Strategic responses to used-goods markets: Airbus and Boeing since 1997

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Abstract

This paper examines the relationship between innovation, production, and used-good markets, then evaluates government subsidies to Airbus and Boeing, which have recently been ruled illegal by the WTO. This research sheds new light on the crucial role of innovation as a competitive tool against used-good markets. Moreover, this paper shows that a production or R&D (research and development) subsidy reduction leads to a delay in firms' innovation; in the aircraft manufacturing industry, a production subsidy reduction has a bigger negative impact on innovation than subsidy reduction in research and development. Finally, this paper finds that, though it reduces innovation and production, the cut in the government subsidies has a minor effect on consumer welfare due to the presence of active used-goods markets.

Keywords: Innovation, Used-good Markets, Government Subsidy, Consumer Welfare

JEL: L13, L11, D22, L62, L50, D43, O31

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1 Introduction

Durable goods markets often give rise to active second-hand markets. In such an environment, producers recognize that what they sell today will become substitutes to their own products in the future. Economists have long been interested in how producers adjust their prices and quantities in response to this issue. Much less is studied about how active second-hand markets stimulate producers to innovate. Firms can escape competition from second-hand goods markets by introducing new products. In this paper I study the tradeoff between quantity reduction and innovation in response to second-hand goods markets in the context of the wide-body aircraft manufacturing industry from 1969 to 2011. I use estimates from a dynamic structural model of oligopoly production and second-hand markets to study the long-standing trade dispute between Airbus and Boeing–a dispute that arose from subsidy policies recently ruled illegal by the WTO.

The analysis of this topic requires a dynamic structural model. Each consumer is static and can either buy a wide-body aircraft or abstain. Unlike previous literature on oligopolistic response to used-good markets, which focuses only on the firms' production, this paper will highlight the intuitive idea that innovation can be the important margin when firms compete with their own used-goods. I model both the production and innovation choices in a dynamic oligopoly with a decentralized used-good market, with innovation defined as new product development with improved quality. Used-good quantity in each period endogenously depends on the new goods produced in the previous period in this framework.

I use the random coefficient logit model to identify heterogeneous consumer demand and the two-stage estimation method suggested by Bajari, Benkard, and Levin (2007), Pakes, Ostrovsky, and Berry (2007) to estimate dynamic innovation and production cost parameters. My calculations take place over two stages. I develop a simplified used-good quantity index to incorporate the vector of used-goods in the first stage: policy function estimation. In the second stage simulation, I compute prices using the consumer demand framework. This implies that equilibrium prices change when firms adjust quantities– the existing literature using the two-stage method estimates profits using a reduced form regression. Based on this computational algorithm, I use the predicted average prices for a rigorous test of the model and recover both innovation and production parameters. Using these estimated parameters, I solve a Bellman equation to obtain the theoretical policy functions for counterfactuals. In the counterfactual, I separately analyze the effects of removing the controversial government R&D and production subsidies on both companies and consumer welfare. Ultimately, in my model, production subsidy causes not only an increase in production but also a rise in innovation.

This paper develops a unique data set on the aircraft manufacturing industry. This rich data set was manually compiled and contains details on each transaction for each wide-body aircraft ever created, including prices and aircraft characteristics for both the used and new goods markets. This data set allows me to capture the double competition from new and used goods markets in rich ways as shown in figure 1 and to construct firms dynamic innovation decision in the presence of used-goods markets.

The reduced form impulse-response shows that the firms' quantity decision is negative on the used-quantity index, while innovation is positive. The magnitude evaluation of the parameters estimated by the reduced form regressions shows that firms are 2.6 times more likely to innovate and 37% less likely to produce with an active used-goods market. Also, 15% depreciation of the currency of a producer's country leads to a 3% increase in innovation rates and a 12% increase in production.

My dynamic results show that the cost of innovation is on average 5 billion dollars (as of 2005), a figure which is comparable to that calculated by Benkard (2004).[1] The quadratic production cost estimates suggest that the markup of more recently developed airplanes is smaller than the markup of those developed earlier. The predicted average prices do not deviate much from the actual average price per product. Dynamic policy functions found by the value function iteration in a monopoly setting predict that manufacturers would not only produce less quantity to indirectly control the used-good quantities, but would also innovate more new products to recover market share when new products replace an existing line. I also find that firms anticipating growth in the

[1] The development cost of the L1011, 747, 777, 380 were known to be 2.52 billion, 3.6 billion, 4.7 billion, and 10 billion U.S. dollars respectively.

used-goods markets reduce quantity production and immediately innovate new products before the used-goods market gets bigger when new products compete with an existing product line.

I find that a 50% decrease in government R&D subsidy reduces not only firms' innovation but also firms' total production when new products replace an existing line. I also find that a 5% reduction in the illegal production subsidy leads to a larger reduction in the innovation rate than a 50% R&D subsidy reduction. My main findings predict that the R&D subsidy reduction will have a long-term negative effect on innovation in situations where product-replacement occurs, whereas it has a short-term negative effect on innovation in the case of multi-product production. Terminating the production subsidy harms both innovation and production.

As expected, producer profits fall as subsidies are reduced. The reduction in producer profit is larger when new products replace an existing line than when firms keep producing the existing lines. Consumer welfare is largely unaffected for both R&D subsidy reduction and production subsidy termination. It declines slightly only when a firm replaces existing products. Hence, the cut in the government subsidies has a minor effect on consumer welfare. These main findings are important not only for manufacturers but also for policy makers. Policy makers and trade authorities can make use of the quantified analysis of this paper in ruling on the trade dispute.

Literature review Used-goods markets and durability have been examined within a monopoly setting in empirical and theoretical literature since Coase (1972) and Stokey (1981). The Coase conjecture explains how durability deteriorates the market power of a monopoly with dynamic consumers. Suslow (1986) shows that recycled aluminum limits the market power of an aluminum manufacturer.

The role of durable goods is also examined in dynamic demand literature, such as Rust (1985), Adda and Cooper (2000), and Berry et al. (1995). More recently, Gowrisankaran and Rysman (2009) and Conlon (2010) focus on the dynamic consumer. Most paper have focused only on consumer purchasing behavior or monopoly production.

In related work on the aircraft industry Gavazza (2011) documents that secondary markets gained importance since the mid 1980. He finds in a static model that aircraft leasing helps in

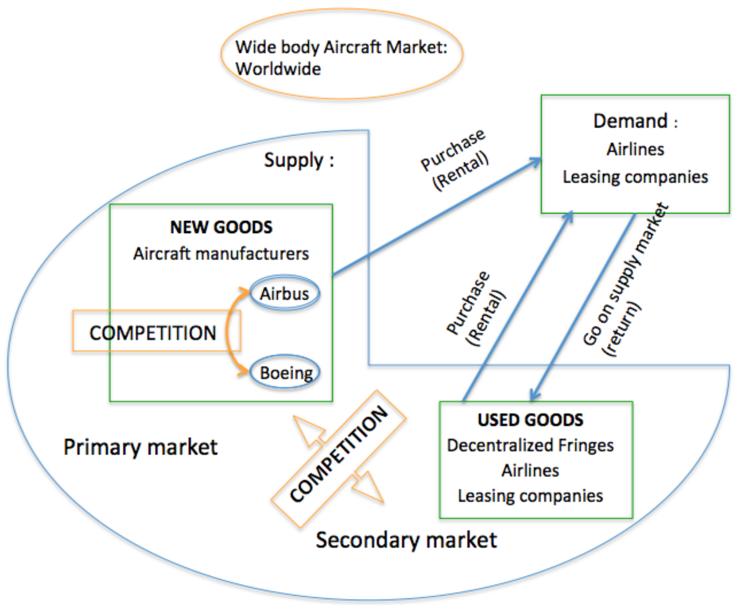


Figure 1: **Worldwide wide-body aircraft market**

allocating aircraft efficiently across operators by reducing transaction costs. Irwin and Pavcnik (2004) examine the effect of the 1992 U.S.-EU trade agreement on aircraft prices. They find using a model of aircraft consumer demand that a 5% increase in the marginal cost as a consequence of the agreement lead to a 3.7% increase in aircraft prices. This paper adds to the literature by examining the importance of secondary markets and subsidies for producers dynamic production and innovation decisions.

Waldman (1996) and Waldman (2003) show that a monopolist might increase their profits in the presence of used-goods markets by taking an advantage of an indirect form of price discrimination to consumers with different valuations of product qualities. Benkard (2004) provides a dynamic analysis for the wide-bodied commercial aircraft market using private data from Lockheed. He constructs a dynamic oligopoly quantity setting model with a learning cost. More recently Esteban and Shum (2007) has examined the production decision in response to secondary markets under the assumption of no product entry or exit. Chen et al. (2011) introduce transaction costs and calibrate instead of estimation. Goettler and Gordon (2011) shows the effect of duopoly market structure on quality decision of Intel, while Igami (2011) examines the the timing gap between incumbents and entrants. They investigate the relationship between primary market structure and innovation, but do not study the interaction between production, innovation, and used-goods markets that is the key framework of my paper.

Solving dynamic game models is computationally intensive. It requires computing all possible equilibria and verifying which of these are chosen by agents. Esteban and Shum (2007) construct a linear-quadratic model without product entry and exit to minimize the computational burden and employ the full solution method. This framework cannot be applied because my paper contains a discrete choice, innovation. In order to sidestep the curse of dimensionality and multiple equilibria, I adopt the two step estimation method suggested by Bajari et al. (2007) and use the method of moments as in Pakes et al. (2007).

2 Data and industry background

Commercial wide-body aircraft industry Wide-body aircraft have several distinguishing features: two passenger aisles, a total capacity of 200 to 600 passengers, and the ability to transport passengers, freight, and cargo. Wide-body commercial aircraft manufacturers have experienced fierce oligopolistic competition due to the small number of firms and their high durability, high start-up costs, and long production-runs. Four major aircraft manufacturers– Boeing, Airbus, McDonnell-Douglas, and Lockheed– competed for the market in 1970-80s without any new entrants. Lockheed exited the market after experiencing economic problems and a big drop in sales in 1984. After McDonnell-Douglas merged with Boeing in 1997, the wide-body aircraft market became a duopoly between Boeing and Airbus.

This industry shows an interesting trend in terms of new product development. As shown in figure 2, Airbus and Boeing have launched new products much more frequently in the last two decades (1991-2011) as compared to their first two decades (1969-1990), despite the potential cannibalization. For example, Airbus developed the A330 even though they expected it to swallow up the market share of their existing model A310. Airbus also recently announced the launch of model

year	Airbus	Boeing	year	Airbus	Boeing
1969		**747-100**	1991	A310-300F	
1970			1992		
1971		747-200B	1993	**A340-2,300**	
1972			1994		
1973	**A300B2**		1995	**A330-300**	767-300F
1974			1996		**777-200**
1975	A300B4		1997	**A300-600ST**	**MD11F**
1976		747SP	1998	A330-200	777-300
1977			1999		
1978			2000		767-400ER
1979			2001	A340-600	
1980			2002	A340-500	**747-400ER(F)**
1981		**767-200**	2003	A340-300En	777-200ER
1982	**A310-200**		2004		777-300ER
1983	A300-600	747-300	2005	**A340-6HGW**	
1984		767-200ER	2006	A340-5HGW	**777-200LR**
1985	A310-300		2007	**A380-8**	
1986		767-300	2008	A310MRT	
1987			2009	**A330-2HGW**	777-F
1988		767-300ER	2010		**747-8F**
1989		**747-400**	2011	A330-200F	**787-8**
1990			2012		

RED: The biggest technological and structural changes (Top)
DARK RED: Numerous technological and structural changes (Middle)
BLACK: Variants with structural improvement (Bottom)

Figure 2: New product development timeline: Airbus and Boeing

Each year represents the year of first flight of each airplane that turns out to be delivered after the first flight. The years can be different from the launching floor models' first flight.

A350 aircraft even though it will partially erode the sales of A340. The more frequent innovation seems to be related not only to competitors' innovation, but also to used-goods markets.

Due to the high durability of aircraft, the manufacturers compete with used-goods markets. Graph 3 describes the number of transactions involving new-goods produced by the four wide-body aircraft manufacturers and the number of transactions of used goods incurred by airlines, leasing companies, and governments. Since 1986, the used-good transaction figure has exceeded the new-good transaction figure, and the gap between them has grown in the 43 years since their inception.

Purchasing and leasing are both types of secondary market transactions. The lease transaction is an interesting phenomenon in the aircraft industry, partially encouraged by government tax schemes promoting the business. Lease expenses and interest payments on borrowed funds generate tax deductions by corporate tax law. This leads to a reduction in total taxable income and, as a result, lower annual taxes payable. The lease/interest rate deduction in corporate taxes has the net effect of reducing the cost of leasing. The tax benefits and the airline deregulation around the 1980s seemed to encourage lease transactions. The advantages of leasing relative to owning and its effects on the aircraft industry are studied in Gavazza (2010) and Gavazza (2011). More discussions on these policies are provided in the appendix.

"Learning by doing" as mentioned in Benkard (1999), is another interesting feature of the

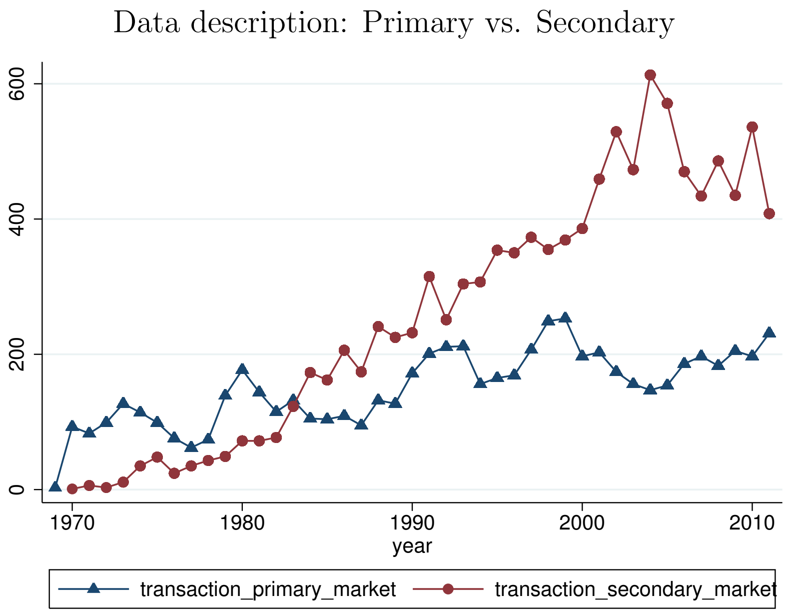
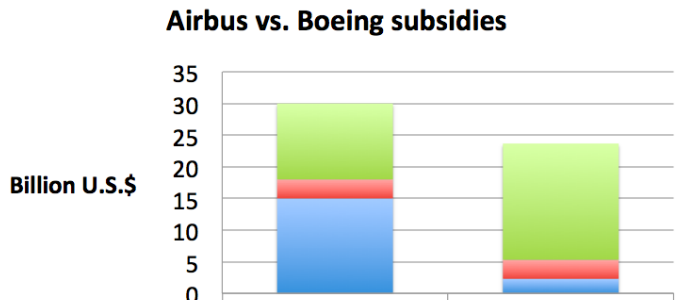


Figure 3: Wide-body aircraft transactions

industry. The expected learning effect could be negated by unexpected production issues such as losing skilled workers or having to train new employees. Also, given that the market is worldwide, the exchange rate seems to be an important factor in the estimates of break-even sales. In order to reduce a computational burden, in this paper I assume that the learning effect is offset by the loss of productivity and increase in education costs incurred by frequent shifts in skilled labor.

