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Shakeout in the Early Commercial Airframe Industry

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Abstract
The commercial airframe industry in the US experienced a shakeout from the early 1930s into the post-Second World War period. Unlike shakeouts in automobiles, tyres, or televisions, the commercial airframe industry's early life cycle was affected by external factors, particularly government demand. Using newly digitized data on all planes introduced in the commercial market between 1926 and 1965, we find that commercial airframe manufacturers with bomber contracts during the Second World War were more likely to have postwar market share than firms without such contracts, controlling for plane characteristics and other forms of government contracting. We attribute the effect of bomber contracts to advantages in R&D learning capacity acquired by firms with military airframe contracts. Despite low (or zero) initial presence in the commercial market, these learning capacity advantages allowed such firms to survive the early period of the shakeout, and later to thrive.

> In a freely competitive economy the number of companies manufacturing a particular product levels off at a point determined by the ordinary laws of economics. In the case of the aircraft industry, however, it would be dangerous to rely only on the operation of these laws.
>
> Aircraft yearbook, 1948[7]

The life cycle of many industries displays a distinctive pattern of entry and exit. In the past three decades, a theoretical literature has emerged to explain this pattern in terms of selection, spending on R&D, and the technological adoption decisions of individual firms.[8] Empirically, this appears to be consistent with the experience of a wide range of industries.[9] However, in many cases, the details of an industry's evolution are shaped by geography, institutions, or historical accident.[10]

The existing literature emphasizes the coevolution of technology and market structure in the standard story of an industry's rise and convergence to long-run equilibrium. Over the industry life cycle, firms that fail to earn positive profits exit and output is reallocated to new arrivals and incumbents. In the early stages, many firms earn profits and entry outpaces exit, which causes the number of firms to increase and the industry to expand. In later stages, as profit opportunities become scarcer, failures outnumber entrants, and survivors are disproportionately high productivity firms with large output. Market forces alone produce an industry's market structure. While the stylized facts of many industries fit within this framework, the historical evolution of some industries relies on institutional details that are not currently emphasized by the standard theory.

In this article, we examine the role of government demand in the early commercial airframe industry. We start by showing how the standard model of industry shakeout due to Klepper can be modified and, in conjunction with commercial airframe history, used to understand the industry's evolution to long-run equilibrium. In particular, we interpret the military airframe market as an avenue for acquiring experience both prior to, and concurrently with, entry into the commercial airframe market.[11] In the theory, experience yields a productivity advantage that allows entrants, even late entrants, to survive and thrive despite low initial market share. We use newly digitized data on market share for all commercial airframe manufacturers from 1926 to 1965 to examine the role of government demand. The data also include detailed information on plane characteristics, which allow us to control for differences in performance due to technological progress and the idiosyncratic R&D capabilities of individual firms.

The results suggest that in the commercial airframe industry, the standard story of shakeout should be augmented to include a role for government demand and regulation. We focus on the role of government demand through Air Mail and military contracts from the interwar period to the 1940s, and provide evidence that the impact of government demand on shakeout was twofold. First, in the industry's infancy during the 1930s, certain manufacturers held Air Mail and military contracts. This allowed some firms to survive periods of low (even zero) market share on the commercial side of their businesses. Second, the rapid growth in demand for military aircraft during the Second World War allowed a select group of firms to increase their R&D learning capacity, that is, their ability to assimilate and exploit technological knowledge in aviation. As the jet engine age dawned in the postwar period, these learning capacity differentials set the stage for the market's eventual evolution to duopoly.

Ultimately, we show that the government played an important role in determining the identity of the industry's participants after 1945. These insights augment the standard account of shakeout in markets with strong civilian-driven demand (for example, automobiles, tyres, and television) and are crucial for identifying the determinants of industry evolution when the role of government is large (for example, aircraft, aluminum, penicillin, and rubber). In addition, by examining the role of the Second World War in shaping the commercial

airframe industry's postwar market structure, we contribute to a long-standing debate about the role of the war in the development of the American economy in the postwar period.[12]
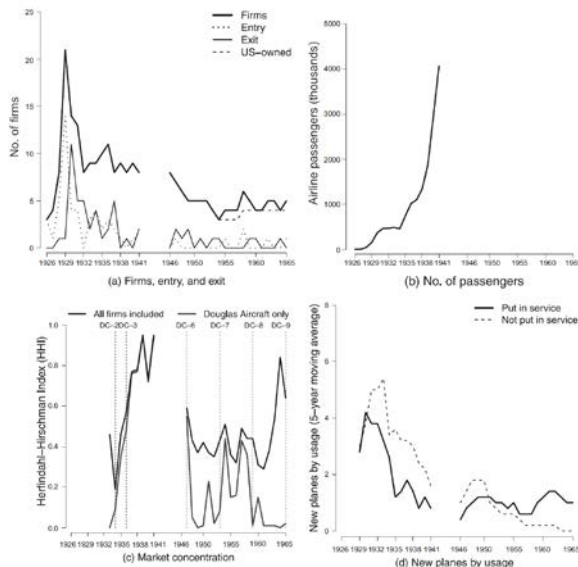
The remainder of the article is organized as follows. Section provides an overview of the early commercial airframe industry, emphasizing similarities and differences relative to the shakeouts in other industries. In section, we review the relevant theoretical argument and relate the model of shakeout presented by Klepper to the details of the early commercial airframe industry. Section III draws on archival and secondary sources to highlight the effect of government contracting and to explain the atypical features of the industry's evolution to its long-run equilibrium. To support the argument presented in section III, section presents empirical analysis that examines the effect of government contracting on the postwar success of commercial airframe manufacturers. Section V synthesizes the theory, history, and empirical results, and section concludes.

