Dynamic Efficiencies of the 1997 Boeing-McDonnell Douglas Merger*

Yonghong An† Wei Zhao‡

October 24, 2018

Abstract

We evaluate the welfare effects of the 1997 merger between Boeing and McDonnell Douglas in the medium-sized, wide-body aircraft industry. We find that the merger led to lower prices. To investigate the cause of the price drop, we develop an empirical model of multi-product firms, allowing for learning-by-doing in a dynamic game. This model allows us to quantify the consumer welfare of the merger while accounting for both increased market power and merger efficiencies from accelerated learning-by-doing. Taking account of all static and dynamic effects, we find that net consumer surplus increased by as much as $5.14 billion. By contrast, a static model ignoring efficiencies of learning-by-doing predicts a consumer loss of $0.92 billion.

Keywords: Learning-by-doing, multi-product firms, dynamic merger efficiencies.
JEL classification: K21; L13; L41

---

*Zhao is extremely indebted to his advisors Joseph E. Harrington, Jr., Przemyslaw Jeziorski, and Richard Spady for their continual guidance, support, and encouragement. We are both grateful to C. Lanier Benkard for making the labor input data of the Lockheed L-1011 available and to Edmund S. Greenslet, publisher of *The Airline Monitor*, for numerous inspiring discussions about the aircraft industry and the merger. Also, we would like to thank Lanier Benkard, Jiawei Chen, Yingyao Hu, Elena Krasnokutskaya, Yiyang "Ellen" Li, Haizhen Lin, Yao Luo, Xun Tang, Michael A. Williams, Jonathan Wright, Ruli Xiao, and participants in seminars at Johns Hopkins University for their helpful comments, discussion, and suggestions. All remaining errors are ours.

†Department of Economics, Texas A&M University, College Station, TX 77843; email: y.an@tamu.edu.

‡Competition Economics LLC, 2000 Powell Street, Suite 510, Emeryville, CA 94608; email: wzhao@c-econ.com.

1 Introduction

In antitrust practice one fundamental question is how to evaluate the short-run impacts of mergers on consumer welfare. A merger can lessen competition and harm consumers, but it can also bring efficiencies that reduce costs, e.g., by generating economies of scale in production. Antitrust policy balances the loss of lessened competition with the efficiencies of the merger. Measuring the loss from mergers has been well studied in the literature, e.g., Nevo (2000). Nevertheless, empirical literature on quantifying efficiencies in merger evaluation is very limited. In this paper we attempt to fill the gap by providing empirical evidence that dynamic efficiencies are realized after a merger and by quantifying the welfare effects of these efficiencies.

Specifically, we evaluate the welfare effects of the 1997 merger between Boeing and McDonnell Douglas in the aircraft industry, where dynamic efficiencies might have occurred due to accelerated learning-by-doing. Our analysis focuses on the market for medium-sized wide-body (hereafter "medium-sized") aircraft. In the pre-merger market, Boeing and McDonnell Douglas were the first- and third-largest producers of civilian jets, respectively. Their merger was approved in August 1997, with Boeing acquiring McDonnell Douglas. After the merger, only Boeing and Airbus remained as major competitors in the global market for large commercial aircraft. The primary impact of the merger on market structure was the elimination of McDonnell Douglas, whose only wide-body product in production was the MD-11, a medium-sized aircraft. Shortly after the merger, Boeing shut down production of the MD-11.

We begin our analysis by investigating changes in aircraft prices. During the five years after the merger, the medium-sized aircraft produced by both Airbus and Boeing experienced significant price drops. Meanwhile, the prices of other wide-body aircraft declined only slightly, and the prices of narrow-body aircraft rose. Our analysis shows that the annual decrease in prices for medium-sized aircraft was 2.36 millions dollars larger after the merger than before it. Focusing only on the post-merger period, the annual prices of medium-sized aircraft dropped 4.46 million dollars more than the prices of all other aircraft. We also find that this pattern disappeared seven years after the merger. These results suggest that the merger generated efficiencies that reduced marginal costs for medium-sized aircraft; the efficiencies were the most prominent for medium-sized aircraft and large enough to offset the effects of increased market power; and the efficiencies evolved over time.

The above analysis ignores how the merger affects the evolution of marginal costs. To further explore the merger's dynamic efficiencies, we propose a dynamic oligopoly game to describe the market for medium-sized aircraft. We incorporate into the model learning-by-doing, a common dynamic force relevant to industry performance. Multi-product firms compete in an infinite-horizon dynamic game. In each period, a firm chooses how much to produce of each product. The production decision affects both current and future profit streams through its impacts on the firm's experience level. Experience accumulates due to learning and depreciates due to forgetting. We model learning-by-doing in a way that the unit production cost is a decreasing function in experience. Moreover, a firm's production is allowed to have spillover effects in terms of experience accumulation from other products of its own and its competitors. Firms are assumed to behave according to a Markov Perfect Equilibrium in which they decide on production in each period given the state variables of firms' experiences, the stochastic realization of market size, and an unobserved characteristic of products.

In the dynamic model, the Boeing-McDonnell Douglas merger may hurt consumers because reduced competition creates an incentive for Airbus and Boeing to restrict production and raise prices; this is the traditional market power effect. However, the merger also may generate efficiencies in several ways. First, there may be an immediate benefit of lowering the marginal cost for Boeing's products because of an one-time experience transfer from McDonnell Douglas after the merger. Second, future experience might be shared more effectively between different products within the same firm (within-firm spillover) than between different firms (across-firm spillover), bringing costs down after the merger. Third, Boeing's choice to shut down MD-11 production shortly after the merger could have two effects. On the one hand, fewer products mean less variety, which makes consumers worse off. On the other hand, there would be more demand for other medium-sized aircraft, e.g., Boeing 777 (B777). More production leads to faster experience accumulation, lower unit cost, and lower future prices, all of which make consumers better off.

To quantify the welfare effects of the Boeing-McDonnell Douglas merger, we employ a multi-step procedure to solve the dynamic game and simulate the paths for prices, quantities, profits, and consumer surplus. The first step is to estimate the demand parameters of the model. The static demand system is captured by a nested logit model and the parameters are estimated using a two-stage least squares (2SLS) approach.

Next, we estimate the parameters in the total variable cost function, the learning curve, and the state transition process of experience using the data on the Lockheed L-1011. Our estimates indicate existence of substantial within-firm spillover: building four aircraft of different types is as helpful in experience accumulation as building one aircraft of the same type. The cross-firm spillover is estimated to be negligible.

Finally, we solve the dynamic game based on the estimates of demand and cost parameters, and evaluate the efficiencies of the merger using the simulated paths of consumer welfare. We consider three different scenarios: (i) merger occurs and MD-11 production is shut down shortly after the merger, which is what actually happened; (ii) merger occurs with continued production of MD-11; and (iii) no merger. In the simulation, we also incorporate possible one-time cost synergy as an experience stock transfer between the MD-11 and the B777. The simulated results indicate that prices drop more rapidly after the merger in scenario (i) relative to scenario (iii), no matter there is one-time experience transfer or not.

Our main finding is that the merger brings dynamic efficiencies, which come from accelerated learning-by-doing after the merger; these efficiencies outweigh the detrimental market power effect. By comparing scenario (i) with (iii) we estimate that consumer surplus increases by \$0.11 billion and \$5.14 billion, respectively, depending on whether experience stock does not transfer or transfers completely between the MD-11 and the B777. By contrast, a static equilibrium model that ignores learning-by-doing predicts a

$0.92 billion loss of consumer surplus.

There are several important features of the merger efficiencies. First, whether MD-11 production is shut down or not after the merger does not change our main finding. We find that if MD-11 were kept, the merger would increase consumer surplus by $0.61 billion and $5.29 billion without any experience stock transfer between MD-11 and B777 versus with complete transfer, respectively. These are qualitatively similar to our main result. Second, the merger brings dynamic efficiencies, mainly because the medium-sized aircraft were at their beginning stage and there was a lot of room for learning. If B777 had have a high level of experience before the merger, the dynamic efficiencies might not be large enough to offset the effect of market power. Finally, the dynamic efficiencies generated by the accelerated learning-by-doing after the merger are intermediate, and disappear in the long run. In summary, our method and findings shed light on merger evaluation in aircraft and other industries where dynamic efficiencies may exist, especially when the efficiencies are generated from learning-by-doing.

Our paper contributes to the existing literature on dynamic effects of mergers. On the theoretical side, Gowrisankaran (1999) examined the dynamic effects of a merger with numerical analyses within the Ericson-Pakes framework (Ericson and Pakes, 1995). Chen (2009) examined the effects of mergers with dynamic capacity accumulation. Nocke and Whinston (2010) provided a new framework to model dynamic merger decisions. On the empirical side, Stahl (2009) studied the consolidation process in the broadcast television industry. Benkard et al. (2010) evaluated the medium- and long-run dynamic effects of airline mergers on market structure. Jeziorski (2014) estimated fixed-cost efficiencies from mergers in the U.S. radio industry using a dynamic oligopoly model. Ashenfelter et al. (2015) found that the merger of the brewers Miller and Coors generates efficiencies by reducing shipping and distribution costs. However, our paper distinguishes itself from the aforementioned literature by introducing a model that focuses on the endogenous dynamics of cost (learning-by-doing).

We add to the literature on spillover effects of a learning curve by focusing both on the aircraft industry and evaluating a merger in the context of a dynamic game. The spillover effect of learning-by-doing had been studied in the semiconductors industry (Irwin and Klenow, 1994), shipbuilding (Thornton and Thompson, 2001), fuel cell vehicles (Schwoon, 2008), steel (Ohashi, 2005), and health care (Chandra and Staiger, 2007). Nevertheless, none of these papers study merger evaluation.

This paper is closely related to Benkard (2000) and Benkard (2004). The former introduced the concept of forgetting in order to explain the rise in cost for the Lockheed L-1011. Benkard (2004) proposed an empirical dynamic oligopoly model for the commercial aircraft industry that incorporates learning-by-doing to analyze industry pricing and performance and optimal industry policy. Our paper follows the methodological path in Benkard (2004) but differs from it in several aspects. First, we apply its methodology to evaluate merger effects. Second, we allow for the existence of cross-product and cross-firm spillover effects in the learning curve. Third, we solve an oligopoly dynamic model with multi-product firms, while in Benkard (2004) each firm only produces a single product. Finally, we focus on the medium-sized wide-body aircraft industry, while Benkard (2004) analyzes the entire wide-body aircraft industry.

The remainder of the paper is organized as follows. Section 2 introduces the industry background and the data, and then provides some non-structural analyses of the merger's effect on prices. Section 3 presents the dynamic oligopoly model. Section 4 estimates the demand system. Section 5 estimates total variable costs and the learning curve. Section 6 evaluates the static and dynamic merger effects. Section 7 presents robustness checks and model limitations. Section 8 concludes. Proofs, figures and tables are presented in the appendix.

2 The Industry and Data

2.1 The medium-sized aircraft market

A wide-body aircraft is a large jet airliner with two passenger aisles. Following the introduction in 1969 of the first wide-body aircraft, the Boeing 747, only four firms (Airbus, Boeing, Lockheed, and McDonnell Douglas) were active in the industry. Lockheed exited the market in 1984. Nine wide-body aircraft (A300, A310, A330, A340 and A380 of Airbus; B747, B767 and B777 of Boeing; and MD-11 of McDonnell Douglas) were in production during the 1991-2009 period. Wide-body aircraft are further split into categories by the number of seats small (around 250), medium (around 300), and large (around 450) and the maximum flying range, as illustrated in panel (a) of Figure 1. The horizontal line in the figure (between 1 and 1.2) marks the nautical distance between Beijing and New York, which is used as a benchmark separating transatlantic and transpacific routes. The subfigure indicates that medium and large aircraft have longer range and are more suitable for transpacific routes than small aircraft.

The primary impact of the 1997 Boeing-McDonnell Douglas merger on market structure was the elimination of McDonnell Douglas, whose only wide-body aircraft in production was the MD-11, a medium-sized aircraft. Prior to the merger, there were three other medium-sized models: A330, A340 and B777. In 1997, the quantity share of medium-sized aircraft was 31.7% among wide-body aircraft. Within the medium-sized group, the quantity shares of Airbus, Boeing and McDonnell Douglas were 40.7%, 22.2% and 37.1%, respectively. Boeing inherited the MD-11 and three narrow-body aircraft models (MD-80, MD-90, and MD-95) from McDonnell Douglas after the merger. Several months later, the new Boeing decided to phase-out the MD-11, which was a competitor of the B777, and later it introduced several submodels of B777. Airbus also introduced submodels of its A330 and A340 after the merger. From 1991-2009, there were twelve submodels of the original four models in the medium-sized category. The six Airbus submodels were A330-200, -300, A340-200, -300, -500, and -600. Their combined quantity share in the medium-sized group was 50% in 2009. That same year, Boeing's five submodels B777-200, -200ER, -200LR, -300, and -300ER accounted for the remaining 50% quantity share. In Table 1 we summarize some important characteristics of these submodels, based on the data that we describe later in this section. The MD-11 is the first product in the medium-sized group, while the B777 is the last to enter the market. "Number of engines" is an important characteristic because it is a key indicator of fuel efficiency. Twin-engine aircraft generally are more efficient than aircraft with more engines.

In this paper we assume that the medium-sized aircraft compete in an independent market, and restrict our analysis to this market. To examine the overlap between medium-sized aircraft with the other two wide-body groups, we define a ratio R_w for any route as the number of medium-sized flights over the total number of wide-body flights. If R_w is close to 0 or 1 for a route, then the medium-sized aircraft hardly compete with other wide-body aircraft; an R_w close to 0.5 indicates that medium-sized aircraft are actively competing with aircraft in the other two wide-body groups. We collect data for 908 U.S. domestic and international routes for the 1991-2009 period from Department of Transportation (www.transportation.gov) and present the histogram of R_w in panel (b) of Figure 1 (the details of constructing R_w are in the online appendix). The distribution illustrates that the ratio concentrates at 0 and 1, and that our assumption of independent markets is valid: only 38.5% of the routes fall in the interval $[0.2, 0.8]$ and only 26% in $[0.3, 0.7]$.