Trade disputes on government subsidies : Despite intense competition, total civilian aircraft shipments were the top recorded US export shipment worldwide. Civilian aircraft, including parts, netted US$74.7 billion in 2009, higher than the 2008 export by 1%. This amounted to about 7.1% of the total US exports in 2009. Moreover, the trade is expected to be worth more than $3 trillion over the next decade. Civilian aircraft export takes a major portion of the countries, Germany, France, UK and Spain in Europe where Airbus manufacturing factories or sales headquarters are located at. So, each government has a high incentive to subsidize its domestic firm. Each firm often accuses the other of receiving unfair subsidies or tax breaks from their respective governments.

The subsidy conflicts between the two firms have a long, complicated history. A 1992 agreement



	Airbus	Boeing
legal subsidies	12	18.37
illegal prod aid	3	3
illegal launch aid	15	2.3

Figure 4: The subsidies of the U.S. government and the European governments

The illegal subsidy amount is based on the WTO rulings released on March 2012.
The actually total amount of subsidies to Airbus and Boeing is not publicly available. I report the approximately estimated amount of subsidies between 1993 and 2006 based on the WTO dispute settlement and *www.defense−aerospace.com* and the articles in the 1992 trade agreement. The illegal subsidy amount ruled by the WTO is between 1989 and 2006. This can be updated upon more information available later.

put a ceiling on the direct government launch investment subsidy: 33% of the total development costs for new aircraft programs.[2] It established that launch investment support would be repaid at an interest rate no less than the government cost of borrowing and within no more than 17 years. Basically, this applies to the form of government support mainly used in Europe. The agreement also established that the American aircraft industry was allowed to continue with indirect federal and state support in the payment range of 3% of the large commercial aircraft yearly sales. In contrast to the European system of repayable launch investment, there is no requirement that indirect support be reimbursed. The 3% is calculated on the larger basis of the turnover of the LCA (large commercial aircraft) industry and applies per individual year.

In 2004, America called for a termination of the 1992 bilateral agreement with the European

[2]The launch investment subsidy agreement allows up to 33% of the development/program cost to be financed through government loans which must be repaid within 17 years with interest and royalties.These loans are held at a minimum interest rate equal to the cost of government borrowing plus 0.25%.

Union and initiated a WTO dispute settlement procedure.[3] Boeing accused Airbus of receiving more reimbursable launch investment from the European governments than was agreed on in the 1992 agreement. Airbus responded immediately with claims that Boeing violated the agreement by receiving illegal subsidies through military contracts and tax breaks from the US government. The amount of illegal subsidies Airbus and Boeing claimed against one another was $19.1 billion and $18 billion, respectively. In March 2012, the WTO final verdict called for 1) the withdrawal of at least $5.3 billion in federal subsidies already received by Boeing; 2) elimination of an additional $2 billion in illegal state and local subsidies due in the future; and 3) termination of all U.S. Department of Defense (DOD) and NASA research grants to Boeing, including funding, Boeing use of government facilities and the illegal transfer of IP rights to Boeing.

Overall, WTO ruled that Boeing received in illegal aid (but far less than the EU had alleged), and that Airbus received $15 billion illegal aid. The graph 4 shows the total subsidies including estimated legal and illegal subsidies.[4] These trade disputes and their economic impacts are examined in the counterfactual section of this paper.

Data construction I constructed my data set by combining data sets obtained from Plane Spotters, Air fleets, and Aero Transport Data Bank. In a broad sense, the data include many areas of sub-data, such as transactions data, transaction prices data, macro variables data, and product characteristics data. The main transaction data set contains individual-level transactions of each aircraft in both new and used, operators (i.e. consumers), the number of orders per year, the number of deliveries per year, delivery dates, first flight dates, first delivery dates, transaction types, duration of lease, age of used airplanes, current status of each aircraft traded, specific aircraft number (MSN), name of financing firms, canceled orders, each aircraft model name, and manufacturer information, among others. Each date is specified by day, month, and year. The categories of transaction types are "purchase with cash flow," "purchase by borrowing," "wet lease," and "dry lease." My methods of counting each transaction are described in the appendix.

[3]Source: the economist, Trading blow, Aug 13th 2009.

[4]The industry expert estimated the R&D subsidy given to the manufacturers as 70% of total development cost before 1992. I estimated the legal R&D subsidy after 1992 based on the 33% cap to Airbus and 3% annual financial support to Boeing.

I record model-lines, variants, and specific identifying numbers of aircraft in the transaction data as shown in the "product-line" table in the appendix. I match the product characteristics with corresponding aircraft based upon the product identification information. In the data, I have 15 main model-lines and 54 variants. Most variants have different configurations. I call these aircraft with different configurations "sub-variants." The crucial factor in determining each sub-variant of aircraft in the data set is engine types. I discovered 92 sub-variants in the data. Moreover, I observed that most sub-variants have different configurations after merging the transaction data with the product characteristics described after the price data below. I call these "customized sub-variants." The number of customized sub-variants is 187, based on maximum take off thrust, maximum take off weight, fuel capacity, number of seats, and range.

The price data are acquired from four sources: an aircraft value appraisal company, airline capital associates, aircraft bluebook, and an aviation consulting firm.[5] The complete price data include new aircraft prices in product-level, based on actual transaction prices, and used aircraft prices. The assumption is that the condition of used traded aircraft is medium. Data also include new and used aircraft appraisal values (based on observed actual transactions as a proxy of actual transaction prices), annual list prices, monthly leasing rates per year, six-month leasing rates, and duration of leases. The panel data on used-aircraft market retail prices at the model-vintage level are manually compiled. All the prices and rates are nominal values expressed in terms of U.S. dollars. Annual list prices, purchase prices/values, and leasing rates from four different sources seem to be proportional to one another.[6] In line with Benkard (2004), if the price data and the rental prices are roughly proportional, the distinction between these two in model estimation should not matter as the difference would be absorbed into the price coefficient.

The product characteristics are collected mainly from an aviation annual publication called *Jane's All the World's Aircraft* (1960 to 2011). In addition, I partly referred to the technical docu-

[5]I owe special thanks to the chair, Edmund Greenslets who kindly answered all my questions on aircraft prices and market size and characteristics of the industry both via email and via phone call. Also, I appreciate Paul Leighton who helped me clarify the appraisal value data via email. I heavily indebted to Professor Pulvino, former professor in University of Chicago, management department for the transaction price data before 1997.

[6]Lease rate contracts express monthly rental as a certain percentage of the prices, and it is known to be roughly *appraisal value*/100 with average configuration and average conditions.

ments released by the *Federal Aviation Administration* (hereafter, FAA). All the relevant properties and configurations of each aircraft model are manually compiled. The complete data set includes the number of seats, maximum payload, maximum take off weight, maximum take off thrust, fuel capacity, flight range, empty operating weight (hereafter, EOW), number of engines, engine types, cockpits, and wingspan. I calculated fuel efficiency and structural efficiency by combining the observed characteristics addressed above in accordance with the industrial definitions for both. The functional form of fuel efficiency that I adopt and the structural efficiency function are as follows: $\text{fuel efficiency} = \frac{\text{max payload} \cdot range}{\text{fuel capacity}}$, $\quad$ $\text{structural efficiency} = \frac{MTOW}{EOW}$.

Age of each aircraft in the used-goods market captures the quality of the used airplanes by assuming that the quality depreciation of an asset is proportional to aging of the asset. The parts that wear out over time are not easily observable unless I track down each aircraft individually. Under these circumstances, age is the best proxy for quality depreciation. Age and other main elements of the data– such as the transaction quantity, prices, and product characteristics– are summarized in the Summary table in the appendix. The description and the source of total market size, exchange rate, hourly wage, consumer price index, oil prices and aluminum prices are illustrated in the appendix.[7]

3 Structural Model

I construct a dynamic oligopoly model with differentiated products. The model is based on the theoretical work in Ericson and Pakes (1995).[8]

3.1 Dynamic game with production cost and innovation cost

Firms compete in an oligopolistic quantity-setting game in each period, taking the (inverse) consumer demand function as given. Products are durable and traded in primary and secondary markets. Firms take competition from their own goods into account in their quantity and inno-

[7] Appendix is separately documented and provided on the website: `http://people.bu.edu/mjkim07`

[8] My model is also similar to other empirical work based on the Ericson-Pakes framework such as Pakes and McGuire (2001) and Benkard (2004) and Ryan (2011).

vation decisions. The game is on discrete time with continuous state space; the quantity vector of the used airplane market of each product of each producer is continuous. The future value is discounted at a rate of $\beta = 0.92$.[9]

The time-line of the firms' decisions follows this progression: First, firms receive private draws on the fixed costs of innovation, and they all make innovation decisions at the same time. Second, firms compete over quantities in a multi-product market. A firm's profits result from selling the products after paying production costs and innovation costs. Each firm's innovation choice is discrete, whereas the production decision is continuous.

Innovation is defined as developing a new product-line. Firms develop new product-lines sequentially, taking the order of development as exogenous. In this model, only the timing of innovation is endogenous. I take the existing sequence of innovations as given and model the binary choice of whether or not to introduce the next one. Each firm can only develop one product per period. For simplicity it is assumed that a product developed today can be produced and sold on the market in the next period.[10] The strategies for production and innovation are functions of both the states and private information known to the firms.

Let q_{fkt} be the quantity firm f chooses at time t to produce of type k. Further assume that the production choice is continuous. Let S_{ft} be the state vector that firm f faces at time t.

The current operations profits π_{ft} depend on today's state S_t, the strategy σ of firm f, and the strategies of other firms σ^-. It can be written as

$$\pi_{ft}(S_t; \sigma(S_t), \sigma_t^-) = \sum_{j \in \mathcal{J}} p_{fjt}(S_t; \sigma(S_t), \sigma_t^-) q_{fjt}(S_t; \sigma(S_t), \sigma_t^-) - \underbrace{\sum_{j \in \mathcal{J}} c\left(q_{fjt}(S_t; \sigma(S_t), \sigma_t^-)\right)}_{C_t^q}. \quad (3.1)$$

$$\Pi_{ft}(S_t; \sigma(S_t), \sigma_t^-, \epsilon_t^I) = \pi_{ft}(S_t; \sigma(S_t), \sigma_t^-) - \underbrace{\left\{I_{ft}(S_t; \sigma(S_t), \sigma_t^-) > 0\right\} C_I}_{C_t^I} \quad (3.2)$$

[9] Ryan (2011), Goettler and Gordon (2011), and Igami (2011) adopt $\beta = .90$, .90, and .88 for markets of cement, microprocessors, and HDD, respectively.

[10] Adding a time lag between development and production is straightforward but increases the computational burden through the introduction of one or several additional state variables.

The Π_{ft} indicates periods t net profit after innovation costs and where $\{I_{ft} > 0\}$ is an indicator function that takes the value one if the firm innovates in period t. $\mathcal{J}$ is the set of currently developed aircraft. The price p_{fjt} is the market clearing price implied by consumer demand that is outlined in the next section. The innovation cost is drawn from a random distribution each period. The firm pays C_I if they develop a new plane. The firm pays nothing if it does not innovate. Let $C_I = c_I + \epsilon^I$, where c_I is a parameter and $\epsilon^I \sim N\ (0,\, \sigma_I)$.

The state S at time $t+1$ evolves according to transition process $\mathbf{P}(S_{t+1}|S_t, \sigma(S_{t+1}))$. The evolution of states depends on the current period's decisions and states. The state variables are total market size m_t, oil prices, fixed cost of innovation C_I, exchange rate and used-good quantities. The used-good quantity is an endogenous state. The quantity of used good j age k is $\left\{\hat{Q}_{fjk}\right\}_{f=1,j=1,k=1}^{F,N,\Omega}$ where N is number of different plane products (model lines), the number of firms $F = 2$, $J = 10$ total products, k is the index of age bins with maximum age bin Ω. I discretize products to have four ages, so that the state space describing used market has $J \times 4$ elements. I suppose that used aircraft of type j of firm f has four stages of age: new, young (y), medium (m), and old (o). The transition is the following:

$$\hat{Q}^y_{fjt+1} = (1-\delta_y)Q^{new}_{fjt} + (1-\delta_{yy})\hat{Q}^y_{fjt} \tag{3.3}$$

$$\hat{Q}^m_{fjt+1} = (1-\delta_m)\hat{Q}^y_{fjt} + (1-\delta_{mm})\hat{Q}^m_{fjt} \tag{3.4}$$

$$\hat{Q}^o_{fjt+1} = (1-\delta_o)\hat{Q}^m_{fjt} + (1-\delta_{oo})\hat{Q}^o_{fjt} \tag{3.5}$$

The $(1-\delta_y)$ is a transition rate from new to used in age stage young. The probability distributions determine sample paths of states and actions conditional on the starting state S_0. This setup allows for some planes to disappear over time. This captures the realistic pattern that some planes are taken out of service and scrapped at an early age or destroyed in accidents.

With the state S and the strategy σ, the value Function of each firm at time t is as follows:

$$V_f(S_t;\sigma(S_t),\sigma_t^-,\epsilon_t^I) = \max_{q_{fjt},I_{ft}} \left(-1(I_{ft}>0)C_I + \sum_{k\in J} \pi_{fkt}(S_t;\sigma(S_t),\sigma_t^-) + \beta E_t V_f(S_{t+1};\sigma(S_{t+1}),\sigma_{t+1}^-,\epsilon_{t+1}^I) \right) \tag{3.6}$$

where π_{fkt} depends on the prices implied by consumer demand outlined in the next section.

3.2 Demand function

In every period, a consumer can either buy a wide-body aircraft or go for the outside option: "not buying wide-body aircraft." I define the outside option to include all new or old narrow-body aircraft. The multiple goods are differentiated by characteristics both vertically and horizontally. Each consumer buys, at most, one product at a point in time t. Since I define each year as each different market, I assume each market is independent. Airlines take resale values into account in their purchasing decision. Instead of introducing purchase price and resale value, I employ rental prices and assume that airlines buy aircraft at the beginning of a year and resell it in the end of the year as in Benkard (2004). That is, each airline optimally reallocates aircraft every year under no transaction cost, so consumers are static optimizers.

Relying on these assumptions, I construct a demand system in which the consumers' optimal decision each period is independent from their future choices as well as their past decisions. The demand system is static without losing important features of the industry. The demand system is defined by a random coefficients logit model as in Berry et al. (1995) (hereafter, BLP) with the single-unit purchase assumption.

There is a continuum of consumers denoted by i. Let $\jmath_t$ denote the set of new aircraft produced at time t and let j denote the product: an aircraft model categorized by aircraft characteristics. Market size is defined as m_t. Each year constitutes a market. Consumer i with tastes (α_i, β_i) choose whether to buy a good j in period t or not. The utility of the outside option "not to buy a wide body aircraft" is normalized to zero. Consumer i who purchases an aircraft j at time t

receives utility as follows:

$$u_{ijt} = \alpha_i p_{jt} + \boldsymbol{\beta_i} \mathbf{x_{jt}} + \xi_{jt} + \eta_{ijt} \tag{3.7}$$

where p denotes the observed price of the aircraft, $\mathbf{x}$ is a vector of observed product characteristics and ξ denotes unobserved characteristics. η_{ijt} is an idiosyncratic taste that each consumer has and follows Type I extreme value distribution.

3.3 Equilibrium concept

Symmetric Markov perfect Nash equilibrium (MPE) Symmetric Markov perfect Nash equilibrium requires that each firm plays its optimal strategy given its competitors' strategy profiles and each firm plays the same optimal strategy if the states they face are the same. Firms choose their quantity and from demand receive the vector of prices that clear the market. At least one pure strategy equilibrium exists following Doraszelski and Satterthwaite (2010). Given that profits are bounded in all states with discounted factor β, the state space is bounded, and that I introduce the private information over the discrete action (i.e. continuity of the innovation cost distribution), existence of at least one symmetric MPNE in pure strategies is guaranteed as the best-response curves are continuous. The uniqueness, however, is not guaranteed. I use two step estimation method with equalities to deal with the possibility of multiple equilibria.

