnell-Douglas at stage C, since now the aircraft produced in segment 2 have no depressant effect on the prices of the MD-80 and the MD-11.

Lambda (2 values):

Chosen at 0.3 and 0.5 to capture degree of historical overlap between stages.

Elasticities of operating costs with respect to development costs (18 values):

For each producer at each stage, h is chosen approximately to satisfy equation (8) with respect to historical outputs and fixed costs. In other words it is assumed that producers were optimising in choosing their development costs. The value of k is then chosen to satisfy equation (9) for historical levels of operating costs. Equation (10) then determines optimal fixed costs, which will by definition be approximately equal to actual fixed costs for the base run. For simulations, (10) and (9) determine the optimal fixed and operating costs respectively.

Appendix 3

Solutions to First Order Conditions

The following are the solutions generated by Mathematica to the system of first order conditions described in Appendix 1:

3 PLAYERS

qi3: $(-((b_i*A_2-b_i*A_3)*(b_i^2-2*b_i*B_1))+C_2*(b_i*A_1-2*A_3*B_1))/E_2$

qi2: $(-((b_i*A_1-b_i*A_2)*(b_i^2-2*b_i*B_3))+C_1*(b_i*A_3-2*A_2*B_3))/E_1$

qi1: $(-((b_i*A_3-b_i*A_1)*(b_i^2-2*b_i*B_2))+C_3*(b_i*A_2-2*A_1*B_2))/E_3$

where:

$A_j= -a_i+m_{ij}-c_i*q_{i-1}-c_{i-1}*q_{i-1,j}-c_i*q_{i+1}-c_{i+1}*q_{i+1,j}+\alpha_{ij}*(r+D)-2*\Gamma*q_{i-1j}*(r+D)-\Gamma*Q_{i-1,j}*(r+D)-2*\Gamma*q_{i+1,j}*(r+D)-\Gamma*Q_{i+1,j}*(r+D)$

$B_j= b_i-\beta_i*(r+D)+\delta*Q_{ij}*(r+D)$

$C_j= b_i^2-2*\beta_i*b_i*(r+D)+2*b_i*\delta*Q_{ij}*(r+D)$

$E_j=(-((b_i^2-2*b_i*B_{j-1})*(b_i^2-2*b_i*B_{j+1}))+C_j*(b_i^2-4*B_{j-1}*B_{j+1}))$

and where $B_0=B_3$ and $B_4=B_1$.

2 PLAYERS

qi2$=(b_iA_1-2*A_2B_1)/(b_i^2-4*B_1B_2)$

qi1$=(b_iA_2-2*A_1B_2)/(b_i^2-4*B_1B_2)$

where,

$A_j=(-a_i+m_{ij}-c_i*q_{i-1}-c_{i-1}*q_{i-1,j}-c_i*q_{i+1}-c_{i+1}*q_{i+1,j}+\alpha_{ij}*(r+D)-2*\Gamma*q_{i-1,j}*(r+D)-\Gamma*Q_{i-1,j}*(r+D)-2*\Gamma*q_{i+1,j}*(r+D)-\Gamma*Q_{i+1,j}*(r+D))$

$B_j= (b_i-\beta_i*(r+D)+\delta*Q_{ij}*(r+D))$

1 PLAYER

$q_i j = A * (B+C)$

where,

$A_j = [(2b_i)/(r+D) - 2*(\beta_i - \delta * Q_{ij})]^{-1}$

$B_j = (-a_i + m_{ij} - c_i*(q_{i+1} + q_{i-1}) - c_{i-1} q_{i-1,j} - c_{i+1} q_{i+1,j}) 1/(r+D)$

$C_j = \alpha_{ij} - \Gamma*(Q_{i+1,j} + 2q_{i-1,j} + 2q_{i+1,j} + Q_{i-1,j})$

The solutions in the three-player case are hard to interpret intuitively. However, it is helpful to begin from the one-player case. The term (B+C) is essentially a measure of how far apart are the intercepts of the monopolist's marginal cost and marginal revenue curves (B defining the marginal revenue and C the marginal cost, taking cross-effects into account). The term A measures the difference in slope between the two curves (which depends on the elasticity of demand but also on the degree of scale economies) and consequently determines at what level of output they will intersect.

The equations in the two-player and three-player cases use the same principle but applied not to market demand but to residual demand (i.e. the demand left over once the rival firms' output has been sold). The term A in both cases measures the distance apart of the intercepts of the marginal cost and marginal revenue curves. One firm's output will, other things equal, be increasing in this distance and decreasing in the analogous distance of its rivals (since has a negative impact on the first firm's residual demand). The term B in both cases represents the difference in slope between the two curves, with once again the value of B for a firm's rivals being a determinant of its own output.

Figure 1 : Main product developments