2.2 Data sources

The data on aircraft quantity, price, market size, and characteristics from 1991 to 2009 come mainly from *Airline Monitor*, *Avmark*, and official websites of Boeing and Airbus. The quantities of aircraft are constructed using the annual fleet and deliveries data from the *Airline Monitor*. Market size is approximated by the total number of used and new wide-body aircraft based on data from the *Airline Monitor*. Annual average value of new aircraft for each aircraft model is provided by *Avmark* and used as plane prices (all prices are converted into 1994 U.S. dollars). In calculating the value of an aircraft, *Avmark* takes into account the fact that aircraft are durable goods and could generate future values (*Avmark* publications: *Transport Aircraft Values*, February 2009, pages e-f). The characteristics of planes, including number of seats, maximum range, number of engines, fuselage, empty operating weight, first flight year, and fuel efficiency, come from the official websites of Boeing and Airbus, as well as various online sources. Another characteristic of aircraft, the product generation, is determined using fuel efficiency data from the *Airline Monitor* and operating cost differences reported in Boeing and Airbus newsletters. *Jet Airliner Production List* provides the first flight date of every wide-body aircraft produced, which we take as the date of production. Production rates and experience are constructed using quantity data and date of production.

The aircraft cost information comes mainly from the production data for the Lockheed L-1011, the third wide-body airliner to enter commercial operations, following the Boeing 747 and the McDonnell Douglas DC-10. Specifically, Benkard (2000) uses the direct man hours incurred by Lockheed in the production of each L-1011 aircraft as labor input.[1] Some cost and demand shifters also are required for our analysis. These shifters include the present and lagged terms of U.S. manufacturing wage rates from the *Bureau of Labor Statistics*, aluminum prices from IMF's *International Financial Statistics Online*

[1]We are grateful to C. Lanier Benkard for making this data available.

Database, present and lagged terms of world and regional GDP from IMF's *International Financial Statistics Online Database*, and oil price data from the *Energy Information Administration.*

2.3 A non-structural analysis

As we discussed in the introduction, dynamic efficiencies from learning-by-doing may offset market power effects, so that post-merger prices will decline. Therefore, lower prices after the merger suggest the existence of efficiencies generated by the merger. In this section, we investigate whether prices of medium-sized aircraft declined after the merger.

First, we plot in Figure 2 the prices of both narrow- and wide-body aircraft, with deliveries before and/or shortly after the merger. The vertical line marks the Boeing-McDonnell Douglas merger and the prices cover the period from 1991, the year that medium-sized aircraft (MD-11) were first delivered, to 2002, the fifth year after the merger. The two subplots on the top row illustrate significant price drops for medium-sized aircraft produced by Airbus (left) and Boeing (right). In the five years after the merger, the average prices of these two groups decreased by 23.4% and 18.4%, respectively. During the same time period, the average price of other wide-body aircraft declined by 3.9% as illustrated in the bottom right subplot, while narrow body's average price rose by 5.6%. One explanation for the discrepancy in price drop after the merger is that the merger generated more efficiencies that lowered the costs of medium-sized than other aircraft. Although the merger could cause prices to rise due to the increased market power of Airbus and Boeing, the reduction in prices indicates that efficiencies seem to have dominated the effects of market power for medium-sized aircraft. An alternative explanation is that medium-sized aircraft are at earlier stages of production than others; thus the effects of learning-by-doing on marginal costs are larger, and this leads to more rapid price decreases.

To distinguish these two alternative explanations, we employ a simple regression analysis controlling for number of years in service and production history. We use a difference-in-difference specification to compare price changes between medium-sized aircraft and other sectors as well. Specifically, we regress first differences of the prices on dummy variables "post-merger", "medium", their interaction, and other covariates that may affect the changes in prices.

$$\begin{aligned}\Delta p_{j,t} &\equiv p_{j,t} - p_{j,t-1} \\ &= \beta_1 \mathbb{I}\{\text{post-merger}\}_t + \beta_2 \mathbb{I}\{\text{medium}\}_j + \beta_3 \mathbb{I}\{\text{post-merger}\}_t \times \mathbb{I}\{\text{medium}\}_j \\ &+ \beta_4 H_{jt} + \beta_5 d_{jt} + \beta_6 D_{jt} + \beta_7 d_{jt}^2 + \beta_8 D_{jt}^2 + \beta_9 \Delta \text{GDP}_t + \beta_{10} \Delta \text{Oil}_t \\ &+ \beta_{11} \mathbb{I}\{\text{Airbus}\}_j + \beta_{12} \mathbb{I}\{\text{Boeing}\}_{jt} + \phi_t + \epsilon_{jt}, \end{aligned} \tag{1}$$

where $\mathbb{I}\{\text{post-merger}\}_t = 1$ for $t = 1998, \cdots, 2002$. The variable H_{jt} is the number of years that product j has been in the market at year t after its first delivery; d_{jt} and D_{jt} are the number of aircraft j delivered in year t and the total delivered number up to year t, respectively. We include the three variables H_{jt}, d_{jt} and D_{jt} to capture the effects of learning-by-doing as well as forgetting: including H_{jt} in the regression mitigates the concern that medium-sized aircraft learn faster because they are at earlier stages of production. We use the growth rate of world GDP and price change of oil to control for the effects of the demand side on the price changes. A linear time trend ϕ_t accounts for the downward trend in price changes. In specification (1), $\beta_1 + \beta_3$ captures difference in price changes before and after the merger for medium-sized aircraft; $\beta_2 + \beta_3$ compares difference in the post-merger price changes between medium-sized and other aircraft.

Our sample for the regression includes a panel of 32 submodels of aircraft, spanning the period from 1958 to 2011: 14 submodels are narrow-body, and of the remaining 18 wide-body submodels, 12 are medium-sized. We employ a pooled OLS estimator and present the results in Table 2. The estimated coefficients in the complete specification (the third column) indicate that the annual decrease in price for medium-sized aircraft is 2.36 million dollars (-2.51+0.15 million dollars) more in the post-merger period than in the pre-merger period. Focusing only on the post-merger period, the prices of medium-sized aircraft annually drop 4.46 million dollars (-2.51-1.95 million dollars) more than prices of all other aircraft. Formal tests demonstrate that these effects are significant at the 1% significance level (p-values are less than 0.01). Therefore, we conclude that: (1) across time, medium-sized aircraft experience faster price decreases in the post-merger period than the period before it; and (2) across aircraft, the prices of medium-sized aircraft drop more during the post-merger period. Since we control for years in service and production history, the lower prices observed in Figure 2 cannot be simply attributed to the fact that the medium-sized aircraft are at their earlier stages of production.

By focusing on all wide-body aircraft rather than just the medium-sized ones in the regression (replace $\mathbb{I}\{\text{medium}\}_j$ by $\mathbb{I}\{\text{wide}\}_j$), we obtain similar results but the scale of the annual price decrease is smaller, as shown in the last three columns in Table 2. To check the robustness of our regression results, we redefine the dummy variable $\mathbb{I}\{\text{post-merger}\}_t$ by varying the post-merger period. The regression results do not change qualitatively as long as the post-merger period is less than seven years.

In summary, we conclude from Figure 2 and the estimates in Table 2 that prices of medium-sized aircraft declined significantly after the merger, and such declines cannot simply be attributed to the fact that medium-sized aircraft were at their earlier stages of production. The results show that the merger efficiencies were the most prominent for medium-sized aircraft and large enough to offset the effects of increased market power on prices. The sources of these merger efficiencies could be: (1) experiences are shared more effectively between different products after the merger; (2) accelerated accumulation of experience occurred through producing more medium-sized aircraft after the MD-11 was phased out, i.e., there were accelerated learning-by-doing (e.g., see Benkard, 2000); or (3) there was an one-time experience transfer for Boeing after the merger, e.g., Boeing consolidated facilities after the merger to improve overall management, and said that "the plan would bring lower costs and keep Boeing competitive" (*Aviation Week & Space Technology*, March 30, 1998). To further explore these sources, we propose a structural model of the market for medium-sized aircraft in the next section.

3 The Model

3.1 Setup

This section presents a dynamic model for the market of medium-sized aircraft as the basis of our dynamic merger analysis. Our model closely follows Benkard (2004) in model setup, transition of state variables, and estimating strategies, but we add two important features: (1) firms produce multiple products, and (2) experience is transferable between different products (models or submodels), both within and across firms.

The industry is composed of $N \geq 2$ multi-product firms competing in discrete time over an infinite horizon, $t = 0, 1, 2, \cdots, \infty$. Firm $n \in \{1, 2, \cdots, N\}$ owns a subset of the available J ($J \geq N$) products. The subset is denoted as $\mathcal{J}_n$ with a cardinality J_n. The quantity and price of product j at time period t are denoted as q_{jt} and p_{jt}, respectively. The market structure of the industry at t is characterized by the state vector $\boldsymbol{\omega}_t = (\omega_{1t}, \omega_{2t}, \cdots, \omega_{Jt}, M_t)$. The state variable of a product j, $\omega_{jt} = (E_{jt}, \xi_{jt})$ consists of two components: E_{jt} is the (production) experience level of product j, which evolves endogenously as a function of the past experience and production of the industry. This variable is incorporated to reflect learning-by-doing. ξ_{jt} is an unobserved characteristic of j. M_t is the overall market size, a common state variable shared by all of the products. In addition, product j's observed characteristics are exogenously given and denoted as a vector X_{jt}.

All firms decide the quantities of their products. In each period, the game can be divided into two stages: First, shocks on demand, M_t and ξ_{jt}, are realized and observed by all firms. Second, firms compete in a simultaneous quantity competition game. Then the experience level for each product is realized based on the quantity choices and is revealed to all firms. We define firm n's quantity choices at t as a vector $Q_{nt} \equiv (q_{n1t}, q_{n2t}, \cdots, q_{nJ_nt})$. The industry quantity vector at t is then denoted as $\boldsymbol{Q}_t = (Q_{1t}, Q_{2t}, \cdots, Q_{Nt}) \equiv (Q_{nt}, Q_{-nt})$. The flow profit of a firm from product j is

$$\pi_j(\boldsymbol{Q}, \boldsymbol{\omega}) = p_j(\boldsymbol{Q}; X_j, \xi_j, M)q_j - C_j(q_j; E_j), \tag{2}$$

where we suppress the index t whenever there is no ambiguity. The term $p_j(\boldsymbol{Q}; X_j, \xi_j, M)$ is the inverse demand function. The cost $C_j(q_j, E_j)$ is the sum of a fixed cost and a total variable cost. We model the total variable cost as a function of quantity and experience level, denoted as $TVC(q_j, E_j)$. Recall that if learning-by-doing exists, then labor input for unit production decreases as production experience accumulates. This implies that the unit variable cost $TVC(q_j, E_j)/q_j$ is a decreasing function of experience in the presence of learning-by-doing.

Let ρ denote the discount factor of firms. Then the model described above can be characterized by the following Bellman equations for firm n,

$$V_n(\boldsymbol{\omega}) = \max_{Q_n} \left\{ \sum\nolimits_{j \in \mathcal{J}_n} \pi_j(Q_n, Q_{-n}, \boldsymbol{\omega}) + \rho \int V_n(\boldsymbol{\omega}')\mathcal{F}(\boldsymbol{\omega}'|\boldsymbol{\omega}, \boldsymbol{Q})d\boldsymbol{\omega}' \right\}, \tag{3}$$

where $\boldsymbol{\omega}'$ is the state variable in the next period, and the conditional density $\mathcal{F}$ is the transition process of state variables $\boldsymbol{\omega}$.

In this dynamic game, firms maximize their expected discounted value of profits by choosing the joint optimal policy (a vector of quantities at each time period), conditional on their expectations of the evolution of competitors. We use the Markov perfect Nash equilibrium (MPE) as the solution concept for our dynamic model and assume an MPE exists and is unique. We refer interested readers to Benkard (2004) for details of issues related to the existence of MPE and multiplicity of equilibria.

We assume away entry and exit decisions on both firm and product levels in our model. Nevertheless, we allow a firm to switch any of its products to a potential entrant product by setting the quantity of that product to be zero in any period, and to reverse the process by setting a positive quantity in any future period.[2] We believe that assuming away entry and exit decisions is a reasonable approximation of the aircraft industry for a number of reasons. First, there are significant entry barriers in the aircraft market. To start a new wide-body aircraft manufacturing business requires substantial initial capital and a complete set of frontier technologies. Second, the learning curve feature also acts as an entry barrier because it implies that an entrant cannot make any profit until it operates for a long period. As for exit, no evidence exists that the only two remaining firms, Airbus and Boeing, will exit the market, particularly considering their important political strategic status.

To estimate the dynamic model, we need to further model the transition of state variables $\mathcal{F}(\boldsymbol{\omega}'|\boldsymbol{\omega}, \boldsymbol{Q})$, the inverse demand function $p_j(\boldsymbol{Q}; X_j, \xi_j, M)$, and the cost function $C_j(q_j, E_j)$. We discuss the transition of state variables in the next subsection and the demand and cost functions in Sections 4 and 5, respectively. We take a two-step approach to estimate the dynamic game. In the first step, we estimate the demand and cost function following Benkard (2004). In the second step, we use the estimates from the first step as primitives to solve the equilibrium of the dynamic game. Such an approach is computationally convenient, because the dynamic game only needs to be solved once, and there is no parameter searching in solving the game.

3.2 Transition of state variables

We assume that the three state variables the market size M, unobserved characteristic ξ_j, and experience E evolve independently. Therefore, we discuss their transition processes separately.

3.2.1 Market size and the unobserved characteristic

As discussed in Benkard (2004), the steady growth of market size M_t is of second-order importance compared to business cycle fluctuations. So first we de-trend the market size variable M_t, which is approximated by the total number of used and new wide-body aircraft, in order to reflect 1994 values, and then we discretize it to three states. This approach results in a stationary state variable M_t; the finite values it takes greatly reduce

[2]Note that in the model, when the quantity of a product is effectively zero, it has no effect on the choices of other products or consumer surplus.

the complexity of the problem. We further assume that the discretized M_t follows a first-order Markov process.