For every firm f for every good k at time t, the optimality condition is:

$$E_t\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial(\sum_j p_{fjt+\tau}q_{fjt+\tau}(S_{ft+\tau}))}{\partial q_{fkt}}|S_{ft}\right] = E_t\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial C^q_{t+\tau}}{\partial q_{fkt}}|S_{ft}\right] + E_t\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial C^I_{ft+\tau}}{\partial q_{fkt}}|S_{ft}\right] \tag{3.8}$$

where S_{ft} is a vector of the state variables for firm f at time t.

4 Estimation

4.1 Structural demand estimation: BLP method

Random coefficient logit leads to more realistic substation patterns than the logit or, as Benkard (2004) uses, the nested logit. To rule out the possible endogeneity problem between the prices and the error term, I use cost shifters as instruments. The cost shifters are aluminum prices and the wage of aerospace manufacturing industry workers. I adopt the aerospace manufacturing industry wage instead of the whole manufacturing industry wage. This instrument has not been used before. I decompose random coefficients on constant, price, and product characteristics into two parts to estimate the demand curve. Let's α and β denote the average values of the price parameter α_i and observed product characteristics parameter β_i, respectively. The utility can be rewritten as:

$$u_{ijt} = (\alpha p_{jt} + \boldsymbol{\beta}\mathbf{x_{jt}} + \xi_{jt}) + (p_{jt}, \mathbf{x_{jt}})\boldsymbol{\Sigma}\boldsymbol{\nu_i} + \eta_{ijt} = \delta_{jt} + \mu_{ijt} + \eta_{ijt} \tag{4.1}$$

where $\boldsymbol{\nu_i}$ is a vector of the effect of consumer's unobservable characteristics on the parameters of price and observed product characteristics. δ_{jt} is the same across all consumers. The second component is a heteroskedastic disturbance that is different across all consumers. The market share of product j for a consumer i at time t is

$$s_{ijt} = \frac{e^{\alpha p_{jt} + \mathbf{x_{jt}}\boldsymbol{\beta} + \mu_{ijt}}}{1 + \sum_{k=1}^{n} e^{\alpha p_{kt} + \mathbf{x_{kt}}\boldsymbol{\beta} + \mu_{ikt}}}. \tag{4.2}$$

Integrating the market shares of each consumer in the equation above across the individual types generates the overall market share of product j in market t. It depends on the distribution of the heteroskedastic disturbance. As in BLP, I use simulation to perform this integration. I estimate the mean coefficients and standard deviations of the random coefficients.

4.2 Supply Estimation: BBL two-step estimator

Tracking used products' quantities by age creates a large number of state variables, and raises the curse of dimensionality in this dynamic oligopoly model estimation.[11] A full solution method by value function iteration is thus infeasible. I employ the two-step estimation method suggested by Bajari et al. (2007) to acceptably avoid the curse of dimensionality, as well as the possibility of multiple equilibria. The first step is estimating the statistical policy functions. The idea is to estimate the statistical policy functions as they are observed in the data. In the second stage, I construct moment conditions as Pakes et al. (2007) and use forward simulation of the optimal policy function from the first stage to estimate cost parameters. The goal is to find cost coefficients that rationalize the observed optimal policy functions in the data. To construct the moment conditions I use the first order conditions for the continuous choice variable of the theoretical model. This approach has been introduced in work by Berry and Pakes (2000). This method is simpler than estimating continuation values in the first step and is computationally-lighter than solving value functions as in fixed point algorithm.

4.2.1 First stage

I estimate transition probabilities of the state variables and optimal policy functions used to govern production and innovation cost on given states in the second stage.

Transition probabilities of state variables This section describes the estimation of the evolutions of the state vector. State variables in the reduced form regressions are exchange rates, oil prices, ratio, total market size, and used-good quantity. The ratio is defined as the number of product-lines produced by competitors over the number of product-lines produced by a firm. The used good quantity follows the transition path described in equation (3.2), (3.3), and (3.4).[12] The total market size and other exogenous variables follow an AR(1) process, $M_t = \mu_M + \rho_M M_{t-1} + \epsilon_{Mt}$.

[11] Aguirregabiria and Mira (2007) examine a class of pseudo maximum likelihood (PML) estimators that deals with these problems.

[12] Used airplanes from age 1 to age 6 are categorized as "young", and the ones from age 7 to age 16 are as "medium", and the rest of them from age 17 are as "old."

In order to guarantee that the AR(1) coefficient is stationary, I adopt the H-P filter.[13] Because the HP-filter also removes the mean of the time series I extract the mean of the trend component of the HP filtered data and add it to the cyclical component of the time series.[14]

Weight function from BLP The firm policy function depends on the other products of the firm and the existing used good quantities. This is a large dimensional state space that is difficult to capture in a reduced form regression. I therefore create a used quantity index and use it in reduced-form regressions of innovation and production policy functions, instead of the entire vector of used quantities.[15] The used good quantity index ω is as follows:

$$\omega_k = \sum_{k \in \mathcal{K}} \int_{\boldsymbol{\nu}} \frac{-\alpha_i s_{ij} s_{ik}}{\alpha_i s_{ik}(1 - s_{ik})} dF_{\boldsymbol{\nu}}(\boldsymbol{\nu}) \frac{s_k}{s_j} q_{kt} \tag{4.3}$$

The index is based on the results from demand function. The appendix describes the mathematical derivation in detail. The thinking is that this weight function captures the competition of the product with all existing used goods in the market. It condenses all the factors that influence a producer's decision-making into a single variable. The market shares used in the weighting function are computed using the relevant product characteristics and their coefficients obtained from BLP. Hence, the weighting function depends on all product characteristics since the market shares in it are computed from all relevant model characteristics from the BLP. I use market shares, S_{ij} and S_j, that are generated by BLP model instead of those from the data.

I use model-implied values only for years *after* the model was introduced. The observations in the regression were those after the plane was introduced. It would imply a missing value every year before the introduction of a model for innovation decision. Thus, I extent the weight function to years *before* model introduction. I removed all observations after a model introduction. So the 1 in the probit regression is my last observation and 0 before that for each model. The idea is

[13] *Hprescott* implements smoothing a time-series with the detrending procedure proposed by Hodrick and Prescott (1997) for the transformation of time-series data to focus on business cycle frequencies.

[14] Transition probabilities estimates of market size and oil prices have coefficients that are too close to 1. This means the two state variables are not stationary, but exploding. This ruins the simulation since it will not converge. To check whether it is stationary or explosive, one can use the "unit-root test" alternatively.

[15] It is hard to interpret the each coefficient of 20-40 used quantity variables. The used quantity index, i.e. weight function, simplifies the complex reduced-form regressions.

that firms at each year take the used quantity as given. Based on the used quantity, they compute a weight function (assuming they would introduce a model at the price and characteristics of the *actual* introduction year). But, they work with the actual oil price. Based on that, they again compute model-implied market shares and the weight function for years before the introduction. The used quantity index ω is estimated with transitions of market size M and used quantity $\hat{Q}_{fjk}$.

Innovation and production policy functions I estimate various model specifications for innovation policy and production policy. The second term, the weighted used-good quantity in the innovation regression does not include the corresponding quantities of good j of the explained variable I_{fjt} due to the construction of the data set and its non-existence at time t when a model is developed. Firms develop new products sequentially[16] that are numbered adjacently. The choice variable in innovation regression is 0 or 1 per year and per firm and identified by probit model. The ratio term works as the indicators of competition between manufacturers in new product development. The innovation policy function is as follows:

$$\mathbf{I}_{fjt} = \begin{cases} 1 \quad \text{if} \quad \gamma_1 + \gamma_2 \sum \omega_k + \gamma_3 \; exchange\ rate_t + \gamma_4 \; ratio_{ft} + \gamma_5 \; \omega_k * \; exchange\ rate_t \\ \qquad\quad + \gamma_6 \; \omega_k * \; ratio_{ft} + \zeta_{ft} + \varepsilon_{fjt} > 0, \\ 0 \quad otherwise. \end{cases} \tag{4.4}$$

The production policy function is:

$$\mathbf{q}_{fjt} = \gamma_1 + \gamma_2 \; \omega_k + \gamma_3 \; exchange\ rate_t + \gamma_4 \; ratio_{ft} + \gamma_5 \; \omega_k * \; exchange\ rate_t + \xi_{jt} + \zeta_{ft} + \gamma_6 \; \omega_k * \; ratio_{ft} + \varepsilon_{fjt} \tag{4.5}$$

where ω_k is the used quantity index and subscript f denotes firms and where $\mathcal{K}$ is the set of used market quantities.

[16] Once product1 is developed, then product2 is introduced, and next is product3, and so forth in turn.

4.2.2 Second stage

The second stage of BBL estimates the cost coefficients based on the policy functions found in the first stage.

Profit and Price Computation: First, I compute the price, the inverse demand function, in order to compute the profit (3.2). The inverse demand function p_{fjt} is computed numerically by matching the quantity from the policy function estimation q_{fjt} with the implied quantities from BLP market share and market size M. The equilibrium prices also depend on the used good quantities q^y,q^m,q^o and their prices.

$$\begin{bmatrix} q_{11} \\ q_{12} \\ \vdots \\ q_{FJ} \\ \hat{q}^y_{11} \\ \hat{q}^y_{12} \\ \vdots \\ \hat{q}^o_{FJ} \end{bmatrix} - M \begin{bmatrix} s_{11}(p_{11}) \\ s_{12}(p_{12}) \\ \vdots \\ s_{FJ}(p_{FJ}) \\ \hat{s}^y_{11}(\hat{p}^y_{11}) \\ \hat{s}^y_{12}(\hat{p}^y_{12}) \\ \vdots \\ \hat{s}^o_{FJ}(\hat{p}^o_{FJ}) \end{bmatrix} = 0 \tag{4.6}$$

Changing a single price is going to affect all market shares implied by BLP and is thus going to impact the entire system of equations above. Hence, I use a bisection algorithm to solve for the prices, iterating on prices one by one until a precision measure is reached. The algorithm procedure is illustrated in detail in Appendix.

First order condition Approach: According to the standard first order condition, the first order condition (3.8) has to hold for every firm f for every good k at time t. Basically the challenge here is to decompose this expression into components that can then be determined.

$$E_t\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial(\sum_j p_{fjt+\tau}q_{fjt+\tau}(S_{ft+\tau}))}{\partial q_{fkt}}\right]=\underbrace{\frac{\partial(\sum_j p_{fjt}q_{fjt}(S_{it}))}{\partial q_{fkt}}}_{(1)}+$$

$$+\underbrace{E_t\left[\sum_{\tau=1}^{\infty}\beta^{\tau}\frac{\partial(\sum_j p_{fjt+\tau}q_{fjt+\tau}(S_{ft+\tau}))}{\partial S_{ft+\tau}}\right]}_{(2)}\underbrace{\frac{\partial S_{ft+\tau}}{\partial q_{fkt}}}_{(3)} \tag{4.7}$$

Term (1) captures how increasing production of good k influences today's revenue. Terms (2) and (3) capture how increasing production today will affect the revenue in the future. In particular term (2) determines how future revenue changes when the state variable changes. This is then multiplied by the change of the state variable induced by the increase in production today. Term (3) is the simplest to solve. The state tomorrow that changes with today's production is the weighted used quantity tomorrow. Thus all that is needed to compute is the used quantity for tomorrow. This can be done using the transition functions estimated by OLS: how much the used goods change in the future when there is one more unit of the new good today. Having derived how the future used quantity changes it is then straightforward to compute how the future weighted quantity changes in the forward simulation. Let's take a look at (2) and decompose it a bit more (I am dropping the sum over τ and the expectation for simplicity): The first term in the following equation describes how revenue is influenced by changes in the quantity policy function as coming from the change in the state. The second term captures how changes in the quantities as induced by the change in the state influence the prices in the future,

$$\sum_j p_{fjt+\tau}\frac{\partial q_{fjt+\tau}}{\partial S_{ft+\tau}}+\sum_k\sum_j\frac{\partial p_{fjt+\tau}}{\partial q_{fkt+\tau}}\frac{\partial q_{fkt+\tau}}{\partial S_{fjt+\tau}}q_{fjt+\tau} \tag{4.8}$$

where $p_{fjt+\tau}$ can be obtained match BLP implied quantities with chosen quantities at each point in time during the forward simulation.[17] The element $\frac{\partial q_{fjt+\tau}}{\partial S_{ft+\tau}}$ is just the derivative of the policy function with respect to the state variable.$q_{fjt+\tau}$ is simply the policy function in that period given

[17]Computing prices is the most costly part in terms of computation. For details see the Appendix.

the state in the period as given. That leaves this term to be solved for: $\frac{\partial p_{fjt+\tau}}{\partial q_{fkt+\tau}}$.

$$\frac{\partial p_{fjt}}{\partial q_{fkt}} = -\frac{\partial R/\partial q_{fkt}}{\partial R/\partial p_{fjt}} \qquad where \qquad R = s_{fkt} - \int_{\boldsymbol{\nu}} \frac{e^{\delta_{fkt}+\mu_{ifkt}}}{1+\sum_{j=1}^{J}\sum_{f=1}^{F} e^{\delta_{jt}+\mu_{ifjt}}} dF_{\boldsymbol{\nu}}(\boldsymbol{\nu}) \tag{4.9}$$

$$\partial R/\partial q_{fkt} = 1/M_t \qquad \text{and} \qquad \partial R/\partial p_{fjt} = -\int_{\boldsymbol{\nu}} \alpha_i s_{ifkt} s_{ifjt} dF_{\boldsymbol{\nu}}(\boldsymbol{\nu}) \tag{4.10}$$

The equation R is coming from demand where i denotes consumer. Then I need to determine the first term (1). $\sum_j \frac{\partial p_{fjt}}{\partial q_{fkt}} q_{fjt} + \sum_j p_{fjt}$. I have already shown above how to solve for both terms. This leaves the presented discount value of the marginal cost to be solved for. Suppose the cost functions take the following form:

$$c(q_{fjt}) = c^q_{j1} q_{fjt} + c^q_{j2} q^2_{fjt} \tag{4.11}$$

$$c(I_{ft}) = (c^I + \epsilon^I_t)\{I \geq 0\} \tag{4.12}$$

where $\epsilon^I_t \sim N(0, \sigma^I)$ and $\epsilon^q_{fjt} \sim N(0, \sigma^q)$. There are a total of $2J$ unknown production cost coefficients and 2 unknown coefficients for the innovation cost. Then the two terms in equation 3.8 that need to be determined are

$$E_t\left[\sum_{\tau=0}^{\infty} \beta^\tau \frac{\partial C^q_{t+\tau}}{\partial q_{fkt}} | S_{ft}\right] = E_t\left[\sum_{\tau=0}^{\infty} \beta^\tau (c^q_{k1} + 2c^q_{k2} q_{fkt+\tau}(S_{ft+\tau})) \frac{q_{fkt+\tau}(S_{ft+\tau}))}{\partial S_{ft+\tau}} \frac{\partial S_{ft+\tau}}{\partial S_{ft+\tau-1}} \ldots \frac{\partial S_{ft}}{\partial q_{fkt}} | S_{ft}\right]$$

$$E_t\left[\sum_{\tau=0}^{\infty} \beta^\tau \frac{\partial C^I_{t+\tau}}{\partial q_{fkt}} | S_{ft}\right] = E_t\left[\sum_{\tau=0}^{\infty} \beta^\tau ((c^I + \epsilon^I_t) \frac{\partial I_{ft+\tau}(S_{ft+\tau}))}{\partial S_{ft+\tau}} \frac{\partial S_{ft+\tau}}{\partial S_{ft+\tau-1}} \ldots \frac{\partial S_{ft}}{\partial q_{fkt}} | S_{ft}\right]$$

$I(S_t)$ denotes the innovation policy function. The only term that needs to be derived is the derivative of the policy function with respect to the state. Finally, the derivations above can be used to construct the first set of J moment conditions: Let L be the number of simulation to run to calculate the expectation over shocks and let S be the total number of states in the sample.