The state variable ξ_{jt} captures the unobserved characteristic of product j at time t. Its fluctuation represents changes in consumers' taste driven by exogenous shocks from various sources, e.g., operating-cost-related macroeconomic shocks that lead to preference for twin-engine aircraft, or the temporary spur in international travel driven by the business cycle that makes relatively larger planes more attractive. Ideally, ξ_{jt} should be modeled as a state variable for each product in the dynamic game. However, that approach would be computationally costly and intractable. Instead we take two alternative approaches to model ξ_{jt}. First, we assume away the transition of ξ_{jt} by specifying it as a product-specific constant, $\xi_{jt} = \bar{\xi}_j$ where $\bar{\xi}_j$ is the mean of the series ξ_{jt} with respect to t. This specification is based on the assumption that the variation in a product's unobserved characteristic does little to explain the variation in its market share. Second, we specify ξ_{jt} as $\xi_{jt} = \bar{\xi}_j + \Delta\xi_{jt}$, where $\Delta\xi_{jt}$ is captured by the weighted average of two independent and binary state variables: two-engine aircraft are preferred or not, and Boeing's products are preferred or not. Because the state variables $\Delta\xi_{jt}$ are constructed using the change in consumers' preferences over two-engine aircraft and Boeing's products, we call them preference rank state variables. We further assume that all of the products share those two variables. The details are presented in Appendix A. Our main results in this paper are based on the first approach; the results using the second approach serve as a robustness check.

3.2.2 Experience

To model the experience transition, we assume that experience is accumulated, i.e., the next period's experience $E_{j,t+1}$ depends on this period's experience $E_{j,t}$. Furthermore, we explicitly allow for the spillover of experience across products and firms. The literature on the aircraft industry documents such spillovers. For example, after the 1997 Boeing-McDonnell Douglas merger, Boeing's Joint Strike Fighter (JSF) program took advantage of McDonnell's Phantom Work and its experience with the AV-8B Harrier and F-18E/F programs (*Aviation Week & Space Technology*, February 16, 1998, page 71). The spillover from McDonnell Douglas to Boeing was realized through significant technology, manufacturing, systems, and "lesson learned" experience from McDonnell's engineers that could be passed onto JSF designers (*Aviation Week & Space Technology*, December 23, 1996, page 13). Moreover, technology diffusion enables a possible experience transfer across products of different firms. Neven et al. (1995) discuss the possibility of learning between Airbus and Boeing.

The transfer of experience between different products (models or submodels), both within and across firms, implies that the experience $E_{j,t+1}$ depends on the entire industry quantity vector $\boldsymbol{Q}_t$. By taking into account the accumulation and spillover of experience, the law of motion for experience can be expressed as

$$f(E_{1,t+1}, \cdots, E_{J,t+1} | E_{1t}, \cdots, E_{Jt}, \boldsymbol{Q}_t) = \prod_{j=1}^{J} f(E_{j,t+1} | E_{jt}, \boldsymbol{Q}_t).$$

We introduce a parametric form of the process $f(E_{j,t+1}|E_{jt}, \boldsymbol{Q}_t)$. The process incorporates the following factors: (1) $E_{j,t+1}$ is increasing in both $E_{j,t}$ and any $q_{k,t}$, $k = 1, 2, \cdots, J$, that is, experience accumulates over time through both direct learning from production (q_{jt}) and spillover from production of other goods (q_{kt}, $k \neq j$); (2) producing a similar product to j contributes more to $E_{j,t+1}$ than does the production of a less similar product; and (3) experience may depreciate due to forgetting, which is captured by E_{jt} as $\partial E_{j,t+1}/\partial E_{j,t} < 1$. Specifically, we assume

$$E_{j,t+1} = \delta E_{jt} + \sum\nolimits_{k=1}^{J} \theta_{jk} q_{kt}, \quad E_{j1} = 1, \ \forall j, \tag{4}$$

where

$$\theta_{jk} \equiv \begin{cases} 1 & \text{if } j = k, \\ \theta_1 & \text{if } j \text{ and } k \text{ are different submodels of the same model,} \\ \theta_2 & \text{if } j \text{ and } k \text{ are different models of the same firm,} \\ \theta_3 & \text{if } j \text{ are } k \text{ models from different firms.} \end{cases}$$

The parameters θ_1, θ_2 and θ_3 capture spillover across submodels (e.g., A330-200 and A330-300), across-product/model in the same firm (e.g., A330 and A340), and across-firm (e.g., MD-11 and B777), respectively.[3]

The transition function of experience in (4) nests the commonly used specification in the literature $E_{j,t+1} = \delta E_{jt} + q_{jt}$ as a special case where $\theta_1 = \theta_2 = \theta_3 = 0$, i.e., there is no spillover of experience across production. In such a specification, learning is reflected by the positive correlation between $E_{j,t+1}$ and q_{jt}, and forgetting is captured by $0 < \delta < 1$. This accumulation function implies that experience accumulates as more aircraft are produced and depreciates due to organizational forgetting. The more general specification in (4) enables us to test the existence of spillovers across production once we estimate θ_1, θ_2, and θ_3.

The process in (4) allows us to obtain $E_{j,t+1}$ from E_{jt} and $\boldsymbol{Q}_t$. To apply E_{jt} as a state variable in the dynamic game, we discretize E_{jt} for all j and t, and then approximate $f(E_{j,t+1}|E_{jt}, \boldsymbol{Q}_t)$ by a Markov transition matrix. We postpone the details of the discretization and the transition matrix to Section 5.

4 Demand Estimation

4.1 The demand function

We assume that consumers do not engage in intertemporal substitution and that their choices are based solely on the observed characteristics, X_j, and the unobserved characteristic, ξ_j for product j. The observed characteristics include number of seats, maximum range, number of engines, fuel efficiency (measured by the number of liters

[3]We also consider a more general transition function of experience, in which the transition between two products depends on their "distance" in two dimensions of characteristics: number of seats and maximum ranges. The details are in the online appendix.

consumed per seat per 100 kilometers), and product generation. The different values of ξ_j capture variations in consumer preference over brand and plane characteristics.

We model yearly aircraft demand using an one-level Nested Logit discrete choice model, as in Benkard (2004). Consumer i's utility function from aircraft j at time t is

$$\begin{aligned} v_{ijt} &= \delta_{jt} + \omega_{ijt}, \\ \delta_{jt} &= X_{jt}\beta - \alpha p_{jt} + \xi_{jt}, \\ \omega_{ijt} &= \zeta_{igt} + (1-\sigma)\varepsilon_{ijt}, \end{aligned} \tag{5}$$

where g refers to groups (nests). We allow for two groups: all new medium-sized wide-body aircraft, and the outside good, which is defined to be all new non-medium-sized wide-body aircraft and all used medium-sized wide-body aircraft. The error terms ζ_{igt} and ε_{ijt} are random tastes at the group and submodel levels respectively, where ε_{ijt} is i.i.d. extreme value and ζ_{igt} has the (unique) distribution such that $\zeta_{igt} + (1-\sigma)\varepsilon_{ijt}$ is extreme value. The nesting parameter $0 \le \sigma \le 1$ captures the consumers' preference correlation across submodels.

We treat each year as a market. Consumer i chooses product $j \in \{0, 1, \cdots, J\}$ in market t if $v_{ijt} > v_{ikt}$ for all $k \neq j$, $k \in \{0, 1, \cdots, J\}$, where 0 denotes the outside product with δ_{0t} being normalized to zero. Integrating over the probability of choosing product j for all consumers yields the well-known formula for market share:

$$ln(s_{jt}/s_{0t}) = X_{jt}\beta - \alpha p_{jt} + \sigma ln(s_{j|g,t}) + \xi_{jt}, \tag{6}$$

where for a given market t, s_{jt}, and $s_{j|g,t}$ are respectively market shares of product j in the entire wide-body aircraft market and the new medium-sized wide-body aircraft market.

$$s_{jt} = \frac{q_{jt}}{M_t},\ s_{0t} = \frac{M_t - \sum_{j=1}^{J} q_{jt}}{M_t},\ s_{j|g,t} = \frac{q_{jt}}{\sum_{k=1}^{J} q_{kt}},$$

where M_t is the market size of the wide-body aircraft industry, and J is the number of products in the group of new medium-sized aircraft.

Note that the demand function above rules out the possibility that submodels of the same model, e.g., A330-200 and A330-300, are closer substitutes for consumers than submodels of different models, e.g., A330-200 and B777-200. To address this issue, we also estimate the demand function using a two-level nested logit model (e.g., see Verboven, 1996) that allows for greater substitution between submodels of the same model. The results are similar to that of the one-level model, and the details can be found in the online appendix.

In the demand function (6), the price p_{jt} is likely to be affected by the unobserved characteristic ξ_{jt}. Thus, the within-group share $s_{j|g,t}$ would be correlated with ξ_{jt}, too. We take a standard instrumenting approach to estimate the parameters through two-stage least squares (2SLS). Instruments used include hourly wage in manufacturing and its lagged terms, price of aluminum and its lagged terms, average characteristics of products manufactured by other firms, and number of other products within the same firm.

Manufacturing wage and aluminum price are cost shifters for aircraft, and are assumed to be orthogonal to the unobserved product characteristic ξ_{jt}. The average characteristics of products manufactured by other firms, e.g., the average fuel efficiency, affect price p_{jt} through consumers' preference. These characteristics are exogenously given and uncorrelated with the unobserved characteristic ξ_{jt}. The number of products within the same firm as product j is correlated with p_{jt} because products from a multi-product firm are more likely to have lower costs due to the spillover effects of learning-by-doing. In our model presented in Section 3, we assume that the set of products of each firm is exogenously given, thus the number of products is uncorrelated with ξ_{jt}. There might be a concern that our instruments are weak. We conduct a first stage test following Stock and Yogo (2005) to address this issue.

4.2 Estimation results

We use demand data from 1991 to 2009 with a total of 12 medium-sized aircraft submodels, leading to 115 submodel-year observations. To estimate the demand system, we approximate the market size M_t by the total number of used and new wide-body aircraft in service in year t, as in Benkard (2004). This approximation is consistent with the assumption that all old and new aircraft are re-sold or rented out each year. If a used aircraft did not change ownership in a year, it is viewed as having been bought by the firm that owned it. If a used aircraft retired before year t, it is not counted in M_t. Therefore, market size or the total number transactions each year equal the total number of used and new aircraft in service.

Estimation results are presented Table 3. Our first-stage test result indicates that we reject the null hypothesis: that our instrumental variables are weak based on the criterion that the maximal bias of the two-stage least squares (2SLS) estimator relative to the bias of the ordinary least squares (OLS) is 10%.

Across all specifications the estimates indicate that price has a statistically significant negative effect on market share. Within-group utility correlation is estimated to be about 0.88. This indicates that different aircraft within the new medium-sized group have a higher substitution effect than they do with the outside good. This implies that the change in an individual aircraft's market share comes largely at the expense of other medium-sized aircraft. One direct implication is that aircraft would have high price elasticities. Specifically, the estimated aggregate own-price elasticities of demand range from -17.83 to -6.29 with a mean of -9.91. The high own-price elasticities have been documented in the existing literature on the aircraft market. For example, focusing on all wide-body aircraft, own-price elasticities are estimated to be -7.8 in Irwin and Pavcnik (2004) and -10 to -4 in Benkard (2004). Considering that the competition in the medium-sized wide-body market is more intense than in the wide-body market (Irwin and Pavcnik, 2004), our high elasticities are consistent with the earlier results.

Columns (a) and (c) of Table 3 show that fuel efficiency affects market share significantly. By comparing specification (a) with (c), we can see that the effect of fuel efficiency is smaller if the generation variable is included in the estimation. Further, the results of specification (b) demonstrate that the generation plays an important role in determining the market share. Nevertheless, once fuel efficiency is taken into account, the effect of product generation is no longer significant, as shown in specification (c). Recall that the generation variable represents a comprehensive measure of aircraft quality. The comparison between (b) and (c) implies that fuel efficiency is a major indicator of aircraft quality in determining the market share. Furthermore, the estimation results indicate that, all other factors being equal, consumers prefer planes with more seats and longer range.

The results of our demand estimation provide us with a panel data of the residuals $\hat{\xi}_{jt}$ for all products. We use the series $\hat{\xi}_{jt}$ to estimate $\bar{\xi}_j$ and the two preference rank state variables that determines $\Delta\xi_{jt}$, that will be used in the dynamic game. The details are in Appendix A. The results of $\bar{\xi}_j$, the values of the preference state variables and their transition matrices are presented in the top and middle panels of Table 4.

The transition probabilities of market size M_t are estimated nonparametrically by using cell means and the market size data for the complete history of the wide-body aircraft industry, 1969–2009. This estimation result is presented in the bottom panel of Table 4, where the three grid points are chosen as the mean of the values below 34 percentile, between 34 to 67 percentile, and above 67 percentile, respectively.

5 Cost Estimation

Here we discuss the estimation of the cost function that will be used in the dynamic game. The three subsections cover: the total cost, the unit labor input, and the experience process.

5.1 Total cost

The costs of producing aircraft vary because of variation in labor inputs, as in many other manufacturing industries. We model total variable cost of product j, TVC_j, as a linear function of its total labor cost, which is a product of the wage rate and total labor inputs L_j. As argued in Benkard (2004), the wage rate had been quite flat and fixed at \$20 per hour in the relevant period, so we use this wage rate in calculating total labor costs.

Because labor inputs are not available for the products in our model, we calculate their total variable costs based on the result of the Lockheed L-1011, the only aircraft for which unit labor cost is available. Our approach has two steps. First, we regress the total variable costs of the L-1011 from Lockheed's annual reports on its total labor hours. This yields

$$TVC_{L-1011} = 36.2 + 0.12 L_{L-1011}, \tag{7}$$

where TVC_{L-1011} is in 1994 million dollars and L_{L-1011} is labor input of L-1011 measured in 1,000 man-hours. Then, we follow Benkard (2004) to assume that labor requirements per pound are a constant across aircraft. Consequently, the total labor cost of product j can be derived from its weight ratio to the L-1011, denoted as r_j. The total variable cost for product j is calculated using (7) and the weight ratio r_j as follows.

$$TVC_j = 36.2 + 0.12 r_j L_{L-1011}.$$

The fixed cost of product j is assumed to be the same as that of the L-1011, an estimated \$200 million per year based on Lockheed's annual report. It is worth mentioning that the fixed cost does not affect prices or consumer surplus in a model without exit and entry, and we include it in the dynamic model only for quantification of firms' profits.

5.2 Labor input function

The unit labor input for product j in year t is determined mainly by its current production rate and the accumulated production of j and other similar products up to year t. Following Benkard (2000) and Benkard (2004), we model the log unit labor input requirement function for product j produced in year t as follows,

$$\ln l_{jt} = \ln A + \gamma_1 \ln E_{jt} + \gamma_2 \ln S_{jt} + \epsilon_{jt}, \tag{8}$$

where A is intercept, E_{jt} is experience level, $S_{jt} \equiv \frac{12}{7} \sum_{\tau=t-3}^{\tau=t+3} q_{j\tau}$ is line speed or production rate commonly included in the engineering literature with $q_{j\tau}$ being the quantity of product j at time τ, and ϵ_{jt} represents an unobserved shock to productivity. γ_1 is the learning parameter, and γ_2 captures the impact of line speed S_{jt} on l_{jt} due to economy of scale. $\gamma_2 > 1$ implies decreasing returns to scale while $\gamma_2 < 1$ implies increasing returns to scale. There is no clear guidance on the value of γ_2 since productivity of labor depends on the level of capital in the short run.

The labor input equation (8) and the experience evolution equation (4) fully summarize learning curve of product j that describes the negative relationship between its accumulated production and the unit labor input requirement. To estimate the learning curve parameters γ_1 and δ, we combine (8) with (4) and use the labor input data for each L-1011 produced plus the production date of each jet aircraft in the same period.[4] Note that the productivity shock ϵ_{jt} could be correlated with both E_{jt} and S_{jt} because productivity interacts with choice of line speed S_{jt} and experience accumulation E_{jt}. Moreover, the shock might be serially correlated. To address these issues, we use the GMM-HAC (Heteroskedasticity and Autocorrelation Consistent) estimator proposed in Andrews (1991). The instrumental variables are standard: demand shifters include world GDP, regional GDP (developed countries and developing countries), the price of oil; cost shifters are the world aluminum price and the U.S. manufacturing wage rate. All shifters include both present and lagged variables.

[4]Estimating the within-firm spillover requires production data for different aircraft produced by Lockheed. Since the L-1011 is the only wide-body aircraft that Lockheed had ever produced, we use the DC-10 of McDonnell Douglas as a within-firm product for Lockheed L-1011. We make this assumption because both the L-1011 andDC-10 plants were in the Los Angeles area, so possible workforce shifts and experience sharing between the two products may be similar to those between within-firm products.

5.2.1 Estimation results

The estimation result for the learning curve is presented in Table 5. All of the parameters except for returns to scale are significant. The intercept A measures the unit labor requirement for the first aircraft built. As discussed before, we make this starting level different across models based on their weight ratios to the L-1011. Therefore, the shape of the learning curve is assumed to be the same while its levels are allowed to vary across models. The learning parameter (γ_1) is estimated to be -1.15, implying that there is a 55 percent ($1 - 2^{-1.15}$) labor savings when experience doubles. This seemingly large learning rate is partly offset by a high annual forgetting rate, 43 percent ($1 - \hat{\delta}^{12} = 1 - 0.95^{12}$). That is 43 percent of experience is lost every year, making it difficult to double experience, especially when the experience stock is already high. This high forgetting rate may be due to the relatively low aircraft production rate and the customized configurations for each aircraft built. In manufacturing aircraft, assembling works repeat at a low rate, and tasks are hardly ever identical. In addition, experience measures a firm's level of human capital, not the skills of each individual worker. Frequent turnover due to layoffs and promotions also implies a high forgetting rate. Both the learning rate and the forgetting rate are high, implying that it is beneficial for a firm to produce more and to force its rivals to produce less. Dynamically, there will be fierce competition among firms who try to reach and maintain high output and experience levels, while attempting to force others to be stuck at low output and experience levels.

Submodel spillover is almost complete ($\hat{\theta}_1 = 0.97$). Because of that, and the fact that demand related characteristics are similar among submodels, we do not differentiate submodels in our dynamic game. There is almost no cross-firm spillover ($\hat{\theta}_3 = 0.02$). This is reasonable, because experience is believed to be accumulated mainly through workers' repeated practice. Within-firm spillover is approximately one quarter ($\hat{\theta}_2 = 0.24$), indicating that building four aircraft of different types is as helpful in experience accumulation as assembling one aircraft of the same type. Estimates of both $\hat{\theta}_2$ and $\hat{\theta}_3$ are significantly different from zero, implying that it is important to account for within-firm and across-firm spillovers. The large difference between the two suggests potential benefits from merger and changing ownership structure if the within-firm spillover rate does not vary much other than by ownership.[5]

We estimate labor input for each L-1011 using the estimated parameters in Table 5, then plot them along with the actual labor input shown in Figure 3. The estimates fit the data reasonably well, so we believe it is safe not to model cost shock $\epsilon_{j,t}$ in the dynamic game.

[5] Several circumstances contribute to a large within-firm spillover effect. First, internal shifts in the workforce are much easier than shifts across firms, and a firm may reallocate workers among different departments to improve efficiencies. Second, internal shifts help firms to avoid organizational forgetting by keeping the workforce busy assembling other models when demand for a certain model is temporarily low. Furthermore, managerial ability and labor cost related production techniques usually can only be shared within a firm, due either to firm differences or the need to keep business secrets.

5.3 The experience process

Once the learning curve parameters γ_1, δ, θ_1, θ_2 and θ_3 are estimated, we can calculate the next period experience using equation (4) for any given experience and quantities of all products in a certain period. The experience defined in equation (4) is a continuous variable, so we follow Benkard (2004) and discretize it into seven grid points for each product in order to apply it as a state variable in the dynamic game.

$$\mathcal{E} = \{1, 10, 20, 40, 70, 110, 165\}. \tag{9}$$

We use $E^k, k = 1, 2, \cdots, 7$ to denote experience at the k-th grid (e.g., $E^3 = 20$). With enough grid points, the experience process can be approximated fairly well. We denote the continuous experience level resulting from (4) as

$$E^*_{j,t+1} = \delta E_{jt} + \sum_{k=1}^{J} \theta_{jk} q_{kt}.$$

Then the experience transition process is modeled as

$$E_{j,t+1} = \begin{cases} E^u_{jt}, & \text{with probability } \frac{E^*_{j,t+1} - E^d_{jt}}{E^u_{jt} - E^d_{jt}}, \\ E^d_{jt}, & \text{with probability } 1 - \frac{E^*_{j,t+1} - E^d_{jt}}{E^u_{jt} - E^d_{jt}}, \end{cases} \tag{10}$$

where E^u_{jt} is the smallest grid in $\mathcal{E}$ larger than $E^*_{j,t+1}$, and E^d_{jt} is the largest grid smaller than $E^*_{j,t+1}$.

6 Effects of the Merger

To evaluate the impacts of the 1997 Boeing-McDonnell Douglas merger, we first solve the equilibrium strategies of the dynamic game in Section 3 using the parameters of demand and cost functions. Then we simulate the counterfactual prices, quantities, and experience stocks. Finally, we use the results of simulation to analyze the merger's effects on firm behaviors, market structure, and consumer welfare.

6.1 Merger simulation

6.1.1 Strategies

We solve the dynamic game presented in Section 3 under three different industry scenarios: (i) Boeing merged with McDonnell Douglas and shut down MD-11 production shortly after the merger ("merger, discontinue MD-11"). (ii) Boeing kept MD-11 after the merger ("merger, keep MD-11"). (iii) There is no merger ("no merger"). The first scenario is what actually occurred; the other two are hypothetical. By comparing the first and third scenarios, we can quantify the impacts of the merger. Similarly, comparing scenarios (i) and (ii) allows us to analyze the effects of shutting down MD-11 production.

We include four aircraft products, A330, A340, B777, and MD-11 in the dynamic game. To solve the equilibrium strategies, we use the demand parameters from column (a) of Table 3 and the costs estimated using the learning curve parameters in Table 5. After solving for equilibrium, we simulate the paths of expected values of prices, quantities, experience stocks, and consumer surplus starting from the state of the market in the year before the merger. The discount factor for all firms is set to be $\rho = 0.925$ as in Benkard (2004).

In the merger simulation, we allow for a possible one-time cost synergy as an experience stock transfer between MD-11 and B777 with a transfer rate $0 \leq \tau \leq 1$. Such a transfer may be due to facilities rationalization, synergies in R&D and business system, lower parts and materials purchasing price. For example, by consolidating facilities to improve management, Boeing would enjoy lower costs: "the merged Boeing Company believes the potential cost reductions could reach as much as $1 billion a year" (Ricks and Pasztor, 1996). Formally, one-time experience transfer is modeled as follows.

$$\begin{aligned} E_B^{Post} &= E_B^{Pre} + \tau E_M^{Pre}, \\ E_M^{Post} &= E_M^{Pre} + \tau E_B^{Pre}, \end{aligned} \tag{11}$$

where the subscripts B and M respectively represent B777 and MD-11, and the superscripts "Pre" and "Post" indicate pre-merger and post-merger, respectively. When $\tau = 0$, no experience stock is transferred; when $\tau = 1$, all experience stock is transferred. For ease of exposition, let "no transfer" and "complete transfer" denote $\tau = 0$ and $\tau = 1$, respectively. In the scenario "merger, keep MD-11", the equation above assumes that experience stocks are symmetrically transferred between MD-11 and B777. The assumption of symmetric transfer is for simplicity; asymmetric transfer can easily be incorporated into the model. We consider all $\tau \in \{0, 0.01, 0.02, ..., 1\}$ to evaluate the effect of the transfer rate.

6.1.2 Counterfactual prices, quantities and experience

We simulate prices, quantities, and experience for a period of 50 years. All paths in different scenarios, except the prices of MD-11, converge within 25 years.[6] We plot them in Figures 4, 5 and 6, respectively. We also illustrate the actual paths of prices and quantities in Figures 4 and 5, respectively, to measure the fit of our dynamic model.

Figure 4 presents the prices for A330, A340, B777, and MD-11 under five cases of the three scenarios: "no transfer" and "complete transfer" for both "merger, discontinue MD-11" and "merger, keep MD-11", and "no merger." The figure illustrates that in the first four years after the merger, the prices for the cases of "complete transfer" are substantially lower than those of "no transfer", and then they converge. We observe that in this period, the simulated prices with a merger drop faster than in the case of "no merger". If experience is transferred completely, then prices drop by 43.0% and 43.1%, respectively, in the scenarios of "merger, discontinue MD-11" and "merger, keep MD-11";

[6] The quantity of MD-11 drops to zero in four years, thus there is no price after the year 2000.

the drop is 39.6% in the scenario of "no merger". Even without any one-time experience transfer, the corresponding drops are 40.5% and 40.6%, about 1% larger than without a merger. Thus, prices are even lower with the merger. These simulated results are consistent with our finding from the non-structural analysis in Section 2.3 that prices of medium-sized aircraft drop significantly after the merger.

It is worth noting that the counterfactual prices are almost always lower than the actual data. One possible explanation is that the efficiencies of learning-by-doing estimated from Lockheed L-1011 are larger than those for the medium-sized aircraft in our analysis, and consequently we overestimate the cost reduction. The discrepancy between the counterfactual and raw prices might affect our merger evaluation. Nevertheless, our welfare analysis that follows is based on the difference between scenarios "merger, discontinue MD-11" and "no merger", and this may alleviate the possible effect of the discrepancy.

Figure 5 reports the counterfactual quantities. The quantities roughly track the trend of the data for A330, B777 and MD-11, especially in the first four years after the merger. We are not able to predict the phasing out of A340 in the long run. This is mainly because during our data period (1991-2009) the production rate of A340 was still sufficiently high. Nevertheless, the counterfactual path of A340 captures the dramatically declined quantity in the data for the first several years after the merger. As we will discuss later, the dynamic efficiencies of the merger come primarily from the intermediate behavior of firms. Thus, it is less likely that our failing to replicate the long-run behavior of A340 qualitatively changes our results.

Our simulation predicts that MD-11 would be phased out in several years after the merger, as illustrated in Figure 5. The quantity paths of MD-11 for the merger scenarios are lower than in the no-merger scenario before they all go to zero. This implies that MD-11 would be phased out faster if the merger occurs. This is consistent with the data, where MD-11 production was shut down shortly after the merger. Intuitively, there is a tradeoff from shutting down the MD-11. On the one hand, MD-11 receives experience spillover and may be more profitable after the merger. On the other hand, Boeing needs to internalize business stealing from its more promising B777 because of production of the MD-11. Our simulation indicates that concerns about the internal business stealing dominated and Boeing found it more profitable to concentrate on production of B777.

Figure 6 illustrates the simulated path of experience, which is simply quantities accumulated through learning, forgetting, and spillover. We observe that in all scenarios experience converges to the same steady state in the long run. In the short run, if there is a complete one-time experience transfer, then B777 would enjoy an accelerated accumulation of experience in the several years after the merger. The cost advantage of the B777 gained from that accumulated experience would be large enough to lower the quantities and experience levels of Airbus' products for several years. Nevertheless, Boeing's cost advantage would not be large enough to discourage Airbus from catching up.

6.2 Welfare analysis

In this section, we first present a static merger analysis without considering the possible cost reduction of the merger. We then analyze the welfare effect of the merger using the results of dynamic merger simulation.

6.2.1 Static welfare analysis

We use the estimates of the demand system to evaluate the welfare effects of the merger. Our static merger simulation is based on the pre-merger market structure in 1996. Following the standard methodology of static merger analysis, e.g., Nevo (2000) and Miller and Weinberg (2017), we first estimate the marginal costs for all of the products from their prices and market shares. Under the assumption of unchanged marginal costs, we further simulate the post-merger prices and quantities.[7] The consumer surplus is computed as (see Small and Rosen, 1981 or Trajtenberg, 1989):

$$CS = \frac{M \cdot \ln(1 + (\sum_j e^{\frac{X_j\beta - \alpha p_j + \xi_j}{1-\sigma}})^{1-\sigma})}{\alpha}, \tag{12}$$

where the parameters β, α, σ and the unobserved characteristics ξ_j are estimated from the demand system. The post-merger equilibrium prices p_j are simulated.