The set of first order moment conditions are

$$M_1 \equiv \frac{1}{LS}\sum_{l=1}^{L}\sum_{S_{ft}=1}^{S}\left(\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial(\sum_j p_{fjt+\tau}q_{fjt+\tau}(S_{ft+\tau}))}{\partial q_{fkt}}|S_{ft}\right]-\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial C^{q}_{t+\tau}}{\partial q_{fkt}}|S_{ft}\right]\right.$$
$$\left.-\left[\sum_{\tau=0}^{\infty}\beta^{\tau}\frac{\partial C^{I}_{ft+\tau}}{\partial q_{fkt}}|S_{ft}\right]\right)^2 \quad \forall j,f \tag{M1}$$

These are a total of $F * J$ conditions. Next, I determine the conditions for developing a new aircraft model. The value of a continuing pursuing strategy σ_f firm can then be written as

$$\begin{aligned}
V_{ft}(S,\sigma(S)) &= \max_{q_{fjt},I_{ft}}\left\{\sum_{\tau=0}^{\infty}\beta^{\tau}E_t\Pi_{ft+\tau}\right\}\\
&= \max_{q_{fjt},I_{ft}}\left\{\sum_{\tau=0}^{\infty}\beta^{\tau}\left(\sum_{j\in\mathcal{J}}p_{fjt+\tau}q_{fjt+\tau}-\sum_{j\in\mathcal{J}}c(q_{fjt+\tau})-\{I_{ft+\tau}>0\}\,c(I_{ft+\tau})\right)\right\}\\
&= \max_{q_{fjt},I_{ft}}\{\Pi_{ft}+\beta EV_{ft+1}(S',\sigma(S)|S)\}\\
&= \max\left[\max_{q_{fjt}}\{\pi_{ft}+\beta EV_{ft+1}(S',\sigma(S)|S,I=0)\},\right.\\
&\qquad \left.\max_{q_{fjt}}\{\pi_{ft}-c(I_{ft})+\beta EV_{ft+1}(S',\sigma(S)|S,I=1)\}\right] && (4.13)\\
&= \max\left[V_f^0(S),V_f^+(S)\right] \qquad \textit{where} && (4.14)
\end{aligned}$$

$$\begin{aligned}
V_f^0(S) &= \max_{q_{fjt}\in\mathcal{J}}\{\pi_{ft}+\beta EV_{ft+1}(S',\sigma(S)|S,I=0)\} && (4.15)\\
&= \max_{q_{fjt}}\left\{\sum_{\tau=0}^{\infty}\beta^{\tau}\left(\sum_{j\in\mathcal{J}}p_{fjt+\tau}q_{fjt+\tau}-\sum_{j\in\mathcal{J}}c(q_{fjt+\tau})-\{I_{ft+\tau}>0\}\,c(I_{ft+\tau})\right)|I_{ft}=0\right\}\\
V_f^+(S) &= \max_{q_{fjt}\in\mathcal{J}}\{\pi_{ft}-c(I_{ft})+\beta EV_{ft+1}(S',\sigma(S)|S,I=1)\} && (4.16)\\
&= \max_{q_{fjt}}\left\{\sum_{\tau=0}^{\infty}\beta^{\tau}\left(\sum_{j\in\mathcal{J}}p_{fjt+\tau}q_{fjt+\tau}-\sum_{j\in\mathcal{J}}c(q_{fjt+\tau})-\{I_{ft+\tau}>0\}\,c(I_{ft+\tau})\right)|I_{ft}=1\right\}
\end{aligned}$$

where $\mathcal{J}$ is the set of products a firm owns. The idea behind the innovation policy estimation is that a firm f decides to innovate if the value after innovation V_f^+ minus the cost is larger than the value of not innovating, V_f^0. Let the probability to innovate be

$$\begin{aligned} Pr(innovate|S_{ft}) &= Pr(V_f^+(S_{ft}) - c_I - \epsilon_t^I \geq V_f^0(S_{ft})) \\ &= Pr(\epsilon_t^I \leq V_f^+(S_{ft}) - c^I - V_f^0(S_{ft})) \end{aligned} \tag{4.17}$$

where V_f^+ denotes the value associated with innovation and V_f^0 the value associated with no innovation of a new product. The probability can be computed using the normal CDF under the assumption that c_I is normally distribution with mean μ_I and standard deviation σ_I - those are to be estimated. Moment Condition 2 then is

$$M_2 \equiv \frac{1}{LS} \sum_{l=1}^{L} \sum_{S_{ft}=1}^{S} \left(Pr(innovate|S_{ft}) - \Phi\left(\frac{V_f^+(S_{ft}) - V_f^0(S_{ft}) - c^I}{\sigma^I} \right) \right)^2 \tag{4.18}$$

As I have only $2J$ first order conditions for quantity and 1 moment condition from the innovation probability I need to create 1 additional moment condition to solve for $2J+2$ unknowns. Let this moment condition be the covariance between the innovation cost shock and one of the states - weighted used quantity.

$$M_3 \equiv \frac{1}{LT} \sum_{l=1}^{L} \sum_{t=1}^{T} \left(\epsilon_t^I \sum_{k \in \mathcal{K}} \omega_k q_{kt} \right)^2 \tag{4.19}$$

Now there are as many equations as unknowns and we can solve

$$\min_c M \quad \text{where} \quad M = [M_1 M_2 M_3]' \tag{4.20}$$

Computational Algorithm For each state S_{it} in the data I use the following procedure:

1. Starting from an initial state S_{it} draw a vector of random shocks ε_{it} for policy functions. In order to compute the expectation I do this and the following steps $L = 30$ times.

2. Calculate policy choices, market shares and prices based on the shock draws using the estimates from stage 1.

3. Update states to S_{it+1} using the transition functions. Draw new random shocks for t+1.

4. Repeat steps 2 and 3 for T=300 periods. At each period add the new contribution to marginal revenue and marginal cost.

5. Finally, after doing this L times compute the average across all L simulations.

6. Make an initial guess for cost parameters: $(\hat{c}^q_{j1}, \hat{c}^q_{j2}, \hat{\mu}_I, \hat{\sigma}_I)$. Thus there are a total of $2J + 2$ unknown coefficients. Then construct moment conditions using fsolve in Matlab and this initial guess. Matlab updates guess until a solution is found. Since updating the cost coefficient does not alter policy functions or prices, the computation of updated cost coefficients is rather fast.

5 Estimation results

5.1 Demand estimation results

The random coefficient logit demand estimation result is reported in Table 1. There are random coefficients on price, constant, and fuel efficiency. The price elasticity of demand is estimated to be -4.53. The hourly wage of aerospace manufacturing sector and the aluminum prices, i.e. cost shifters, are used as a set of instruments to deal with the possible endogenous regressor. The real wages are the combination of both the U.S. real wage and the corresponding countries' real wage in Europe. The wages are adjusted to 2005 currency. The product dummies can capture the consumers' product loyalty. The new good dummy captures consumers' sensitivity to new goods. Age is the proxy of quality deterioration of used products. The older aircraft become, the smaller the market share of the good is. The graph 5 shows the dispersed distribution of own price elasticities of new goods and all of them are below zero. The highest own price elasticity is from the new Boeing 787.

5.2 Dynamic oligopolistic game estimation results

5.2.1 Estimates of transition probability

The Table 4 presents the evolution of used good quality estimated by the equations (4.5), (4.6), and (4.7). The transition rate from new airplane to used airplane of age stage "young" is 0.557. The transition rate of today's young airplane staying at age stage "young" next period is 0.563 while the one of its moving to age stage "medium" is 0.437. Table 3 shows the transition probability estimates of other exogenous state variables. I use the Hodrick-Prescott high-pass filter to estimate the cyclical component of state variables such as market size and oil price. I provide the evolution of each exogenous state variable in Table 3. They are all stationary over time and significant in 0.1%.

5.2.2 Production and innovation policy results

The optimal policy estimates are presented in Table 5 and Table 6. The used quantity index is negative by construction. To make the relationship between the production decision and the used good quantity understandable, I use an absolute value of the weight function so that the used quantity index has a positive value. This means firms produce new goods less when there are more used goods available in the market. Also, firms develop a new airplane model more frequently when there are more used goods.

Optimal innovation policy function: This function is estimated by probit. The estimate of the used quantity index is highly significant with positive sign in the (1) specification and is significant at a 10% significance level in the (3) specification. This could mean that a higher used-good market share indicated more frequent launching announcements on new products. I included time trend. The magnitude and sign do not change noticeably, only the level of significance deteriorates. Given that I only use the coefficient and not use the standard error of the regressor, I use the specification (3). The interaction terms are negligible.

Optimal quantity policy function: The estimate of used quantity index is highly significant within 1% with negative sign in the (1) specification and is significant in 5% significance level in the (3) specification. The relationship between the used quantity index and firms' production decision is negative. That implies firms possibly reduce their new good quantity in response to an increase in used good quantity. In addition, the significant exchange rate means when U.S. dollar or Euro is weaker, Boeing or Airbus has a relative advantage to the foreign competitors, respectively. Time trend does not change the sign and the difference in coefficient is only 0.5. Hence, I use the specification (3).

5.2.3 Impulse-response

Before I study counterfactuals and policy experiments, I evaluate the estimated policy functions. The purpose of this exercise is to explore sensible economic implications of the reduced-form policy estimates, and evaluate the magnitude of the parameters. This exercise illustrates the relationships between innovation, production decisions, and state variables under the assumption that the estimated policy functions remain the same. This is not a counterfactual, but simple impulse-response exercises because the reduced-form estimated optimal policies in the first stage are statistical representations of the theoretical policy functions that can be obtained from solving the Bellman equation. I find the theoretical policy functions by solving the Bellman equation in the counterfactual section.

Currency depreciation effect I simulate hypothetical situations such as the US dollar depreciating by 15% and then mean-reverting to its long run average. The result is presented in figure 8. The shock leads to a 3% increase in innovation rate and a 12% increase in production. This is preliminary anecdotal evidence that aircraft manufacturers' profit is driven not only by learning and forgetting but also by the fluctuation of the exchange rate.

No trade in used-goods markets In this experiment I shut down the used-goods market permanently by setting the used good quantity permanently to zero. I then compare in simulation how the implication of this model differs from the baseline model with active used-goods markets. The results, shown in table 7, predict that the probability of manufacturers' developing new product models decreases to 14.31% on average without the active used-good markets, whereas the probability of innovation is 36.96% on average with the used-good markets. This implies that manufacturers would not only produce less quantities in order to indirectly control the used-good quantities as the Durable Good Theory predicts, but also innovate more new products to increase profits in the presence of the active used-goods market.

5.2.4 Dynamic cost estimation results

I use the second stage of BBL in the cost estimation. The cost estimation results presented in table 10 show that innovation cost is on average about 5 billion dollars adjusted to 2005 US dollars. This estimate is reasonable compared to the average development cost 5.205 billion dollars addressed in Benkard (2004).[18] Development costs of more recently developed aircraft are well known to be much bigger than the ones developed from the 1970s through the 1990s. Given that I assume the development cost parameters are the same across all aircraft, the estimated development costs seem to be a bit smaller compared to the cost of the recently developed aircraft such as 330, 777, A380, and 787. I interpret this by introducing the government subsidies given to Airbus and Boeing, which have been a source of international trade dispute between the US and the EU. The estimated cost parameters contain the government subsidies so that it can be smaller than actual investment incurred by introducing a new aircraft model.

The quadratic production cost estimates shown in table 9 suggest that the markup of more recently developed airplanes is smaller than that of those developed earlier. The first column presents a constant marginal production cost and the third column presents an increasing production cost term in producing a unit of aircraft. The unit is one million US dollars. Comparing the model-predicted prices with actual prices observed in the data accomplishes a rigorous test of the model. The table 8 shows that the predicted average prices do not deviate much from the actual

[18]Development cost of L1011, 747, 777, 380 was known to be 2.52 billion, 3.6 billion, 4.7 billion, 10 billion U.S. dollars respectively. Recently Airbus addressed that the development cost of A380 at the end was much more than initially estimated. The recently adjusted amount is about 17-18 billion dollars.

average price-per-product, except product 3 of firm1 and product 5 of firm 2. The actual prices of the two products are much lower than the predicted prices.

6 Counterfactuals & policy experiments

I solve the Bellman equation to obtain the optimal theoretical policy functions and perform policy experiments. The BBL two-stage estimation makes the dynamic cost estimation with a very large state space feasible. However, the policy functions generated by the data in the first stage will not hold any more if the policy regime changes. Hence, I use value function iteration to analyze hypothetical counterfactuals.

Counterfactual: Innovation and used-goods replacement and no product exit In this section, I examine the importance of innovation in the presence of used good markets by solving the bellman equation. I study a monopoly with 2 new goods and 2 used-goods. A monopolist has two choices: production and innovation. The firm starts with one product. Next period, he faces competition from his own used good in the market. He develops a new product at some point, and the newly developed product shows up next period as the second used good. In other words, after the firm faces competition from his own used aircraft1 it decides when to develop aircraft2. Once aircraft2 is developed, the old aircraft 1 exits and there are 2 goods in the market. I compare this case with the case that the used aircraft1 stays in the market so that there are 4 goods in the market as a consequence of the firm's innovation. The optimal innovation policy functions in the two cases are very different. I use value function iteration to solve for the optimal policy functions.

The results with product exit predict that used-goods quantity and firms' innovation rate have a positive relationship as shown in graph 9. This implies that innovation is spurred by the increase in quantity of used goods. Under product exit, a profit maximizing monopolist loses the revenue of aircraft1 when introducing aircraft2. Therefore the problem is similar to an optimal stopping problem. It is optimal to produce aircraft1 until the innovation cost draw is sufficiently low. On the contrary, the innovation incentive decreases with an increase in used-good quantities when new products does not replace the existing line. This leads firms to innovate as soon as possible. The difference is explained by the graph 11. The graph depicts the percent change of the first good price as a function of second new good quantity with high and low of used-good market size. This shows that the first new good price is more sensitive to the second new good quantity when the used-good market is large. Hence, a firm would innovate as early as possible when less used goods are available and higher profits from innovation are expected. The optimal production policy functions are downward-sloping with responses to the used-goods quantity in both cases as expected. When a firm can replace the existing line with new products, the quantity produced diminishes faster in response to the used-good quantity, relative to the case without product exits.

This finding means that a firm is more likely to innovate when the used-good quantity increases when it is allowed to replace the existing good with a newly developed good. A firm is going to innovate immediately in response to the increasing used-good quantity if it produces the existing line and new products at a time without product replacement. In terms of producer profit it must be true that profits in the case of no product exit must be larger than in the case of replacement, in which firms are forced to discontinue the first product after introducing the second product. This is detrimental relative to the no product exit case.

I simulated the two cases for 50 years for 10,000 times. The results show that The averaged innovation rate over time increases rapidly in both cases. Especially, when new products do not replace the existing line firms innovate new product by about 9 periods earlier than when new products replace the existing line.