Our simulation results, based on the demand estimates of column (a) in Table 3, are presented in Table 6. To compare the static analysis with the dynamic results in the next section, we present profit and welfare as total discounted expected values for 50 years. We find that if MD-11 production is kept after the merger, then the impact of the merger relative to "no merger" is small: the expected consumer surplus decreases from \$41.15 billion to \$40.23 billion, a 2.2% or \$0.92 billion loss. This is consistent with the finding in our demand estimation that price elasticities are high, so the effects of market power are small. However, if the MD-11 is discontinued in the post-merger market, then the expected consumer surplus drops from \$41.15 billion to \$34.88 billion, a 15.24% or \$6.27 billion loss. Discontinuing MD-11 in the post-merger market substantially affects consumer surplus. The effect can be decomposed into the variety effect and the price effect (e.g., see Hausman and Leonard (2002)). The variety effect is the decrease in welfare caused by shutting down MD-11, which leads to fewer options in the choice set for consumers. The effect is estimated by leaving the prices unchanged before and after the merger but dropping MD-11 in the post-merger market. The result is a 6.67% drop in consumer surplus. The price effect comes from price changes due to the increased market power of Airbus and Boeing in the post-merger market, although the number of products remains the same. Our simulation results indicate that both Airbus and Boeing charge higher prices for the remaining products relative to the case of keeping MD-11; the price effect leads to an 8.57% drop in consumer surplus.

[7] We also simulate a static model using the marginal costs estimated from the learning curve in the year of merger. The results of the merger analysis are similar to what we present in this subsection, so we do not include them in the paper. The details of the analysis are available upon request from the authors.

If the merger brings efficiencies and reduces costs, then the loss of consumer surplus should be smaller, or consumers may even be better off. We simulate the percentage of cost reduction that would keep consumer surplus unaffected by the merger and present those results in the last two columns of Table 6. If MD-11 is discontinued, then the required cost reduction for B777 is 15.80%, which is substantial. However, only 2.35% and 3.18% cost reductions are needed for MD-11 and B777, respectively, if MD-11 is kept after the merger. In the dynamic merger analysis below, we investigate whether learning-by-doing helped Boeing and Airbus obtain the cost reduction required to offset the market power of the merger.

6.2.2 Dynamic welfare analysis

We simulate consumer welfare and firms' profits in the dynamic game and present the discounted values over 50 years in Table 7.[8]

Our main finding is that the merger generated sufficiently large efficiencies to outweigh the market power effect; consequently, the merger increased consumer surplus. By comparing the scenario "merger, discontinue MD-11" with "no merger", we find that consumer surplus increases by $0.11 billion after the merger for "no transfer". For "complete transfer", that increase would be $5.14 billion. In the left plot of Figure 7 we further illustrate that the change in consumer surplus strictly increases in the experience transfer rate τ. These results indicate that even though there is no one-time experience transfer, the efficiencies from the accelerated learning-by-doing after the merger were still large enough to offset the effects of increased market power. By contrast, a standard static merger analysis, by comparing "no merger" and "merger, keep MD-11" as in Table 6 shows that the merger is detrimental to consumers by decreasing consumer surplus by $0.92 billion. One policy implication of these results is that merger efficiencies from accelerated learning-by-doing can be quantified in a dynamic model and the estimated efficiencies could be substantial.[9]

There are several important features regarding the dynamic efficiencies generated from the merger. First, whether MD-11 was shut down or not does not change our main results. Comparing "merger, keep MD-11" with "no merger" in Table 7, we find that consumer surplus increases by $0.61 billion and $5.29 billion, respectively, for "no transfer" and "complete transfer" after the merger. These results are qualitatively similar to our main finding. The effects of merger are larger than the scenario where MD-11 was shut

[8]The simulated profit of MD-11 is negative. This is because the production is effectively zeros while the fixed cost per product is estimated to be 200 million dollars per year as discussed at the end of Section 5.1. Fixed cost does not affect our estimation of prices and consumer surplus.

[9]The classic static model, as in Nevo (2000), provides us with similar results to our dynamic model if we apply the cost reductions estimated from the dynamic model to the static merger analysis. We present the consumer surplus in the last row of Table 7. In the scenarios of "merger, discontinue MD-11", consumer surplus increases by $3.39 and $14.62 billion relative to "no merger", respectively, when there is no and complete experience transfer. The merger effect is larger than that of our dynamic model, but qualitatively similar. This implies that learning-by-doing generates larger cost reductions than are required to offset the market power effect.

down. This is because consumer benefits of having an additional variety of products. Not surprisingly, keeping MD-11 would lower profits for both Boeing and Airbus versus shutting it down because Airbus would face more competition and Boeing would be forced to keep an unprofitable product.

Second, the merger brings dynamic efficiencies mainly because the products of both Airbus and Boeing were at their beginning stage and there was a lot of room for learning. If B777 had a high level of experience before the merger, then the dynamic efficiencies might not be large enough to offset the market power. To illustrate this point, we consider a hypothetical case where both B777 and MD-11 receive complete experience transfer in the scenario of "no merger" even Boeing and McDonnell Douglas compete. In both scenarios, the experience level is high and there is little room for learning. We present the results in the last column of Table 7. Comparing the last column and (i.b), we can see that the merger leads to a \$7.37 loss in consumer surplus. This implies that learning-by-doing would not generate large enough efficiencies to offset the detrimental effect from consolidation of the market if the experience of B777 and MD-11 were sufficiently high before the merger.

Finally, the welfare effect of the merger is intermediate. We plot the evolution of expected consumer welfare beginning in 1997 for each scenario in panel (b) of Figure 7. The figure illustrates that the merger has only intermediate influence on consumer welfare, and that consumer surpluses are the same in the long run for all scenarios because of the convergence of market equilibrium. Two points are worth mentioning regarding the absence of long-run effects. First, this does not render the dynamic analysis futile. Actually, finding that the dynamic efficiencies are realized mainly in the several years after the merger makes the efficiencies more relevant in antitrust practice.[10] Second, the long-run effect here is specific to the Boeing-McDonnell Douglas merger, and is particularly due to the inferiority of MD-11. In general, the long-run effect could emerge for a different merger in a dynamic analysis.

7 Robustness and Limitations

7.1 Robustness checks

We conduct two robustness checks to address concerns that our results may be sensitive to: (1) the assumption that the unobserved characteristic ξ_{jt} does not transit across time; and (2) possible improvement of product quality after the merger. We confirm that our findings are robust to these potential concerns.

Table 8 presents the results of merger analysis when the unobserved characteristic $\xi_{jt} = \bar{\xi}_j + \Delta\xi_{jt}$, where $\Delta\xi_{jt}$ is approximated by a weighted average of two preference state variables (please see appendix A for details). Comparing Tables 7 and 8 suggests that the two methods of modeling ξ_{jt} have no significant impact on the results. In particular, if

[10] The 2010 Horizontal Merger Guidelines state that "The Agencies normally give the most weight to the results of this analysis over the short term... Delayed benefits from efficiencies... will be given less weight because they are less proximate and more difficult to predict."

experience is completely transferred, then consumer surplus increases by \$5.14 and \$5.15 billion in the baseline model and the preference rank case, respectively. There is a small discrepancy in consumer surplus when there is no experience transfer: it increases by \$0.11 billion in the baseline model but decreases by \$0.31 billion with preference rank. Nevertheless, the left plot in Figure 7 illustrates that the break-even transfer rate is $\tau = 3\%$ if we use preference rank state variable, i.e., whenever $\tau > 3\%$ the dynamic efficiencies of the merger offset the market power effect. Our estimate of the learning curve in Table 5 indicates that Boeing is likely to obtain a transfer larger than 3% after the merger: the within-firm spillover (after-merger) is 22% larger than the cross-firm spillover (pre-merger). In summary, the alternative modeling of ξ_{jt} does not alter our main finding: that the accelerated learning-by-doing after the merger brings sufficiently large efficiencies to offset the market power effect.

Improvements in product quality (generation) may be another possible source of dynamic merger efficiencies. Nevertheless, the effect of quality improvement is ambiguous ex ante. Such dynamic efficiencies exist only if the pre-merger investment is inefficient, i.e., either too low or too high. It could be too low because firms may not realize the returns to investment, or too high because of strong business-stealing incentives.[11] As a robustness check, we assess how these forces net out in terms of firm behavior and consumer welfare. We include quality improvement as a state variable in the dynamic game and present the details in the online appendix. We summarize our simulation results in Table 9. Comparing Tables 7 and 9 suggests that including quality improvement as a state variable has no significant impact on the results. In the case of complete experience transfer, consumer surplus increases by \$5.14 and \$4.74 billion respectively in the baseline model versus the model with quality improvement. If there is no experience transfer, then consumer surplus decreases by \$0.76 billion when we include the quality improvement, while the baseline model predicts a \$0.11 billion increase in consumer surplus. As illustrated in the left plot in Figure 7, the break-even transfer rate is $\tau = 7\%$ when we include quality improvement. As discussed above, it is likely for Boeing to obtain a transfer exceeding 7% after the merger. To summarize, including quality improvement as a state variable does not change our main finding.

7.2 Caveats and Limitations

As we discussed in Section 6.1.2, our simulated paths do not track changes in the industry over time very well. As is typical in structural econometric models, perfect fit is difficult to achieve because the industry is too complicated for a tractable model to mimic it perfectly. In our case, one of the main restrictions affecting the model's fit is that the demand and cost parameters are estimated before we solve the dynamic game. We observe from Figures 4 and 5 that the discrepancies between fitted and actual values have a similar pattern in scenarios with or without the merger. This may alleviate the concern that imperfect fit affects our merger analysis, because the merger effects rely on the difference between the scenarios with merger and no merger. Another obvious caveat

[11] We thank an anonymous referee for this suggestion.

is that the learning curve is estimated using the cost information for the Lockheed L-1011, the only aircraft for whom cost data are available. There could be a non-negligible difference between the learning curve of the L-1011 and that of the four products in our dynamic model, and the model's performance would be affected by that difference.

Our dynamic merger analysis focuses on medium-sized aircraft while Boeing and McDonnell Douglas in fact have overlapped market shares other than these aircraft. For example, the MD-90 from McDonnell Douglas and the Boeing 737 were competing in the narrow-body market at the time of merger. Ideally, if the necessary data are available, the effects of the narrow-body aircraft should be taken into account in evaluating the merger. Nevertheless, ignoring narrow-body aircraft may not affect our results significantly. First of all, the medium-size wide-body market is relatively independent, as we argued using the empirical evidence in Section 2. Second, learning-by-doing also might exist between the MD-90 and the Boeing 737NG because the latter is in the early stage of production while the former is approaching the end of its production life. In fact, no the MD-90 orders were received after Boeing and McDonnell Douglas merged in 1997 because of internal competition with the Boeing 737 (Becher, 2002). This might lead to additional benefits of the merger. Finally, at the time of the merger, the market for narrow-body aircraft was dominated by Boeing (the quantity share for Airbus, Boeing and McDonnell Douglas were 23.2%, 58.4% and 18.4%, respectively) and the market was small relative to that of wide-body aircraft: the quantity of narrow-body aircraft was 38.8%, 24.4% and 33.8% of the total quantity of narrow- and wide-body aircraft for Airbus, Boeing and McDonnell Douglas, respectively.

8 Conclusions

In this paper we show that there are dynamic efficiencies from the 1997 Boeing-McDonnell Douglas merger in the medium-sized aircraft industry, and we quantify the welfare effects of those efficiencies. To do so, we set up a dynamic oligopoly model that allows for multi-product firms and the dynamic evolution of marginal costs through learning-by-doing. The parameters in the demand and cost functions are first estimated in static models. Then we use these estimates to simulate the dynamic merger effects using the dynamic model.

We find that the merger increases consumer surplus whether or not one-time experience transfer due to the merger exists. By contrast, a static model ignoring efficiencies of learning-by-doing predicts a consumer loss. Accelerated learning-by-doing is the major source of merger efficiencies, and it is large enough to offset the detrimental effect of the increased market power after the merger. The impacts of the merger on consumer welfare and market structure are intermediate; the merger only accelerates experience accumulation towards the steady state, and there is no merger effect in the long run. An important implication of our results is that dynamic efficiencies can be quantified and they play an important role in evaluating the 1997 Boeing-McDonnell Douglas merger.

References

Andrews, D. W. K., "Heteroskedasticity and Autocorrelation Consistent Covariance Matrix Estimation," *Econometrica* 59(3) (1991), 817–858. 5.2

Ashenfelter, O. C., D. S. Hosken and M. C. Weinberg, "Efficiencies brewed: pricing and consolidation in the US beer industry," *The RAND Journal of Economics* 46 (2015), 328–361. 1

Becher, T., *Douglas Twinjets: DC-9, MD-80, MD-90 and 717* (UK: Crowood Press, 2002). 7.2

Benkard, C., "Learning and Forgetting: The Dynamics of Aircraft Production," *American Economic Review* 90(4) (2000), 1034–1054. 1, 2.2, 2.3, 5.2

———, "A Dynamic Analysis of the Market for Wide-Bodied Commercial Aircraft," *Review of Economic Studies* 71 (2004), 581–611. 1, 3.1, 3.1, 3.2.1, 4.1, 4.2, 5.1, 5.1, 5.2, 5.3, 6.1.1

Benkard, C., A. Bodoh-Creed and J. Lazarev, "Simulating the dynamic effects of horizontal mergers: US airlines," Technical Report, Citeseer, 2010. 1

Chandra, A. and D. Staiger, "Productivity spillovers in healthcare: evidence from the treatment of heart attacks," *Journal of Political Economy* 115 (2007), 103. 1

Chen, J., "The Effects of Mergers with Dynamic Capacity Accumulation," *International Journal of Industrial Organization* 27(1) (2009), 92–109. 1

Ericson, R. and A. Pakes, "Markov-Perfect Industry Dynamics: A Framework for Empirical Work," *Review of Economic Studies* 62(1) (1995), 53–82. 1

Gowrisankaran, G., "A dynamic model of endogenous horizontal mergers," *RAND Journal of Economics* 30(1) (1999), 56–83. 1

Hausman, J. A. and G. K. Leonard, "The competitive effects of a new product introduction: A case study," *The Journal of Industrial Economics* 50 (2002), 237–263. 6.2.1

Irwin, A. D. and P. J. Klenow, "Learning-by-Doing Spillovers in the Semiconductor Industry," *Journal of Political Economy* 102(6) (1994), 1200–1227. 1

Irwin, D. A. and N. Pavcnik, "Airbus versus Boeing revisited: international competition in the aircraft market," *Journal of International Economics* 64 (2004), 223–245. 4.2