Policy experiments 1: A reduction in government R&D subsidy Based on the findings of the first counterfactual, I examine the effect of a change in the government subsidy policy. The government subsidy to production lowers the production cost and the R&D subsidy to innovation reduces the investment cost. According to the World Trade Organization (WTO) , both Airbus and Boeing received illegal government subsidies even after the 1992 bilateral trade agreement. The WTO ruled that both parties must remove their illegal R&D subsidy and \$3 billion of illegal production subsidies in March 2012. I first study the government R&D subsidy policy, then examine the production subsidy.

I add the reported R&D subsidy amount to the innovation cost function while assuming that there is a reduction of the R&D subsidy in order to see the effect of the subsidies on firms' innovation and production, used-goods markets, and welfare.

The results predict that reducing government R&D subsidies reduces not only firms' innovation but also firms' production under monopoly in the product-replacement case. A 10% reduction of the R&D subsidy results in no more than a 2% decrease in innovation as shown in graph 9. The 20-year simulation result shows that the total production diminishes by 5% from a 10% R&D subsidy reduction. Moreover, a 50% reduction of the R&D subsidy leads to a roughly proportional decrease in the innovation rate and slows down the innovation timing. However, in the multi-product production case, the 50% R&D subsidy reduction does not have an impact on total production after the second period and postpones innovation timing by only one period.

A reduction in innovation subsidy reduces firm profits and insignificantly reduces consumer welfare for both scenarios– replacement and no product exit. Table (11) displays the results for both cases. Row 1 shows the results for the replacement case: Consumer welfare decreases by \$133.47 million or 5.56%. Firm profits decrease by \$1.133 billion or 12.55%. So, a reduction in innovation subsidy leads to a significant delay in the introduction of the second good. The second good is more technologically advanced and provides consumers with higher utility. Thus the delay results in a decrease of consumer welfare. Producer welfare declines for two reasons: First, innovation is simply more expensive which in turn reduces firms profit. Second, a delayed introduction of the second model leads to an increase in the quantity of the used first good. This reduces prices that the monopolist can yield on the market.

In the case of no product exit, welfare also decreases, but the decline is much smaller as shown in Row 2 of table (11). Firm profits decrease by \$ 227 million or 1.28% while consumer welfare decreases by \$1.28 million or 0.005%. As can be seen from the impulse response in this case the introduction of the second model sees only a very minor delay. Consequently the effects on welfare are rather small. The producer profits decreases more than consumer welfare, as the producers have to bear the reduced investment subsidy. The prices producers can yield on the market do not depend on the subsidy but only on existing used market quantities and outside option. Thus the producer is not able to roll over the cost to the consumers.

Policy experiments 2: Termination in government production subsidy I assume a 3 billion dollar production subsidy is evenly distributed over 20 years. About 150 million dollars are given to a firm per year. I assume each product's production takes up an equal amount of subsidy. In simulations this corresponds to roughly 4-5% of unit production costs. on average. In this policy experiment I examine the impact of an elimination of the production subsidy. The results predict a reduction in the illegal production subsidy– which implies a 4% increase in unit production cost, leads to a larger decrease in the innovation rate than the 50% R&D subsidy reduction case and diminishes total production. Unlike the R&D subsidy reduction, the production subsidy reduction alters both firms' production and innovation strategies. Furthermore, the innovation is delayed one period, similar to the R&D subsidy reduction case.

Welfare decreases for both producers and consumers when production subsidies are cut. The effects of the production subsidy decrease leads to a 15.96% decline in producers profits ($ 1.499 billion). Relative to the innovation subsidy case the reduction in production subsidy leads to an even longer delay until the introduction of the second product. This leads to an larger loss for producers than under the innovation subsidy experiment. Consumer welfare declines by $191 million or 8.18%.

7 Conclusion

This paper shows aircraft manufacturers' strategy responses to active used-goods markets. The trade-off between production level and innovation level is well-documented in the first part of this paper: Used-good markets cause manufacturers to decrease production while increasing innovation. They differentiate their products and increase the product quality in terms of fuel efficiency and structural efficiency to compete with their own used products. This new product development allows them to recover market share diminished by the active used-goods markets. I also estimate the dynamic production cost for each aircraft and the dynamic innovation cost. I make use of the estimates in order to examine the controversial U.S. and E.U. government subsidy policy for Boeing and Airbus in a rigorous model framework. I find that a reduction in the R&D subsidy not only diminishes the innovation rate but also leads to a decrease in total production under the product-replacement case. The main findings predict that the R&D subsidy reduction has a long-term negative effect on innovation in the product-replacement case, whereas it has a short-term negative effect on innovation in the multi-product production case. Terminating production subsidies reduces both innovation and quantity production more than R&D subsidy reduction. The welfare analysis showed that producers are more significantly affected by a reduction in subsidies than consumers. In particular under the multi-product case the effects on consumer welfare are minor.

In ongoing work, I am studying the interaction of airline competition and aircraft portfolio decisions. Extending my data set to narrow-body aircraft, I have an exact account of airlines' product portfolios over time. Combining my data set with departure and destination information of Transtat from the Bureau of Transportation Statistics, I construct a panel data set containing competition information of airlines on all routes in the US. Using this measure of competition I ask if airlines that operate in a more competitive environment invest more into their aircraft portfolio than airlines that operate in less competitive markets.

Table 1: Demand estimation results

Random coefficient logit		
Explained variable:	Market share of good j at time t	
Explanatory variables	coefficients	robust standard error
Price/100	-4.52943	0.78409
Fuel efficiency*	0.01443	0.00667
Age	-0.10568	0.02126
Range	0.04299	0.01104
Seats	0.01310	0.00347
Max take-off thrust†	0.00284	0.00101
Oil price	-0.05982	0.03007
New good dummy	included	
Product dummy	included	
GMM obj. function	71.171	

The set of instruments is the hourly wage of manufacturing sector and the aluminum prices, i.e. cost shifters. Random coefficients on prices, fuel efficiency, and constant. I try a specification with the additional characteristic *Length overall* measured in m. It deteriorates *price* and *range* coefficients. So, I report the specification without *Length overall*. All prices are adjusted to 2005 U.S. dollars. †Max take-off thrust is used instead of structural efficiency simply because the replacement produces bigger price coefficient. The results with structural efficiency can be reported upon request.

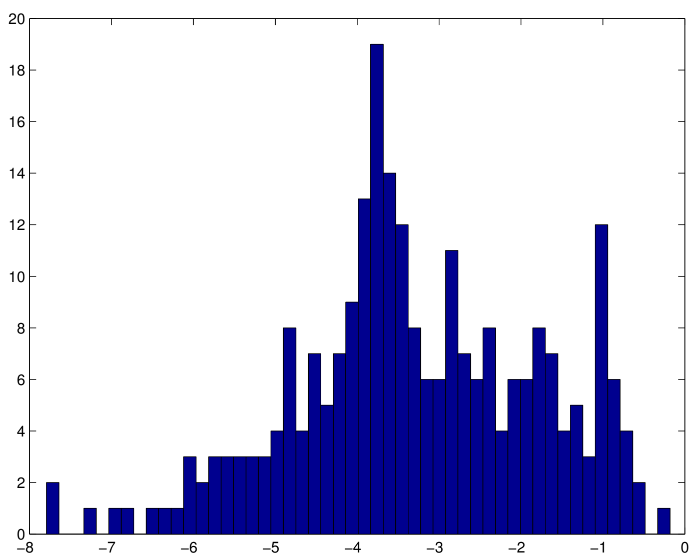


Figure 5: Distribution of Own price elasticities of new goods

Cross price elasticity and Own price elasticity tables for Used-Goods and for New-Goods are illustrated in Appendix.

Table 2: Cross Price Elasticity of New Aircraft with respect to Used Aircraft

New	380^Y	$11F^M$	$11F^Y$	777^Y	777^M	340^Y	340^M	340^O	310^O	310^M	310^Y	11^O	11^M	11^Y	330^O	330^M	330^Y	767^O	767^M	767^Y	300^O	300^M	300^Y	1011^Y	1011^M	10^O	10^M	10^Y	747^Y	747^M	747^O
787	0.007	0.000	0.000	0.033	0.052	0.069	0.082	0.000	0.026	0.016	0.000	0.075	0.000	0.058	0.046	0.016	0.235	0.069	0.016	0.149	0.060	0.044	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.045	0.033
7478	0.004	0.017	0.000	0.020	0.021	0.132	0.064	0.000	0.015	0.004	0.000	0.057	0.000	0.083	0.036	0.010	0.143	0.041	0.007	0.132	0.038	0.013	0.000	0.000	0.001	0.000	0.000	0.001	0.023	0.037	0.016
380	0.002	0.014	0.000	0.030	0.015	0.246	0.048	0.019	0.015	0.001	0.012	0.019	0.000	0.061	0.080	0.012	0.064	0.057	0.009	0.236	0.038	0.007	0.000	0.000	0.001	0.000	0.000	0.001	0.027	0.031	0.015
11F	0.000	0.002	0.063	0.044	0.003	0.166	0.013	0.039	0.019	0.000	0.113	0.000	0.000	0.090	0.056	0.010	0.098	0.065	0.011	0.188	0.051	0.015	0.000	0.007	0.007	0.000	0.021	0.005	0.031	0.050	0.016
777	0.000	0.004	0.027	0.027	0.006	0.169	0.034	0.032	0.017	0.001	0.093	0.019	0.009	0.091	0.064	0.010	0.097	0.052	0.009	0.177	0.051	0.010	0.000	0.007	0.004	0.002	0.011	0.004	0.034	0.037	0.014
340	0.000	0.003	0.026	0.026	0.005	0.150	0.030	0.034	0.016	0.000	0.091	0.016	0.016	0.099	0.074	0.010	0.099	0.056	0.009	0.184	0.054	0.011	0.000	0.013	0.005	0.002	0.014	0.005	0.035	0.039	0.015
310	0.000	0.001	0.034	0.028	0.002	0.115	0.030	0.036	0.019	0.000	0.120	0.016	0.016	0.101	0.060	0.014	0.106	0.058	0.009	0.152	0.068	0.010	0.000	0.015	0.006	0.003	0.018	0.006	0.034	0.040	0.015
11	0.000	0.000	0.000	0.000	0.000	0.026	0.000	0.029	0.000	0.000	0.073	0.000	0.059	0.150	0.067	0.000	0.121	0.057	0.000	0.166	0.041	0.010	0.000	0.046	0.012	0.005	0.027	0.011	0.044	0.041	0.016
330	0.000	0.002	0.016	0.018	0.005	0.093	0.022	0.021	0.011	0.001	0.059	0.013	0.015	0.106	0.061	0.008	0.104	0.047	0.006	0.171	0.059	0.009	0.040	0.026	0.007	0.020	0.019	0.006	0.042	0.043	0.018
767	0.000	0.002	0.016	0.017	0.005	0.090	0.021	0.020	0.011	0.001	0.057	0.013	0.015	0.102	0.060	0.008	0.101	0.046	0.006	0.168	0.058	0.009	0.042	0.027	0.007	0.022	0.020	0.006	0.044	0.043	0.017
300	0.000	0.001	0.012	0.013	0.004	0.070	0.016	0.016	0.008	0.000	0.043	0.010	0.012	0.077	0.044	0.006	0.077	0.034	0.005	0.149	0.044	0.006	0.057	0.024	0.005	0.037	0.018	0.004	0.059	0.041	0.013
1011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.006	0.000	0.000	0.083	0.014	0.000	0.118	0.024	0.000	0.086	0.016	0.000	0.093	0.037	0.000
10	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.008	0.000	0.000	0.019	0.000	0.017	0.069	0.020	0.000	0.056	0.017	0.000	0.115	0.028	0.003	0.089	0.032	0.005	0.058	0.020	0.004	0.081	0.038	0.009
747	0.000	0.001	0.011	0.010	0.001	0.064	0.011	0.015	0.006	0.000	0.038	0.004	0.011	0.065	0.031	0.004	0.059	0.025	0.003	0.127	0.032	0.004	0.055	0.019	0.003	0.037	0.014	0.003	0.071	0.034	0.009

Cross price elasticity and Own price elasticity tables for Used-Goods and for New-Goods are illustrated in Appendix.
Appendix is provided in $http://people.bu.edu/mjkim07$

Table 3: Transition probabilities of exogenous state variables

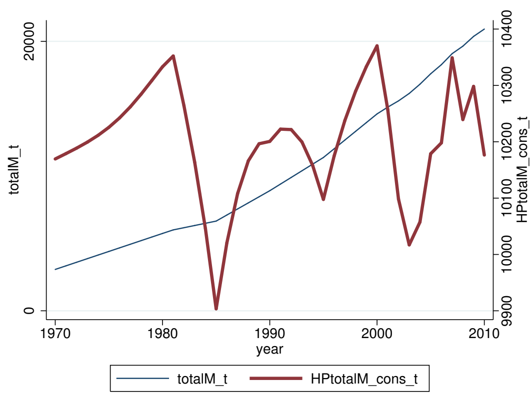
	ρ	μ
TotalM	0.726***	2796.1*
	(0.116)	(1186.4)
Oil_Price	0.364***	18.05***
	(0.0738)	(1.909)
EXC_rate	0.650***	0.437*
	(0.144)	(0.181)
Aluminum price	0.436**	826.5***
	(0.125)	(174.0)

Robust standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Total M and oil price are de-trended by H-P filter

Table 4: **Transition matrix of used-good quantity $\widehat{Q}$**

	$\widehat{Q}^{young}_{fjt+1}$	$\widehat{Q}^{medium}_{fjt+1}$	$\widehat{Q}^{old}_{fjt+1}$	$Disappear_{fjt+1}$
$\widehat{Q}^{new}_{fjt}$	0.557	0	0	0.443
$\widehat{Q}^{young}_{fjt}$	0.562	0.437	0	0.001
$\widehat{Q}^{medium}_{fjt}$	0	0.703	0.209	0.088
$\widehat{Q}^{old}_{fjt}$	0	0	0.848	0.152

The endogenous state variable $\widehat{Q}$ has four age(quality) ladder: new, young, medium, and old. Some of aircraft each age level can disappear.



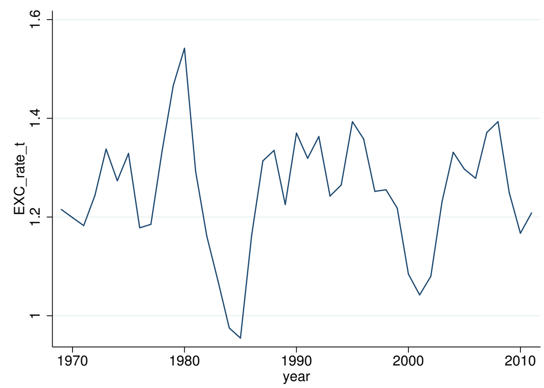
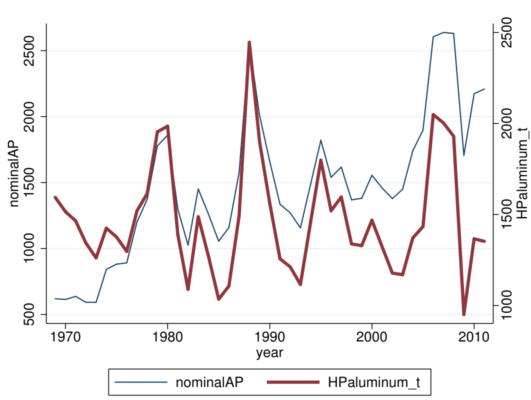


Figure 6: Stationary evolutions of total market size M and exchange rate: U.S. Dollar over Euro



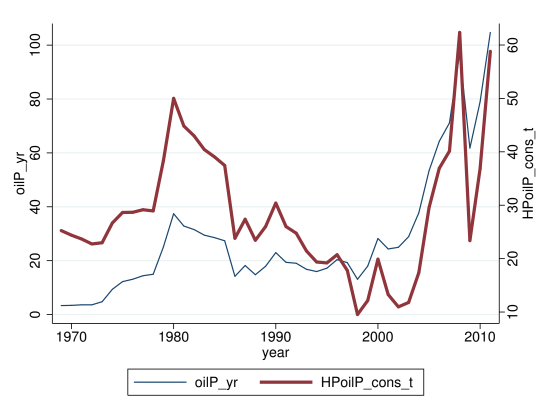


Figure 7: Stationary evolution of aluminum price(AP) and crude oil price

The solid thick line stands for the H-P filtered stationary evolution of state variable.
The thin blue line represents the actual values observed in the corresponding data sets.
The crude oil price is a proxy of the jet fuel price.