Jeziorski, P., "Estimation of cost efficiencies from mergers: application to US radio," *The RAND Journal of Economics* 45 (2014), 816–846. 1

Miller, N. and M. Weinberg, "Understanding the Price Effects of the Miller/Coors Joint Venture," *Econometrica* (2017), forthcoming. 6.2.1

Neven, D., P. Seabright and G. M. Grossman, "European industrial policy: The Airbus case," *Economic policy* (1995), 313–358. 3.2.2

Nevo, A., "Mergers with differentiated products: The case of the ready-to-eat cereal industry," *RAND Journal of Economics* (2000), 395–421. 1, 6.2.1, 9

Nocke, V. and M. D. Whinston, "Dynamic Merger Review," *Journal of Political Economy* 118 (2010), 1200–1251. 1

Ohashi, H., "Learning by doing, export subsidies, and industry growth: Japanese steel in the 1950s and 1960s," *Journal of International Economics* 66 (2005), 297–323. 1

Ricks, T. and A. Pasztor, "Deal would test Pentagon policies about competition," *Wall Street Journal* December 17 (1996), A3–A4. 6.1.1

Schwoon, M., "Learning by doing, learning spillovers and the diffusion of fuel cell vehicles," *Simulation Modelling Practice and Theory* 16 (2008), 1463–1476. 1

Small, K. A. and H. S. Rosen, "Applied Welfare Economics with Discrete Choice Models," *Econometrica* 49(1) (1981), 105–130. 6.2.1

Stahl, J., "A dynamic analysis of consolidation in the broadcast television industry," *Finance and Economics Discussion Series* (2009). 1

Stock, J. H. and M. Yogo, "Testing for weak instruments in linear IV regression," in D. W. K. Andrews and J. H. Stock, eds., *Inference for Econometric Models: Essays in Honor of Thomas Rothenberg* (UK: Cambridge University Press, 2005), 80–108. 4.1

Thornton, R. and P. Thompson, "Learning from experience and learning from others: An exploration of learning and spillovers in wartime shipbuilding," *American Economic Review* 91 (2001), 1350–1368. 1

Trajtenberg, M., "The Welfare Analysis of Product Innovations, with an Application to Computed Tomography Scanners," *Journal of Political Economy* 97(2) (1989), 444–479. 6.2.1

Verboven, F., "International price discrimination in the European car market," *RAND Journal of Economics* (1996), 240–268. 4.1

Appendix

A Preference Rank State Variables

In this section, we provide details on approximating $\Delta\xi_{jt}$ by a weighted average of two preference state variables, as described in Section 3.2.1.

We assume that the transition of unobserved characteristic ξ_{jt} is driven mainly by the variation in consumers' preference over more fuel efficient twin-engine types and firm brands. Thus, we decompose ξ_{jt} as,

$$\begin{aligned} \xi_{jt} &= \bar{\xi}_j + \Delta\xi_{jt}, \\ \Delta\xi_{jt} &= w_j^T \cdot \kappa_{jt}^T + w_j^F \cdot \kappa_{jt}^F, \end{aligned} \tag{A.1}$$

where the time invariant term $\bar{\xi}_j$ is the mean value of time series ξ_{jt}, w_j^F and w_j^T are constant coefficients. κ_{jt}^T and κ_{jt}^F are both binary state variables; they capture respectively whether twin-engine and Boeing's products are preferred or not at time t.[12] κ_{jt}^T and κ_{jt}^F are the same for all products with the same relevant characteristics. For example, all twin-engine products share the same value for κ_{jt}^T.

We define κ_t^T, $T \in \{T_0, T_1\}$ and κ_t^F, $F \in \{F_0, F_1\}$ to be the *preference rank* state variables in the dynamic game and evolve stochastically over time. If a twin-engine aircraft is preferred at time t, $\kappa_t^T = \kappa^{T_0}$, where κ^{T_0} is a two-dimensional vector with its first element being the value for all twin-engine aircraft and its second for all non-twin-engine aircraft. Similarly, $\kappa_t^T = \kappa^{T_1}$ if twin-engine is not preferred at time t. Analogously, let κ^{F_0} and κ^{F_1} be the vector of values κ_t^F takes when Boeing's products are preferred or not, respectively.

Next we discuss how we estimate the vectors κ^{T_0}, κ^{T_1}, κ^{F_0}, κ^{F_1}, and the two weights w_j^F and w_j^T using the series $\Delta\xi_{jt} = \xi_{jt} - \bar{\xi}_j$. Among the four products in our analysis, A330 and A340 are from the same firm, but only A330 has twin-engines. Based on (A.1), the differences in the series $\Delta\xi_{A330,t}$ and $\Delta\xi_{A340,t}$ come from engine-difference only. Thus $\{\kappa^{T_0}, \kappa^{T_1}\}$ and the transition of κ_t^T are computed as follows.

- For any time period t, if $\Delta\xi_{A330,t} \geq \Delta\xi_{A340,t}$, $\kappa_t^T = \kappa^{T1}$. Otherwise, $\kappa_t^T = \kappa^{T0}$.
- The first and second elements of the vector κ^{T_1} are calculated as the conditional mean $\Delta\xi$ for all products with twin-engine and non-twin-engine, respectively, conditional on $\Delta\xi_{A330,t} \geq \Delta\xi_{A340,t}$. κ^{T0} is calculated similarly.
- Using the time series of κ_t^T above, we estimate its (two-by-two) transition matrix as a Markov chain.

[12] McDonnell Douglas only has a few observations for the MD-11, so we cannot estimate separate preference for it. Instead, we grouped MD and Airbus and let the preference be for Boeing or otherwise. The merger's effect on ownership is then switching MD-11 from taking non-Boeing values to Boeing values.

Analogously, we can compute the vectors κ^{F_0} and κ^{F_1}, and the transition matrix κ^F by using the time series of $\Delta\xi_{A330,t}$ and $\Delta\xi_{B777,t}$, the two products with a twin-engine but different brands. The parameters w_j^T and w_j^F are chosen to minimize the distance between observed series $\Delta\xi_{jt}$ and the computed series $w_j^T \cdot \kappa_t^T + w_j^F \cdot \kappa_t^F$. The estimates of values for κ^{T_0}, κ^{T_1}, κ^{F_0}, and κ^{F_1}, and the transition matrices of κ_t^T and κ_t^F are in Table 4.

B Computation of Expected Value Function

Let us denote the transition of state variables $\Pr\left(E', M', \kappa^{T\prime}, \kappa^{F\prime} | E, M, \kappa^T, \kappa^F, \boldsymbol{Q}\right)$. Considering the independence of transition probabilities for the state variables, we define the transition probability defined above as:

$$\Pr\left(E', M', \kappa^{T\prime}, \kappa^{F\prime} | E, M, \kappa^T, \kappa^F, \boldsymbol{Q}\right) = \Pr\left(E' | E, \boldsymbol{Q}\right) \cdot \Pr\left(M' | M\right) \cdot \Pr\left(\kappa^{T\prime} | \kappa^T\right) \cdot \Pr\left(\kappa^{F\prime} | \kappa^F\right),$$

where only the transition of experience depends on the vector of quantity Q. Given this transition probability, the expected value function is

$$\begin{aligned}
& EV_j(E, M, \kappa^T, \kappa^F, \boldsymbol{Q}) \\
= & \sum_{\kappa^{F\prime}} \sum_{\kappa^{T\prime}} \sum_{M'} \sum_{E'} V_j\left(E', M', \kappa^{T\prime}, \kappa^{F\prime}\right) \Pr\left(E', M', \kappa^{T\prime}, \kappa^{F\prime} | E, M, \kappa^T, \kappa^F, \boldsymbol{Q}\right) \\
= & \sum_{\kappa^{F\prime}} \sum_{\kappa^{T\prime}} \left\{ \sum_{M'} \left[\sum_{E'} V_j\left(E', M', \kappa^{T\prime}, \kappa^{F\prime}\right) \Pr\left(E' | E, \boldsymbol{Q}\right) \right] \Pr\left(M' | M\right) \right\} \Pr\left(\kappa^{T\prime} | \kappa^T\right) \Pr\left(\kappa^{F\prime} | \kappa^F\right) \\
= & \sum_{\kappa^{F\prime}} \sum_{\kappa^{T\prime}} \left\{ \sum_{M'} EV_j(E, M', \kappa^{T\prime}, \kappa^{F\prime}) \Pr\left(M' | M\right) \right\} \Pr\left(\kappa^{T\prime} | \kappa^T\right) \Pr\left(\kappa^{F\prime} | \kappa^F\right) \\
= & \sum_{\kappa^{F\prime}} \sum_{\kappa^{T\prime}} EV_j(E, M, \kappa^{F\prime}, \kappa^{T\prime}) \Pr\left(\kappa^{T\prime} | \kappa^T\right) \Pr\left(\kappa^{F\prime} | \kappa^F\right). \qquad \text{(B.1)}
\end{aligned}$$

The expected value function is computed sequentially above. We exemplify the first step as follows: Based on the transition process of experience in equation (10), we define the transition probabilities of experience as follows

$$\eta_j\left(h_j; q\right) \equiv \left(\frac{E_{j,t+1}^*(q) - E_{j,d}(q)}{E_{j,u}(q) - E_{j,d}(q)}\right)^{h_j} \left(1 - \frac{E_{j,t+1}^*(q_j) - E_{j,d}(q)}{E_{j,u}(q) - E_{j,d}(q)}\right)^{1-h_j},$$

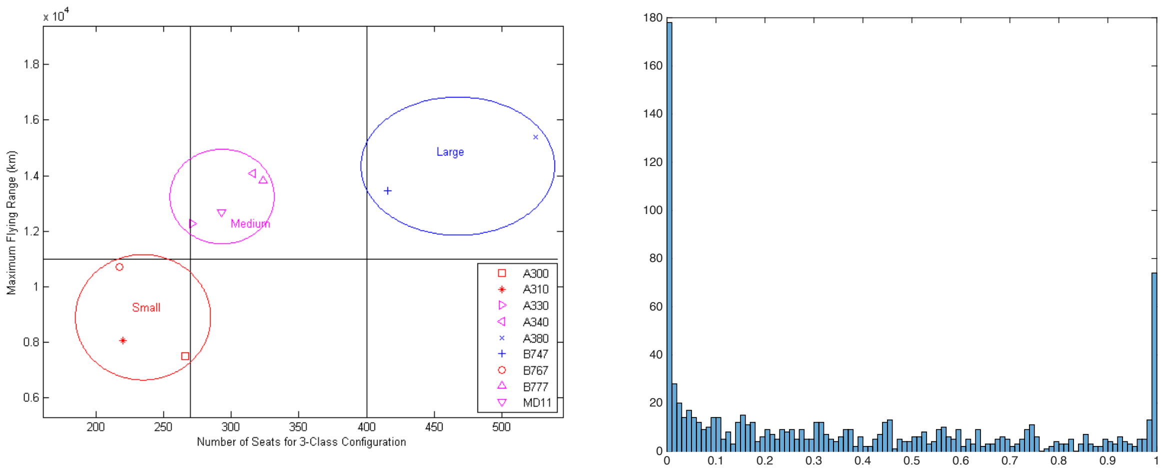
where $h_j \in \{0,1\}, j = 1, 2, \cdots, J$. Then the expected value function is (for ease of notation, we drop the state variables $M', \kappa^{T\prime}, \kappa^{F\prime}$)

$$\begin{aligned}
& EV_j(E) \equiv \sum_{E'} V_j(E') \Pr\left(E' | E, \boldsymbol{Q}\right) \\
= & \eta_j(1; q_j) V_j\left(E_u, E[E'_{-j}(\boldsymbol{Q})]\right) + \eta_j(0; q_j) V_j\left(E_d, E[E'_{-j}(Q)]\right) \\
= & \sum_{h_1 \in \{0,1\}} \ldots \sum_{h_k \in \{0,1\}} \ldots \sum_{h_J \in \{0,1\}} \left(\prod_k \eta_k(h_k, q_k)\right) V_j\left(E_{1,h_1}, \ldots E_{k,h_k}, \ldots E_{J,h_J}\right), \qquad \text{(B.2)}
\end{aligned}$$

where the vector of quantities $\boldsymbol{Q} = (q_1, \cdots, q_J)$ and the experience state transition $\Pr(E'|E, \boldsymbol{Q})$ is simply

$$\Pr(E'|E, \boldsymbol{Q}) = \sum_{h_1 \in \{0,1\}} ... \sum_{h_k \in \{0,1\}} ... \sum_{h_J \in \{0,1\}} \left(\prod_{k=1}^{J} \eta_k (h_k, q_k) \right).$$

Figure 1: Illustration of Aircraft Market



(a) Seats and range of wide-body aircraft (1991-2009) (b) Frequency distribution of medium-wide-ratio R_w

Note: In subfigure (a), the horizontal line (between 1 and 1.2) marks the nautical distance between Beijing and New York. The line is used as a benchmark to separate transatlantic and transpacific routes. In subfigure (b), R_w for any route is defined as the number of medium-sized flights over the total number of wide-body flights. The distribution is based on 908 U.S. domestic and international routes for the 1991-2009 period from Department of Transportation (www.transportation.gov).

Table 1: Summary of Aircraft Characteristics

Product		Average price (1994 Million $)	Seats	Range (km)	Number of engines	Fuel efficiency gal./100km/seat	First delivery	Generation
A330	-200	60.84	253	13400	2	3.11	1998	0
	-300	73.13	295	10800	2	2.98	1993	0
A340	-200	89.92	261	12400	4	2.86	1993	0
	-300	77.74	295	13700	4	3.25	1993	0
	-500	70.46	313	16670	4	3.41	2003	0
	-600	73.92	380	14600	4	2.93	2002	0
B777	-200	81.38	305	9700	2	2.73	1995	0
	-200ER	80.81	301	14305	2	2.89	1997	0
	-200LR	78.97	301	17395	2	3.69	2006	1
	-300	92.63	368	11120	2	2.61	1998	0
	-300ER	88.44	365	14685	2	2.70	2004	1
MD-11	—	89.11	293	12670	3	3.44	1990	0

Source: Aircraft prices are from *Avmark*. Aircraft characteristics come from the official websites of Boeing and Airbus, as well as various online sources.