Table 5: Optimal Policy Function Estimation: quantity production

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Q_{fjt}	Q_{fjt}	Q_{fjt}	Q_{fjt}	Q_{fjt}	Q_{fjt}	Q_{fjt}	Q_{fjt}
Used quantity index	-2.584***	-2.670***	-2.576*	-1.799	-1.570	-1.601	-5.158	-4.269
	(0.798)	(0.803)	(1.368)	(1.845)	(1.041)	(1.067)	(5.186)	(5.688)
Exchange rate	15.64**	22.57***	18.32**	16.730**	3.370	4.965	10.303	9.095
	(7.483)	(8.489)	(8.012)	(7.053)	(13.915)	(15.715)	(8.741)	(9.196)
ratio†	-1.914***	-1.876***	-2.415**	-1.087	2.877	2.759	-1.148	-2.184
	(0.514)	(0.505)	(1.159)	(1.277)	(3.872)	(4.986)	(7.447)	(8.144)
Oil price	-0.0843	-0.0555			-0.064	-0.059		
	(0.069)	(0.0715)			(0.090)	(0.093)		
Wage	0.208	0.188			0.557	0.543		
	(0.362)	(0.361)		(0.570)	(0.581)			
Aluminum price		-0.00525*				-0.001		
		(0.003)				(0.003)		
Used quantity index*Exchange rate			-0.048	0.021			-0.081	0.022
			(0.055)	(0.069)			(0.073)	(0.069)
Used quantity index*ratio			0.167	-0.021			2.232	2.253
			(0.301)	(0.331)			(3.117)	(3.163)
Constant	20.23**	19.04**	21.81**	884.563***	14.890	14.867	24.058	424.680
	(9.141)	(9.202)	(9.774)	(277.341)	(16.589)	(16.603)	(17.779)	(444.370)
Firm fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Product fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time trend	No	No	No	Yes	No	No	No	Yes
Observations	319	319	319	319	217	217	217	217

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

† the ratio of the number of product-lines introduced by competitors to the one introduced by its own firm.

Including time trend does not change the signs but only the level of significance.

Table 6: Optimal Policy Function Estimation: innovation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Inno	Inno	Inno	Inno	Inno	Inno	Inno	Inno
Used quantity index	0.259***	0.300***	1.642*	1.525	0.217**	0.209*	1.349	1.191
	(0.0948)	(0.113)	(0.927)	(1.187)	(0.098)	(0.124)	(1.003)	(1.096)
Exchange rate	1.162	0.704	6.885**	6.461*	1.260	1.327	6.140*	5.573
	(0.773)	(0.943)	(3.341)	(3.430)	(0.952)	(1.106)	(3.661)	(3.747)
ratio†	0.153	0.100	-0.140	-0.012	-0.027	-0.021	-0.058	0.092
	(0.228)	(0.216)	(0.437)	(0.464)	(0.283)	(0.279)	0.501	(0.575)
Oil price	0.036*	0.035*			0.039*	0.040*		
	(0.020)	(0.019)			(0.021)	(0.021)		
Wage	-0.254	-0.329			-0.235	-0.225		
	(0.263)	(0.286)			(0.292)	(0.308)		
Aluminum price		0.0003				-0.0001		
		(0.0003)				(0.0003)		
Used quantity index*Exchange rate			-1.263	-1.114			-0.942	-0.764
			(0.844)	(0.900)			(0.853)	(0.921)
Used quantity index*ratio			0.121	0.107			0.015	-0.004
			(0.117)	(0.111)			(0.157)	(0.167)
Constant	1.075	2.650	-10.612**	-44.445	0.916	0.711	-9.624**	-45.679
	(5.668)	(5.931)	(4.268)	(65.069)	(6.242)	(6.545)	(4.468)	(68.140)
Firm fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Product fixed-effects	No	No	No	No	No	No	No	No
Time trend	No	No	No	Yes	No	No	No	Yes
Observations	117	117	117	117	80	80	80	80

Standard errors in parentheses

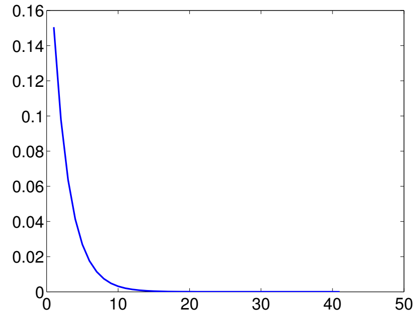
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

(1)-(8): binary choice: 1 if innovation is placed, otherwise 0.

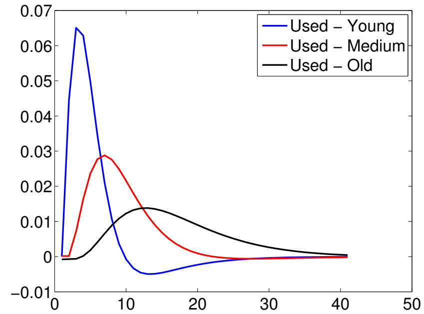
† the ratio of the number of product-lines introduced by competitors to the one introduced by its own firm.

Including time trend does not change the signs but only the level of significance.

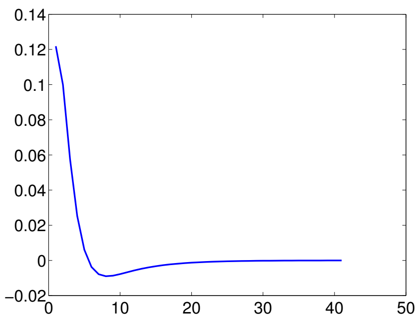
Figure 8: Impulse-response check: 15% depreciation of the currency shock (i.e. U.S. dollar for Boeing and Euro for Airbus). Zero line stands for a stationary point.



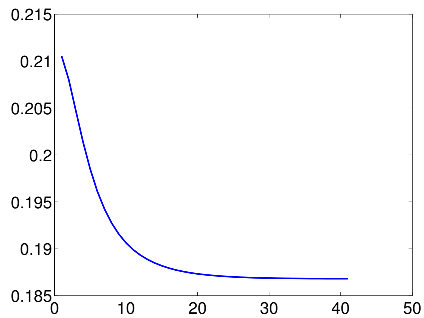
(a) shock in exchange rate (% dev)



(b) used goods' response (% dev)



(c) quantity response (% dev)



(d) innovation prob. response

Table 7: Impulse-response check: all airlines are forced not to trade aircraft in the secondary market and shuffle aircraft every year.

	active trade of used-goods	no trade of used-goods	
	mean quantity	mean quantity	% change
Firm1			
production of product1	21.70	36.27	67.15
production of product2	25.35	40.17	58.41
production of product3	10.03	21.86	117.96
production of product4	20.85	35.23	68.93
production of product5	16.23	29.93	84.51
Firm2			
production of product1	31.88	47.17	47.97
production of product2	33.15	47.93	44.57
production of product3	59.52	75.03	26.06
production of product4	9.89	21.99	122.27
production of product5	6.73	16.99	152.37
probability of innovation	0.3696	0.1431	−61.28

Idiosyncratic shocks are averaged by simulating along 30 paths of length 100 each.

Table 8: Dynamic calculation: mean prices

products per firm	Mean prices	% deviation†
product1firm2	95.75	0.83
product1firm1	71.02	-9.56
product2firm2	57.15	-11.36
product2firm1	86.80	0.85
product3firm1	227.00	26.11
product3firm2	100.38	-8.75
product4firm1	99.26	-6.58
product4firm2	252.14	6.61
product5firm1	241.17	-2.67
product5firm2	287.12	58.99

Prices are expressed in terms of **million** U.S. dollars.
Prices are adjusted to 2005 U.S. dollars.
† % deviation of model-implied prices from the observed-prices on average
I find dynamic prices by matching quantities implied by the estimated policy function with the quantities implied by the demand(BLP) estimates.
I simulate the discounted value function for 100 time periods forward and then simulate the process 30 times to average the shocks for each state. I report the averaged prices per product found by the process.

Table 9: Dynamic Parameter Estimates: Production Cost

Parameter:	c^q_{fj1}	s.e.	c^q_{fj2}	s.e.
product1firm2	74.39	20.77	0.6335	0.43
product1firm1	58.46	14.96	0.4369	0.37
product2firm2	23.88	7.02	0.7763	0.39
product2firm1	80.85	8.41	0.3256	0.16
product3firm1	94.45	25.63	0.6532	0.28
product4firm1	41.03	13.12	0.8892	0.31
product3firm2	35.18	10.36	0.3176	0.29
product5firm1	93.15	29.09	0.8208	0.35
product4firm2	156.53	32.85	0.9552	0.43
product5firm2	45.54	9.52	0.0195	0.01

Prices are expressed in terms of million U.S. dollars.
c^q_{fj1} is a constant marginal cost.
c^q_{fj2} is the second term, an increasing function, of the production cost function

Table 10: Dynamic Parameter Estimates: Innovation Cost

Parameter	Innovation cost	s.e.
c^I_μ	4958.49	783.58
c^I_σ	425.96	107.24

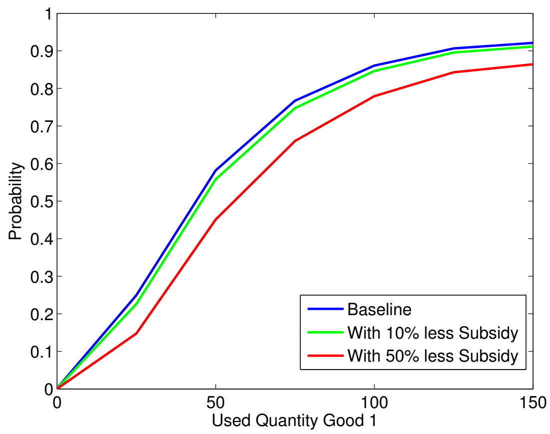
The values are expressed in terms of **million** U.S. dollars.
c^I_μ is mean and c^I_σ is standard deviation drawn from mean zero distribution.
Development cost of L1011, 747, 777, A380 was known to be 2.52 billion, 3.6 billion, 4.7 billion, 10 billion U.S. dollars respectively according to Benkard (2004). However, the realized development cost of A380 is approximately 18 billion U.S. dollars.

Table 11: Welfare Analysis

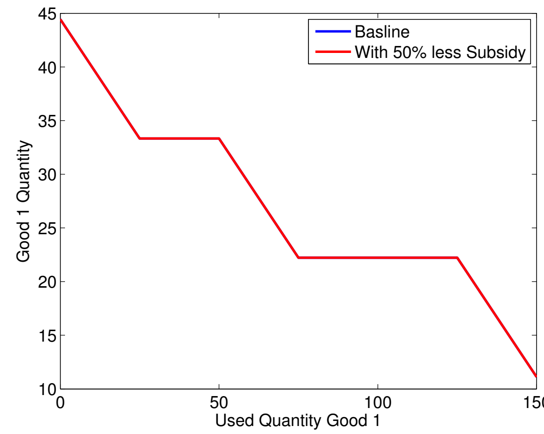
		Producer profit	Consumer welfare
50% R&D subsidy reduction	Replacement	-12.55%	-5.56%
		(-1133)	(-133.47)
	No product exit	-1.28%	-0.0049%
		(-227.62)	(-1.28)
Terminating production subsidy	Replacement	-15.96%	-8.18%
		(-1499)	(-191)
	No product exit	5.37%	-0.69%
		(951.45)	(-19.14)

This table show % change in producer profit and consumer welfare from the base-line model with full subsidies.
I simulate this for 50 periods for 10,000 times and sum it up over 50 years.
Consumer welfare is computed with BLP based on the modified method described in *Measurement of Consumer Welfare (Nevo, 2012).*
Million US dollars in parentheses
Both production subsidy reduction and R&D subsidy reduction have negligible influence on consumer welfare in terms of million US dollars.

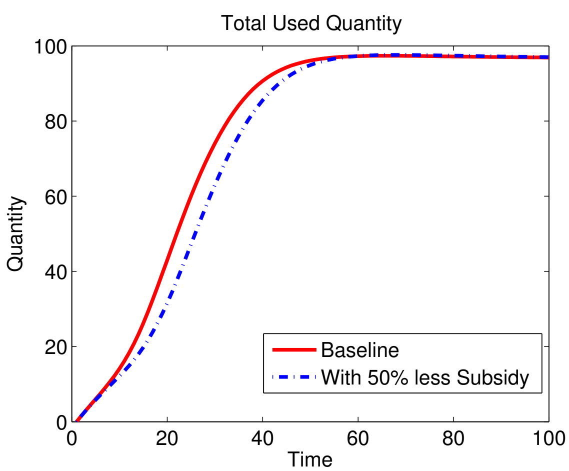
Figure 9: **Counterfactual: R&D subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product replaces the existing line, part(1)



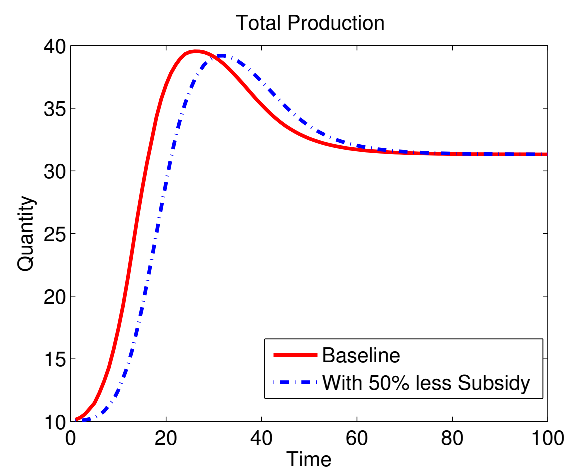
(a) Innovation policy function



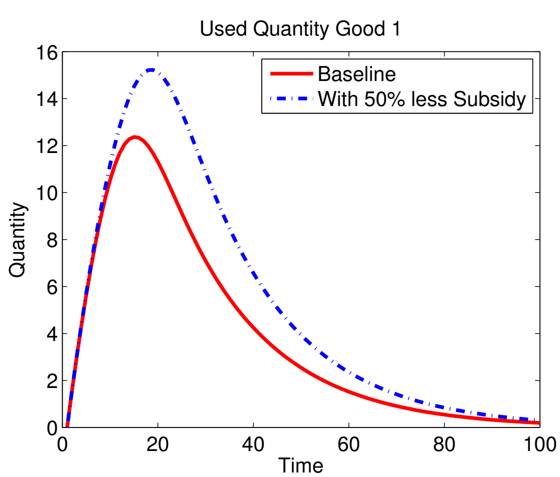
(b) Quantity policy function



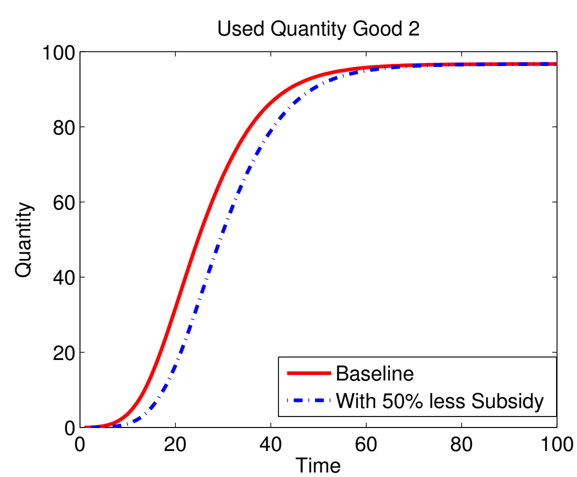
(c) 100-year simulation: Total used goods quantity