Table 2: Change in Aircraft Prices (in millions of 1994 dollars)

Variable	(a)	(b)	(c)	(d)	(e)	(f)
$\mathbb{I}\{$post-merger$\}$	0.059	0.059	0.15	0.082	0.035	0.25
	(0.56)	(0.57)	(0.57)	(0.70)	(0.70)	(0.71)
$\mathbb{I}\{$medium$\}$	-2.06***	-2.05***	-1.95***			
	(0.53)	(0.55)	(0.56)			
$\mathbb{I}\{$post-merger$\}\times\mathbb{I}\{$medium$\}$	-2.33**	-2.33**	-2.51**			
	(0.97)	(0.97)	(0.98)			
quantity/100	-0.11	0.17	0.53	0.33	0.91	1.30
	(0.48)	(1.09)	(1.11)	(0.49)	(1.12)	(1.13)
accum.q/1000	0.0073	-0.26	-1.36	-0.39	0.19	-1.33
	(0.65)	(1.49)	(1.63)	(0.71)	(1.59)	(1.74)
history	-0.072*	-0.067	-0.040	0.0060	-0.0062	0.029
	(0.041)	(0.047)	(0.050)	(0.042)	(0.050)	(0.052)
ΔGDP	-0.091	-0.090	-0.12	-0.075	-0.088	-0.13
	(0.12)	(0.12)	(0.12)	(0.12)	(0.13)	(0.13)
Δoil	-0.049**	-0.049**	-0.047**	-0.056***	-0.055***	-0.052**
	(0.020)	(0.021)	(0.021)	(0.021)	(0.021)	(0.021)
quantity/100$\times$ quantity/100		-0.12	-0.23		-0.24	-0.37
		(0.42)	(0.43)		(0.44)	(0.44)
accum.q/1000$\times$accum.q/1000		0.13	0.47		-0.18	0.29
		(0.63)	(0.66)		(0.65)	(0.68)
$\mathbb{I}\{$Boeing$\}$			0.67			0.91**
			(0.41)			(0.43)
$\mathbb{I}\{$McDonnell Douglas$\}$			0.75			0.85
			(0.60)			(0.62)
$\mathbb{I}\{$wide$\}$				-0.53	-0.35	-0.37
				(0.46)	(0.49)	(0.50)
$\mathbb{I}\{$post-merger$\}\times$ $\mathbb{I}\{$wide$\}$				-2.24**	-2.20**	-2.49***
				(0.93)	(0.93)	(0.94)
R^2	0.128	0.129	0.135	0.078	0.081	0.091
adj. R^2	0.110	0.106	0.108	0.059	0.057	0.063

Note: The number of observations is 432. The dependent variable is $\Delta p_{j,t} \equiv p_{j,t} - p_{j,t-1}$. All specifications include a linear time trend. Columns (a)-(c) are results for medium-sized wide-body aircraft; columns (d)-(f) are for all the wide-body aircraft. Standard errors in parentheses: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: Estimate of Demand Estimation

Variable	Estimate (a)	(b)	(c)
Constant	-2.92***	-4.15***	-3.22***
	(0.36)	(0.26)	(0.26)
Price/100	2.09***	2.04***	2.11***
	(0.26)	(0.27)	(0.26)
Fuel eff.	-0.31***	—	-0.26**
	(0.10)		(0.11)
Seat/100	0.36***	0.40***	0.35***
	(0.080)	(0.081)	(0.081)
Range/10000	1.01***	0.74***	0.93***
	(0.15)	(0.13)	(0.15)
Engine	-0.14***	-0.15***	-0.13***
	(0.025)	(0.026)	(0.025)
911 (dummy)	-0.66***	-0.65***	-0.66***
	(0.081)	(0.085)	(0.081)
Generation	—	0.23**	0.15
		(0.10)	(0.098)
InGroup corr. (σ)	0.88***	0.86***	0.88***
	(0.035)	(0.037)	(0.034)
Own-price elasticity	[-17.83,-6.29]	[-15.14,-5.39]	[-18.33,-6.46]
The first stage test			
the Cragg-Donald Wald F statistic†	10.83	10.89	11.57

Note: The number of observations is 115. The dependent variable is $\ln(s_{jt}/s_{0t})$. There are two endogenous variables (p_{jt} and $\ln(s_{j|g,t})$) and ten instrumental variables. Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

†The critical value for the weak instrument test based on 2SLS bias (the desired maximal bias of the IV estimator with two endogenous variables and ten instrumental variables relative to the bias of OLS is 10%) at the significance level 5% is 10.58.

Table 4: Transition of Market Size and Preference Rank

Parameter	Estimate
$\bar{\xi}_j$	(-0.010, 0.076, 0.12, -0.057)
κ^{T_1}	(0.092 0.0076)
κ^{T_0}	(-0.10 -0.0085)
κ^{F_1}	(0.034 -0.091)
κ^{F_0}	(-0.038 0.14)
transition matrix of κ_t^T	$\begin{pmatrix} 0.38 & 0.75 \\ 0.63 & 0.25 \end{pmatrix}$
transition matrix of κ_t^F	$\begin{pmatrix} 0.67 & 0.43 \\ 0.33 & 0.57 \end{pmatrix}$
M	(2823, 2966, 3100)
Transition matrix of M	$\begin{pmatrix} 0.85 & 0.21 & 0.00 \\ 0.15 & 0.71 & 0.14 \\ 0.00 & 0.071 & 0.86 \end{pmatrix}$

Note: The results in the top and middle panels are estimated using the residuals of the demand estimation, $\hat{\xi}_{jt}$.

Table 5: Estimate of Learning Curve

Parameter	Explanation	Estimate
$\ln A$	Labor cost intercept	9.31***
		(3.17)
γ_1	Learning parameter	-1.15***
		(0.13)
γ_2	Return to scale	0.31
		(0.56)
δ	Depreciation of experience	0.95***
		(0.0012)
θ_1	In-family spillover	0.97***
		(0.02)
θ_2	In-firm spillover	0.24***
		(0.0001)
θ_3	Across-firm spillover	0.02***
		(0.0001)
$1-2^{\gamma_1}$	Implied Learning Rate†	55%

Note: †The implicit learning rate (defined as $1-2^{\gamma_1}$) measures the percent of labor saving when experience doubles. Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: Merger Effect: the Static Model

Value	Scenario (i) merger discontinue MD-11	Scenario (ii) merger keep MD-11	Scenario (iii) no merger	Difference (ii)-(iii)
CS	34.88	40.23	41.15	-0.92
π_{all}	11.54	9.68	9.18	0.50
TS	46.42	49.91	50.33	-0.42
π_{A330}	4.20	3.08	2.93	0.15
π_{A340}	6.02	4.41	4.20	0.21
π_{B777}	1.51	0.45	0.43	0.02
π_{MD-11}	N/A	1.74	1.62	0.12
ΔC_{B777}	3.18%	15.8%		
ΔC_{MD-11}	N/A	2.35%		

Note: All values except ΔC are total discounted expected values (for 50 years) in billions of 1994 dollars. In scenarios (i) and (ii), the MD-11 production was either shut down shortly or kept, respectively, after the merger. There is no merger in scenario (iii). CS is consumer surplus, TS is total surplus, π is profit. ΔC is the percentage of cost reduction that would keep consumer surplus unaffected by the 1997 merger.

Table 7: Merger Effect: the Dynamic Model

	Scenario (i) merger discontinue MD-11		Scenario (ii) merger keep MD-11		Scenario (iii) no merger	Diff. of (i) and (iii)		Scenario (iii) no merger $\tau = 1$
Value	(a) $\tau = 0$	(b) $\tau = 1$	(a) $\tau = 0$	(b) $\tau = 1$		(i.a)-(iii)	(i.b)-(iii)	
CS	128.32	133.35	128.82	133.50	128.21	0.11	5.14	140.72
π_{all}	58.83	67.48	56.07	64.90	56.19	2.64	11.29	61.71
TS	187.15	200.83	184.90	198.40	184.39	2.75	16.44	202.43
π_{A330}	11.91	9.42	11.76	9.40	11.25	0.67	-1.82	8.46
π_{A340}	16.07	14.49	15.88	14.45	16.16	-0.09	-1.67	12.43
π_{B777}	30.85	43.56	30.76	43.43	31.06	-0.21	12.50	43.09
π_{MD-11}	N/A	N/A	-2.32	-2.38	-2.28	2.28	2.28	-2.28
$CS^{\dagger}$	115.06	126.29	115.00	124.35	111.67	3.39	14.62	—

Note: All values are total discounted expected values in billions of 1994 dollars. In scenarios (i) and (ii), the MD-11 production was either shut down shortly or kept, respectively, after the merger. There is no merger in scenario (iii). In each scenario, $\tau = 0$ and $\tau = 1$ refer to no experience transfer and complete experience transfer after the merger, respectively. "Scenario (iii) no merger $\tau = 1$" is the hypothetical case where the experience between B777 and MD-11 is fully transferred but there is no merger. CS is consumer surplus, TS is total surplus, and π is profit. $CS^{\dagger}$ is consumer surplus calculated using the static merger analysis in 6.2.1, together with the cost saving rates simulated in the dynamic model.

Table 8: Robustness Check: the Dynamic Model with Preference Rank

Value	Scenario (i) merger discontinue MD-11 (a) $\tau = 0$	Scenario (i) merger discontinue MD-11 (b) $\tau = 1$	Scenario (ii) merger keep MD-11 (a) $\tau = 0$	Scenario (ii) merger keep MD-11 (b) $\tau = 1$	Scenario (iii) no merger	Diff. of (i) and (iii) (i.a)-(iii)	Diff. of (i) and (iii) (i.b)-(iii)
CS	127.56	133.02	127.95	133.12	127.87	-0.31	5.15
π_{all}	59.98	68.93	57.26	66.33	57.18	2.80	11.75
TS	187.54	201.95	185.21	199.45	185.05	2.49	16.90
π_{A330}	12.14	9.74	12.01	9.71	11.74	0.40	-2.00
π_{A340}	16.25	14.52	16.11	14.49	16.17	0.08	-1.66
π_{B777}	31.59	44.68	31.51	44.58	31.60	-0.01	13.08
π_{MD-11}	N/A	N/A	-2.36	-2.45	-2.34	2.34	2.34

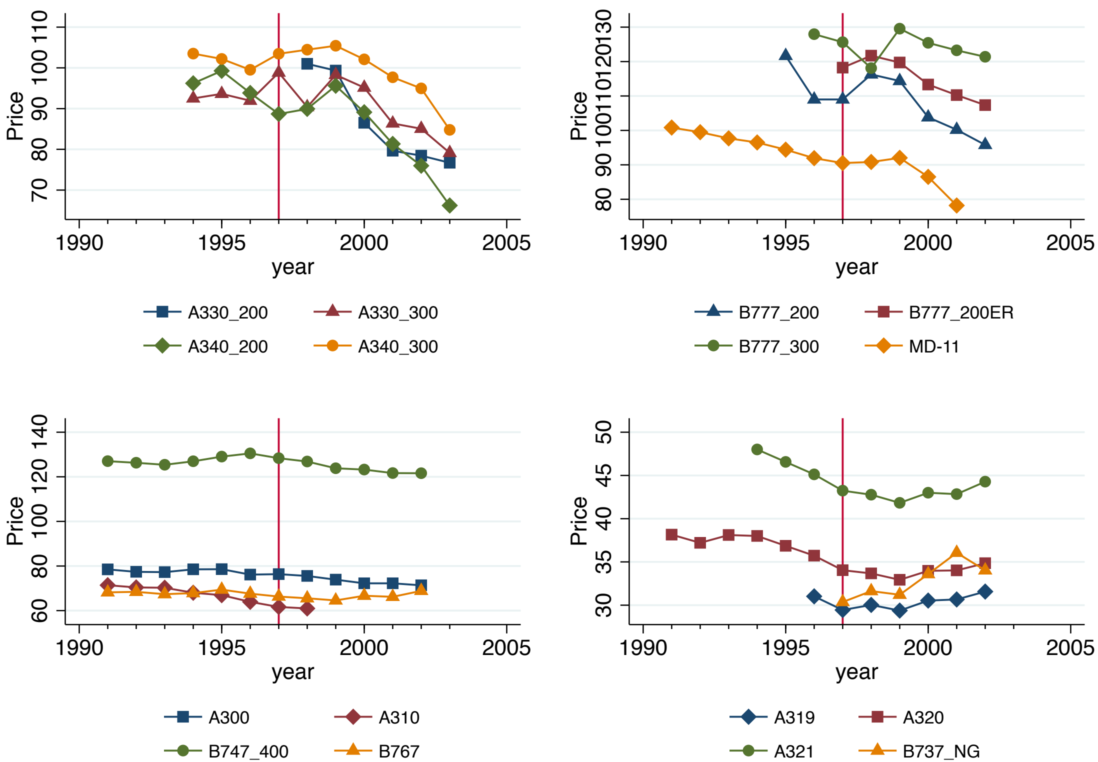
Note: All values are total discounted expected values in billions of 1994 dollars. In scenarios (i) and (ii), the MD-11 production was either shut down shortly or kept, respectively, after the merger. There is no merger in scenario (iii). In each scenario, $\tau = 0$ and $\tau = 1$ refer to no experience transfer and complete experience transfer after the merger, respectively; CS is consumer surplus, TS is total surplus, and π is profit.