(d) 100-year simulation: Total quantity production

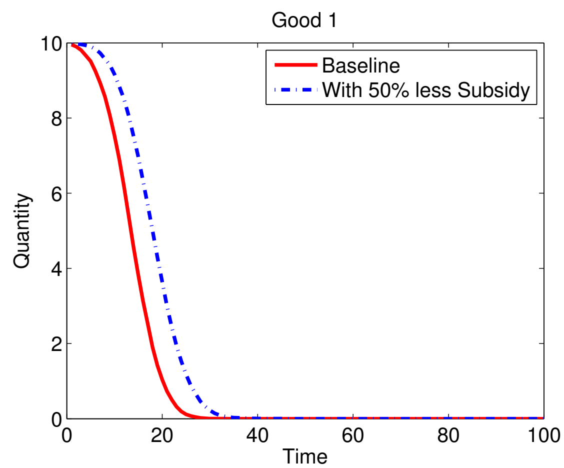


(e) 100-year simulation: Used-good1 quantity

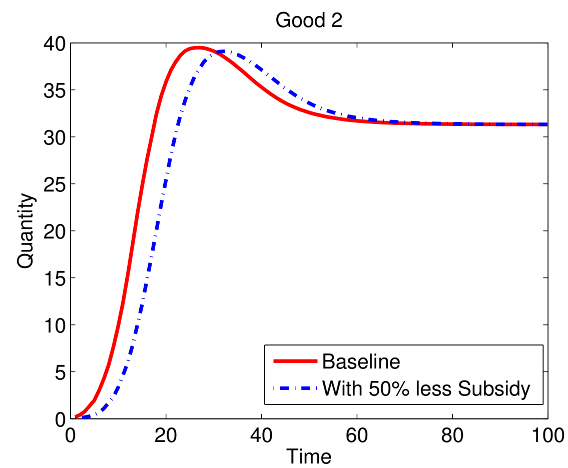


(f) 100-year simulation: Used-good2 quantity

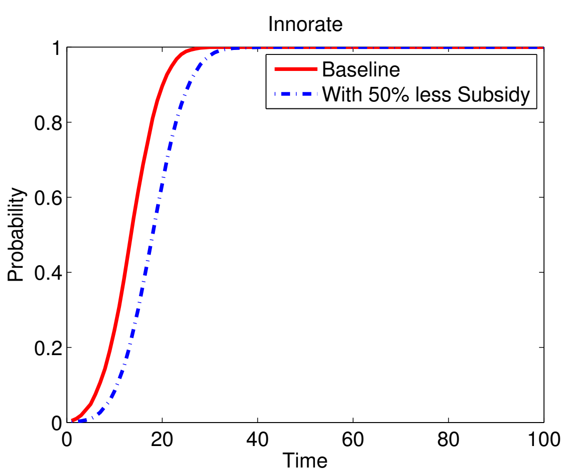
Figure 10: **Counterfactual: R&D subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product replaces the existing line, part(2)



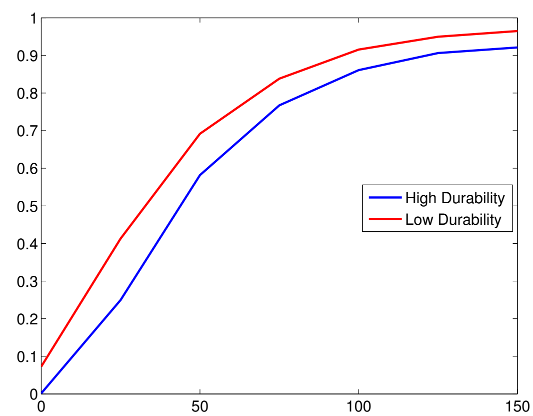
(a) 100-year simulation: New-good1 quantity



(b) 100-year simulation: New-good2 quantity

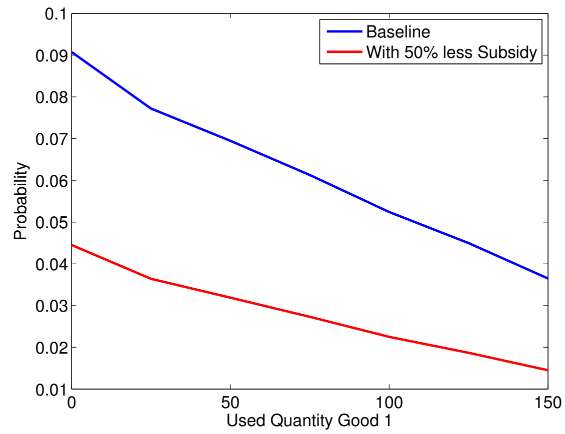


(c) 100-year simulation: Innovation

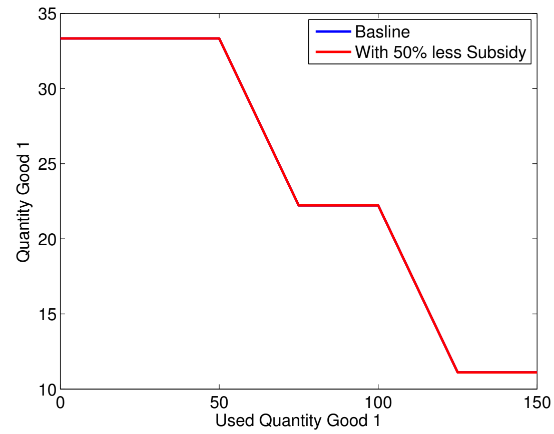


(d) Innovation and change in depreciation δ

Figure 11: **Counterfactual: R&D subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product does *not* replace the existing line, part(1)

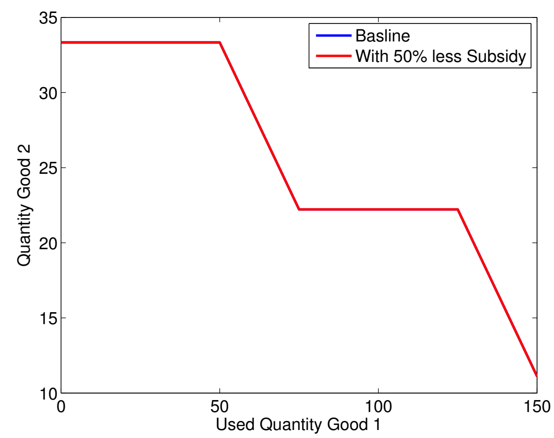


(a) Innovation policy function

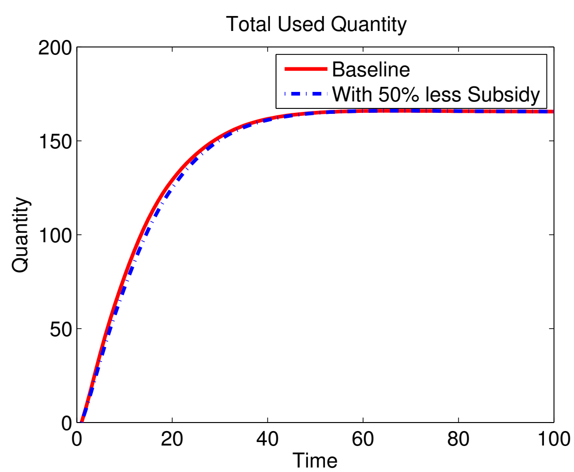


(b) Quantity policy function for good1

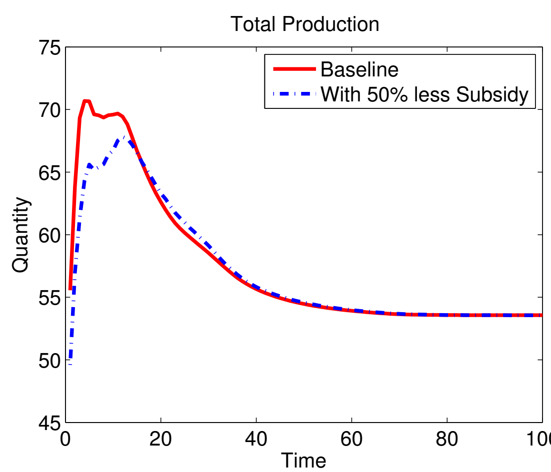
(c) %change of good1 price to good2 quantity



(d) Quantity policy function for good2

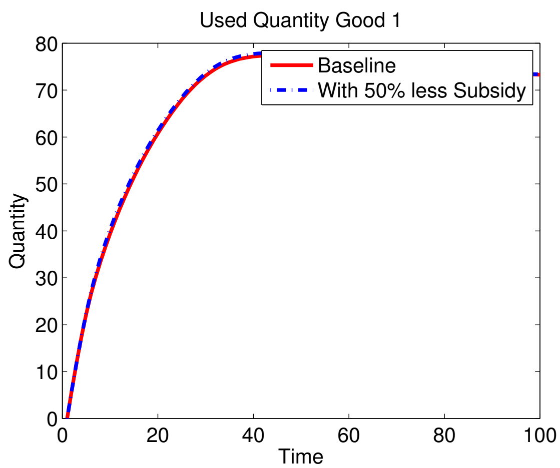


(e) 100-year simulation: Total used goods quantity

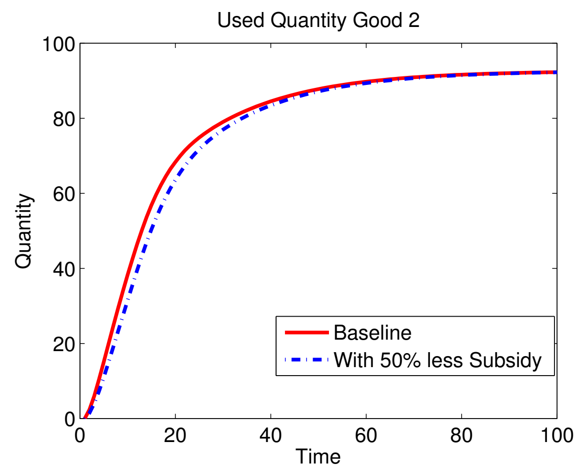


(f) 100-year simulation: Total quantity production

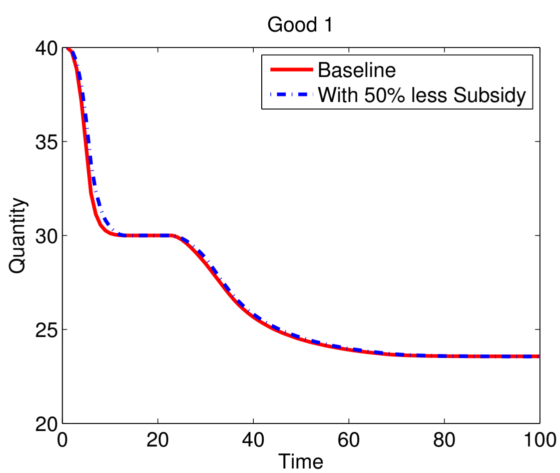
Figure 12: **Counterfactual: R&D subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product does *not* replace the existing line, part(2)



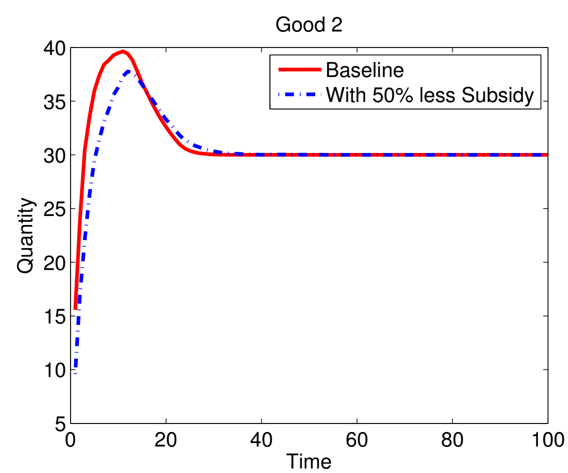
(a) 100-year simulation: Used-good1 quantity



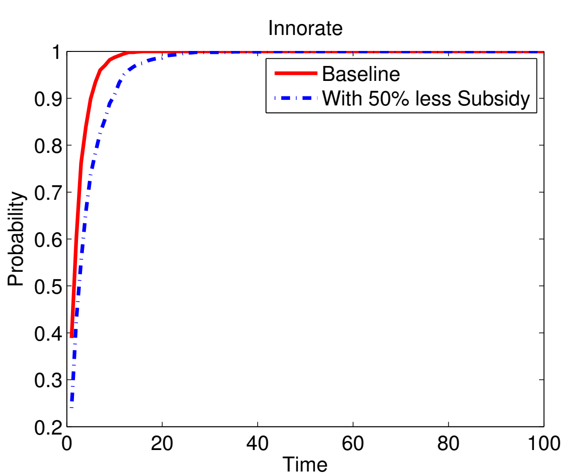
(b) 100-year simulation: Used-good2 quantity



(c) 100-year simulation: New-good1 quantity

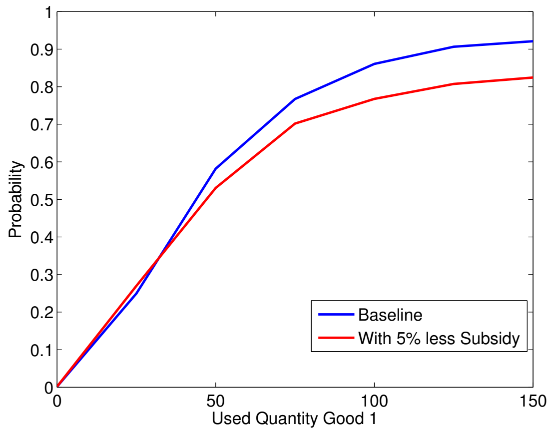


(d) 100-year simulation: New-good2 quantity

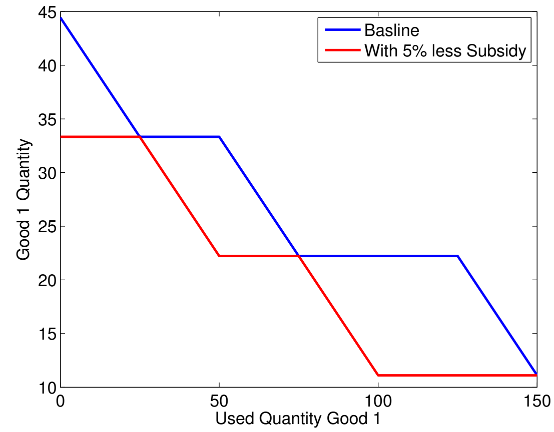


(e) 100-year simulation: Innovation

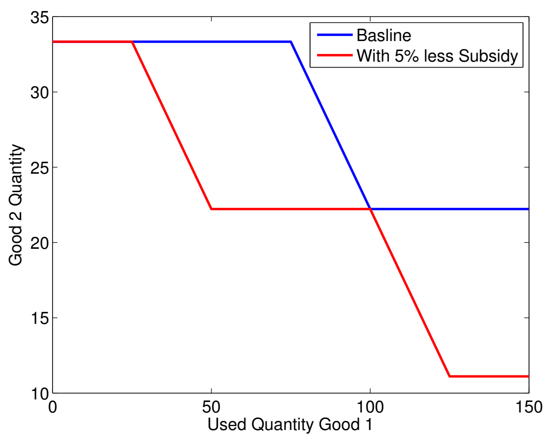
Figure 13: **Counterfactual: Production subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product replaces the existing line, part(1)



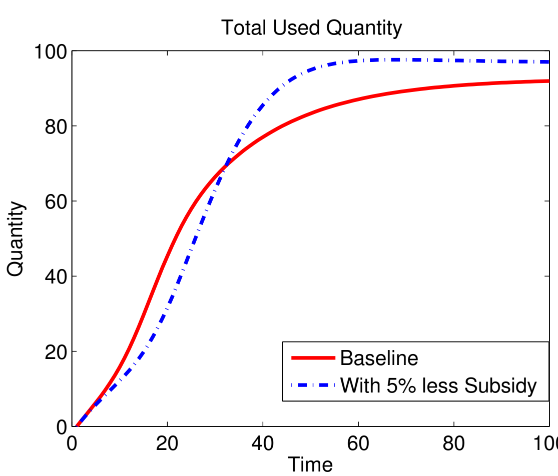
(a) Innovation policy function



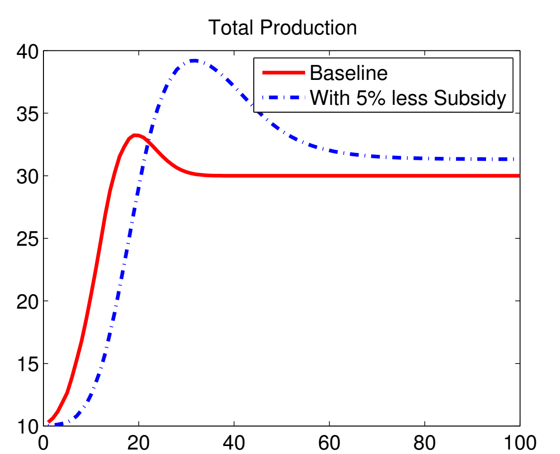
(b) Quantity policy function for good1



(c) Quantity policy function for good2

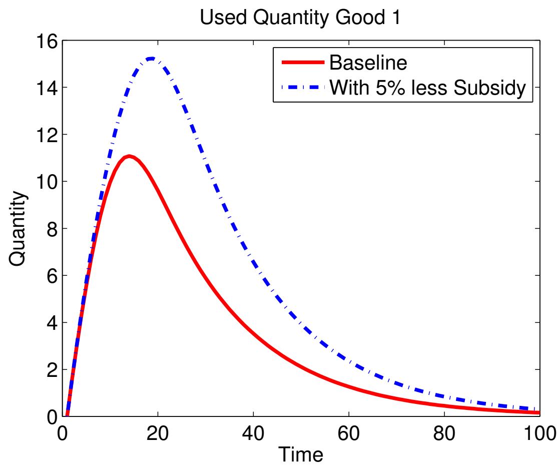


(e) 100-year simulation: Total used goods quantity

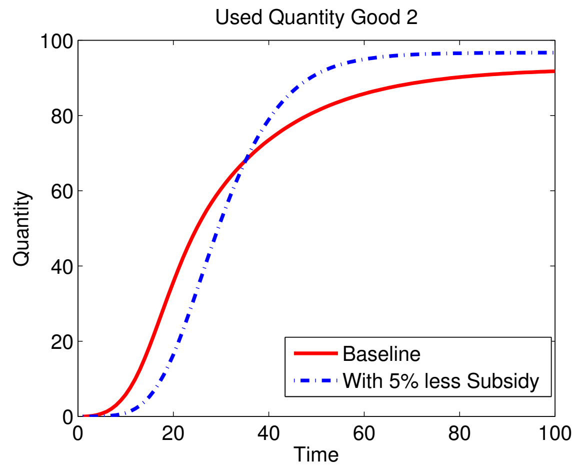


(f) 100-year simulation: Total quantity production

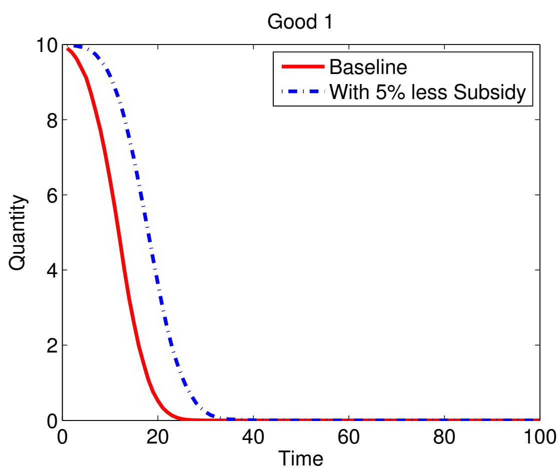
Figure 14: **Counterfactual: Production subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product replaces the existing line, part(2)



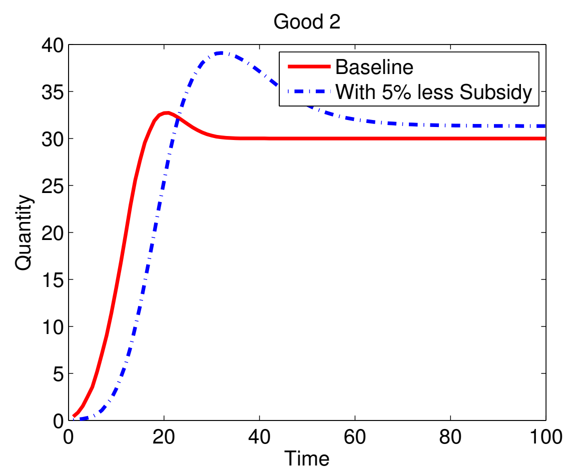
(a) 100-year simulation: Used-good1 quantity



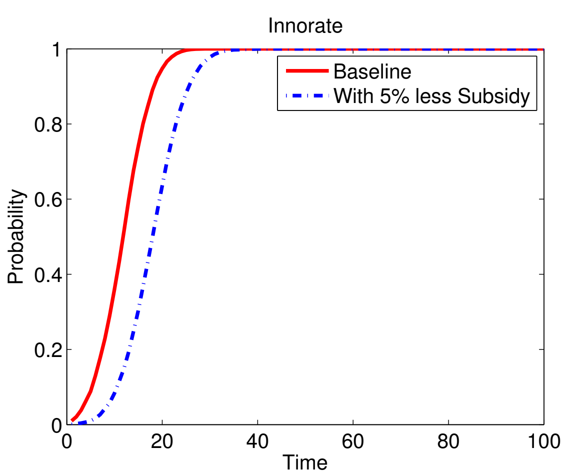
(b) 100-year simulation: Used-good2 quantity



(c) 100-year simulation: New-good1 quantity

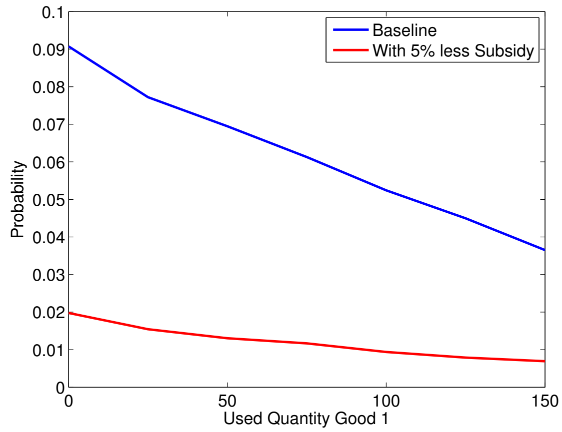


(d) 100-year simulation: New-good2 quantity

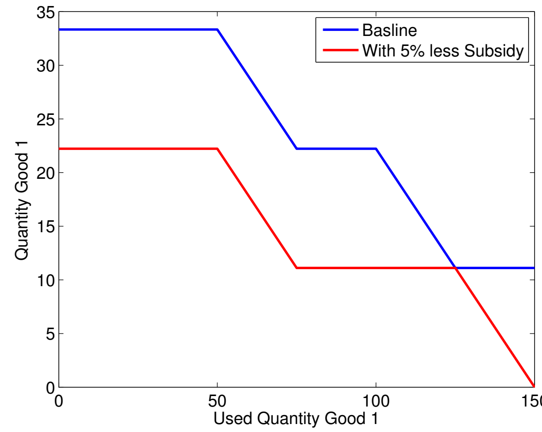


(e) 100-year simulation: Innovation

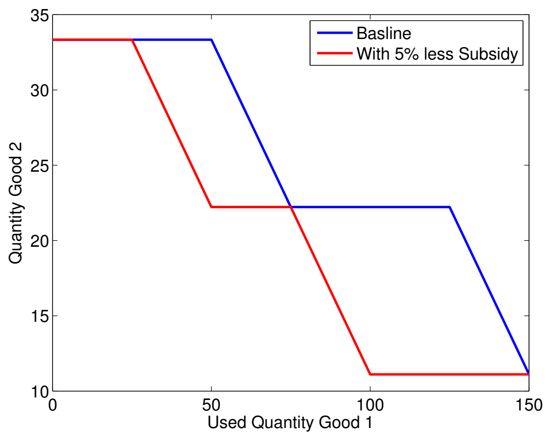
Figure 15: **Counterfactual: Production subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product does *not* replace the existing line, part(1)



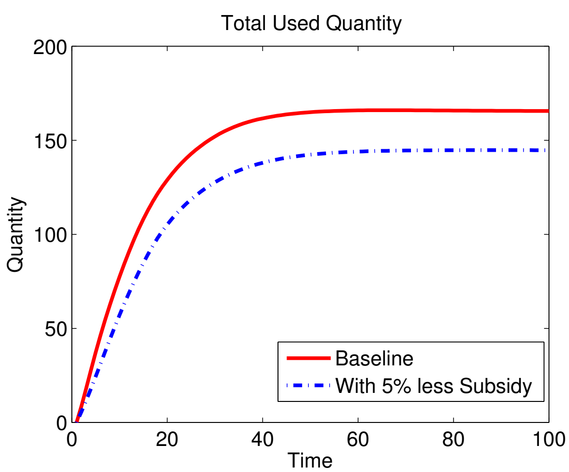
(a) Innovation policy function



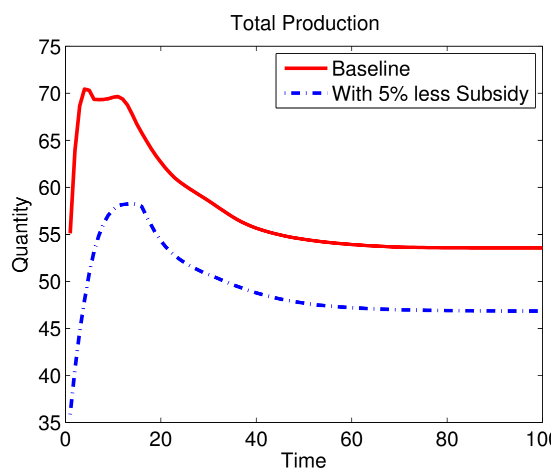
(b) Quantity policy function for good1



(c) Quantity policy function for good2

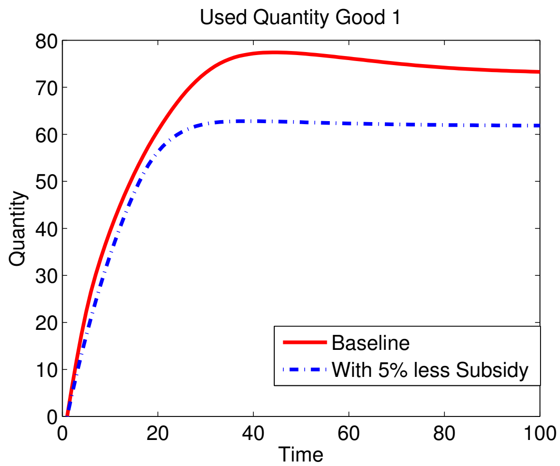


(e) 100-year simulation: Total used goods quantity

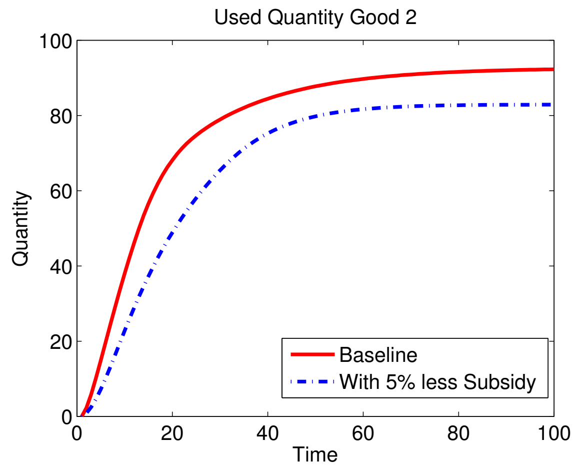


(f) 100-year simulation: Total quantity production

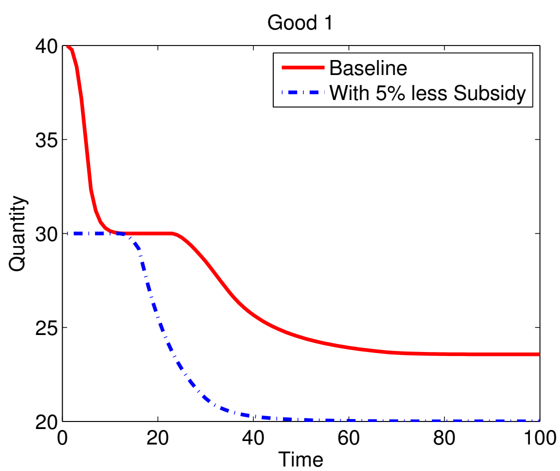
Figure 16: **Counterfactual: Production subsidy experiment** Monopoly with four goods, two new and two used goods, when a new product does *not* replace the existing line, part(2)



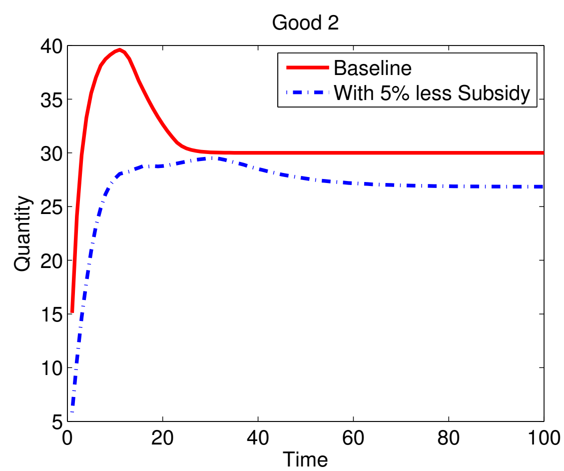
(a) 100-year simulation: Used-good1 quantity



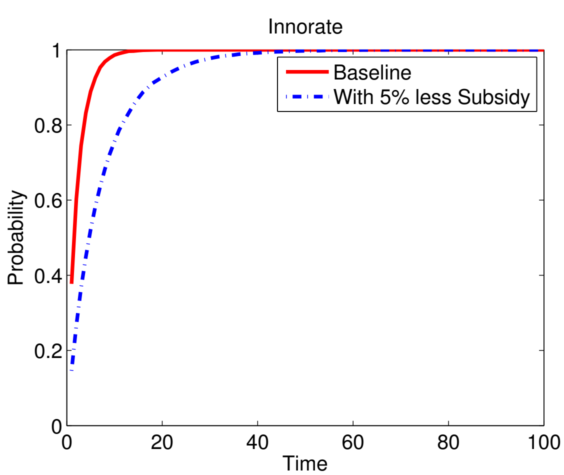
(b) 100-year simulation: Used-good2 quantity



(c) 100-year simulation: New-good1 quantity



(d) 100-year simulation: New-good2 quantity



(e) 100-year simulation: Innovation

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