Table 9: Robustness Check: the Dynamic Model with Generation Upgrade

Value	Scenario (i) merger discontinue MD-11 (a) $\tau = 0$	Scenario (i) merger discontinue MD-11 (b) $\tau = 1$	Scenario (ii) merger keep MD-11 (a) $\tau = 0$	Scenario (ii) merger keep MD-11 (b) $\tau = 1$	Scenario (iii) no merger	Diff. of (i) and (iii) (i.a)-(iii)	Diff. of (i) and (iii) (i.b)-(iii)
CS	103.78	109.28	106.49	110.29	104.54	-0.76	4.74
π_{all}	40.50	48.99	37.80	46.07	37.46	3.04	11.53
TS	144.27	158.27	144.29	156.36	142.00	2.28	16.27
π_{A330}	5.38	2.90	6.22	4.24	5.31	0.07	-2.41
π_{A340}	6.59	5.57	4.31	4.06	6.18	0.41	-0.61
π_{B777}	28.52	40.52	29.78	39.74	28.36	0.16	12.15
π_{MD-11}	N/A	N/A	-2.51	-1.97	-2.40	2.40	2.40

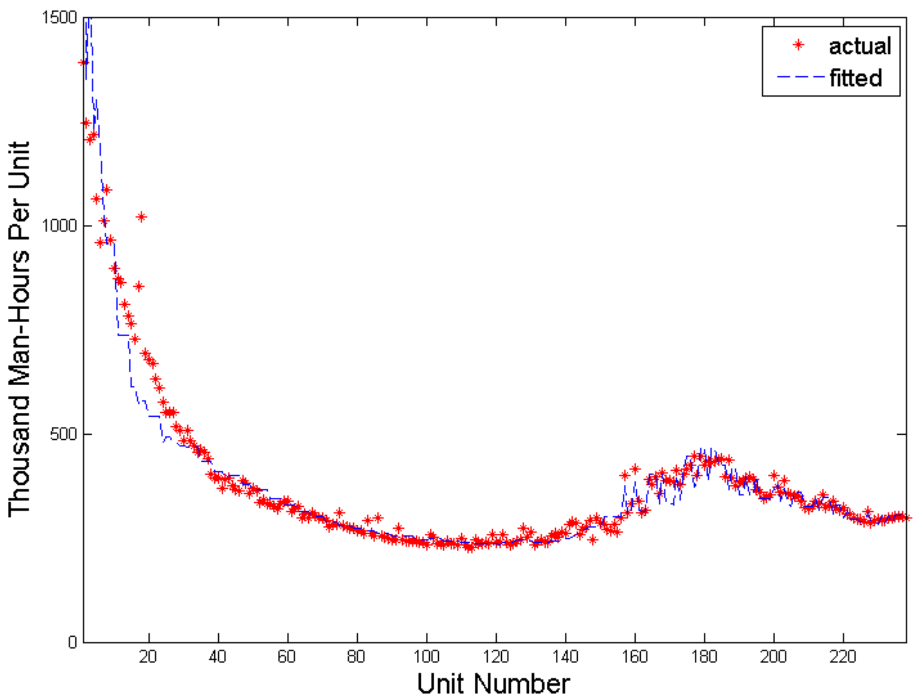
Note: All values are total discounted expected values in billions of 1994 dollars. In scenarios (i) and (ii), the MD-11 production was either shut down shortly or kept, respectively, after the merger. There is no merger in scenario (iii). In each scenario, $\tau = 0$ and $\tau = 1$ refer to no experience transfer and complete experience transfer after the merger, respectively; CS is consumer surplus, TS is total surplus, and π is profit.

Figure 2: Prices of aircraft



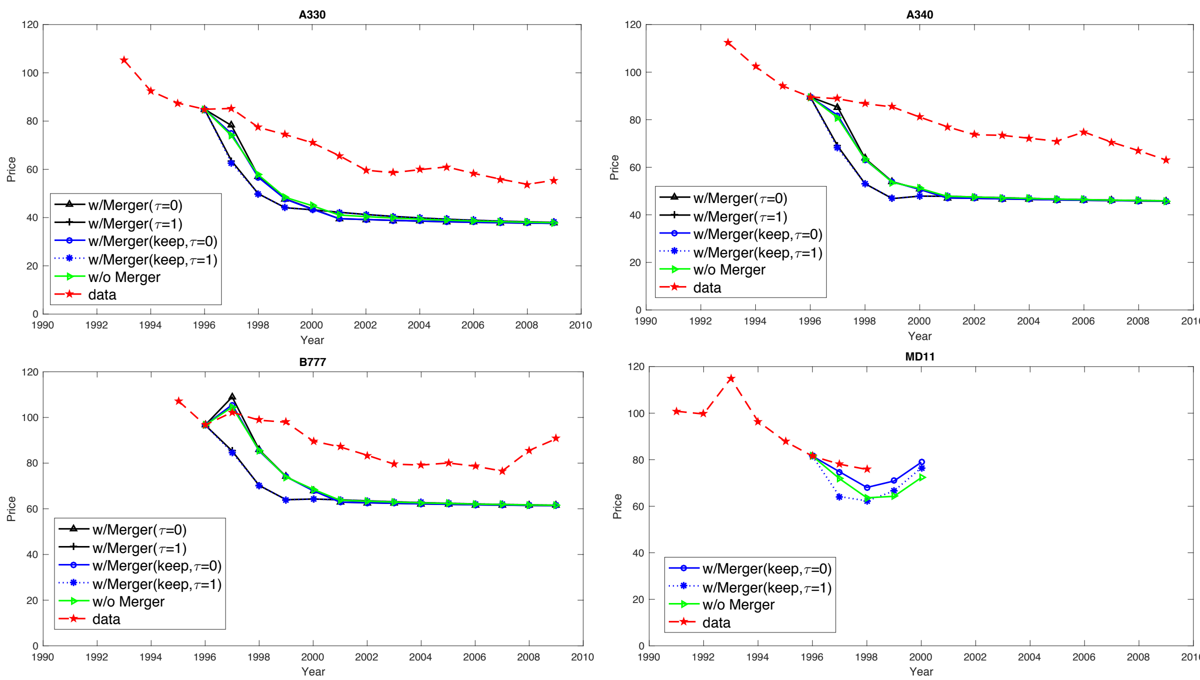
Note: The subfigures in the top row are for medium-sized wide-body aircraft for Airbus and Boeing, respectively. The bottom-left subfigure is for non-medium sized wide-body aircraft, and the bottom-right subfigure is for narrow-body aircraft. The vertical line indicates the year of the merger. The unit of the y-axis is millions of 1994 dollars.

Figure 3: Fit of Labor Input for L-1011



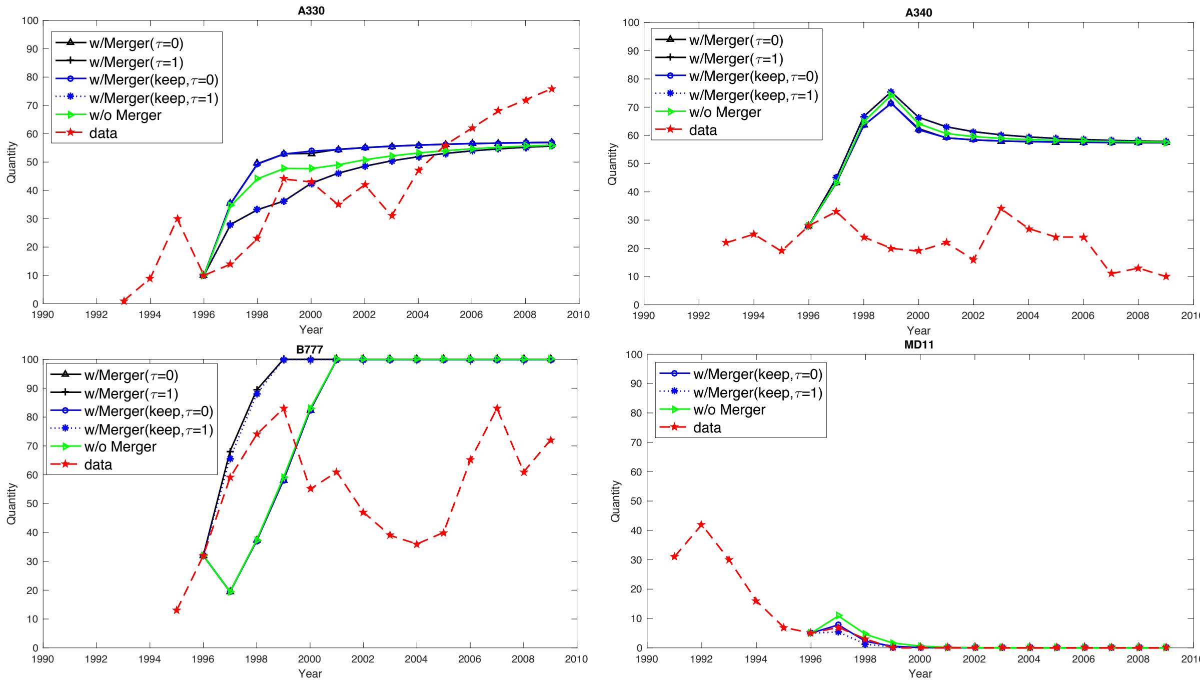
Note: The fitted labor requirements curve for Lockheed L-1011 is generated by the learning curve estimates in Table 5.

Figure 4: Actual and Counterfactual Prices



Note: Actual prices are for the period 1993-2009 for A330 and A340, 1995-2009 for B777, and 1991-1998 for MD-11. The quantity of MD-11 drops to zero after four years for all the counterfactual scenarios. Thus there is no price after the year 2000. The unit of prices is millions of 1994 dollars.

Figure 5: Actual and Counterfactual Quantities



Note: Actual quantities are for the period 1993-2009 for A330 and A340, 1995-2009 for B777, and 1991-1998 for MD-11.

Figure 6: Counterfactual Experience

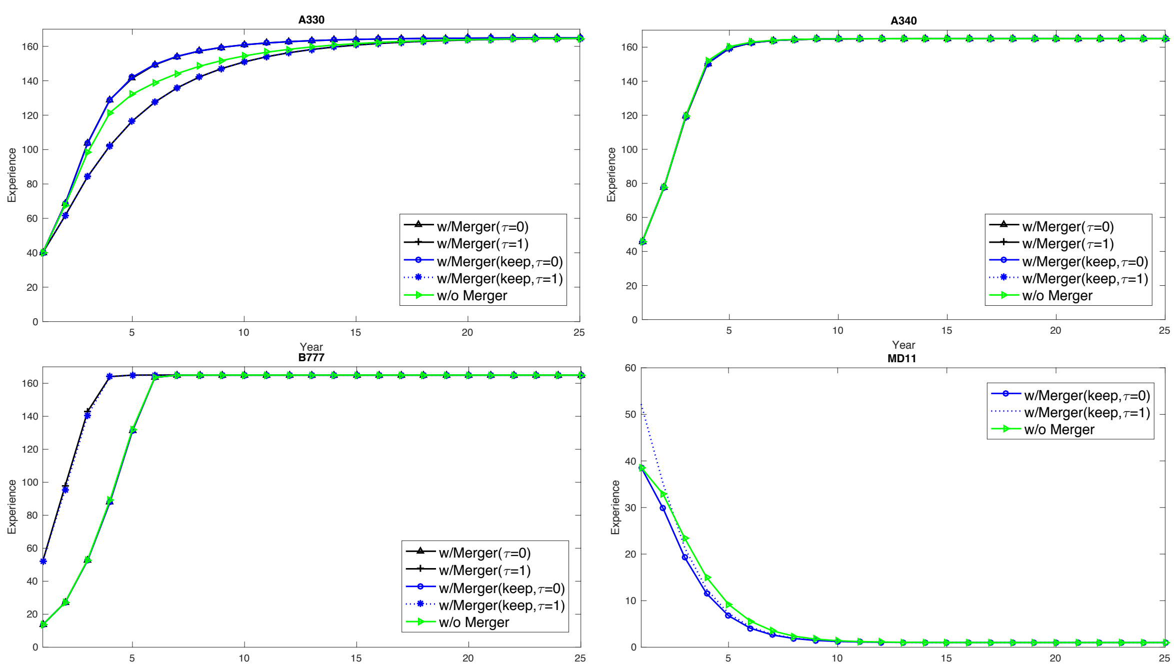
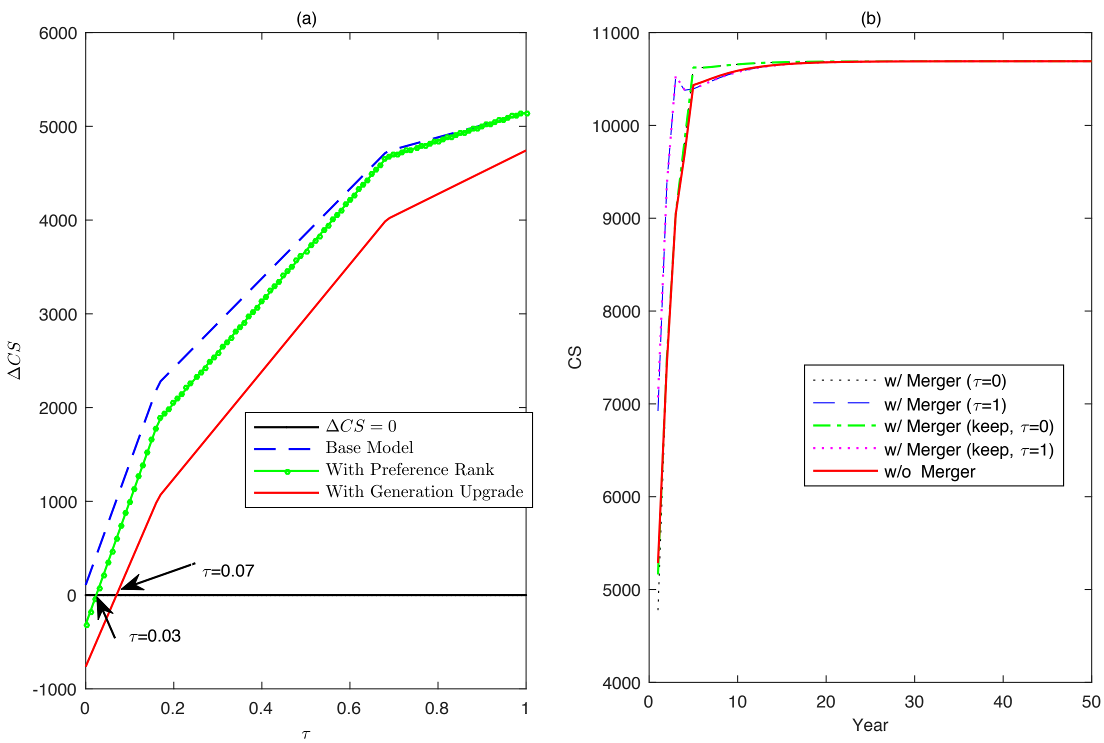


Figure 7: Comparison and Path of Consumer Surplus



Note: The left plot illustrates the relationship between the change in consumer surplus due to the merger and the one-time experience transfer rate τ. The horizontal line marks zero consumer effect of the merger. The right figure plots the change in consumer surplus over time in three scenarios.