Overview of the commercial airframe shakeout

The conventional view of industry shakeout is based on two related observations: the pattern of entry and exit, and the evolution of market concentration. The time series of the total number of firms, entry, and exit is shown in panel A of figure for the commercial airframe industry from 1926 to 1965. The number of firms increased from the mid-to-late 1920s and peaked in 1929.[13] Consistent with the standard story, Rae observes that 'the big [airframe] companies were not in an oligopolistic position in 1929', at the beginning of the industry's shakeout.[14] Starting in 1930, the number of existing firms decreased sharply. After the Second World War, a much smaller decrease occurred, and by the mid-1950s the number of firms in the industry was roughly constant until the end of our sample period in 1965.

The macroeconomic turmoil of the early 1930s adversely affected the survival of commercial airframe firms. But if Depression-era demand was the main reason for the industry's evolution, we should see a decrease in airline passenger traffic following the 1929 stock market crash. Instead, panel B shows that the number of airline passengers increased in the early 1930s and then again after 1934. Mowery and Rosenberg note, 'Even in the midst of the depression, airline traffic boomed'.[15] The data suggest that the microeconomic details of the commercial airframe industry's technology and market structure were crucial determinants of entry and exit.

Figure 1. Stylized facts of the commercial airframe shakeout (a) Firms, entry, and exit. (b) No. of passengers. (c) Market concentration (d) New planes by usage.

Notes: Panel A shows the no. of commercial airframe firms (US and foreign), entrants, and exits on time. Panel B shows the no. of airline passengers in the prewar period. Panel C shows commercial airframe market concentration on time. The

vertical lines indicate the release dates of major Douglas Aircraft planes. Panel D shows the moving average of new commercial planes, both used and unused, on time.
Source: Phillips, Technology and market structure; Aeronautical Chamber of Commerce of America, Aircraft yearbook.

The second stylized fact of shakeout is that the industry becomes more concentrated over time. Panel C shows the Herfindahl-Hirschman Index for the addition of planes to airlines from 1933 to 1965. The rapid increase in concentration before the war is consistent with the conventional view of shakeout. During this period, Douglas Aircraft dominated the commercial market with the DC-3; from its introduction in 1936 to 1941, the DC-3 accounted for over 80 per cent of all new aircraft put in service by airlines.[16] The DC-3 was so successful because it dramatically reduced operating costs for airlines. According to Sutton, 'No aircraft, before or since, has cut unit operating costs so sharply'.[17]

The industry's postwar trajectory is surprising in view of this prewar growth in concentration. Panel D shows the five-year moving average for the number of new commercial airframe models, broken down by whether the new plane was put in service by an airline or not. Shakeout theory predicts that entry dwindles as market concentration increases because potential entrants cannot profitably enter and compete with high-volume, cost-efficient incumbents. Yet in the early commercial airframe industry, despite rising market concentration, the number of unsuccessful planes exceeded the number of successful ones throughout the 1930s, and this trend was not reversed until the mid-1950s.

Moreover, firms that have little or no market share for an extended period should exit during a shakeout, but this did not occur in the commercial airframe industry in several notable cases. Consolidated-Vultee Aircraft (Convair) and its predecessor firms did not introduce a successful commercial aircraft from 1931 to 1947. During this period, Convair's average yearly market share was 0.5 per cent, yet the company enjoyed an average market share of 18.8 per cent from 1947 to 1964. Similarly, Boeing Aircraft did not have significant commercial market share during a 25-year period (averaging 4.3 per cent) before finally gaining prominence with its 707 model in 1959. These experiences are in stark contrast to firms in the infant automotive industry. Early entrants and once-prominent automakers simply disappeared and did not enjoy the later life cycle successes of Boeing and Convair.

The stylized facts suggest a commercial airframe shakeout beginning in 1929 and, on one hand, the shakeout appears typical. There was a sharp drop in the number of firms immediately after 1929, and market concentration increased throughout the 1930s. On the other hand, there is evidence that the commercial airframe shakeout was unusual. Firms that survived the shakeout were almost exclusively part of one of a handful of holding companies (see section III), the number of planes introduced and adopted did not exceed the number of planes introduced but never used until the mid-1950s, and several firms experienced strong market gains after years of zero or near-zero market share.

One factor that affected shakeout in the commercial airframe industry that was not present in other shakeout episodes was strong military demand. Phillips writes: '[T]he decrease in numbers would likely have been greater and the possibility of entry by new producers would likely have been much less had there not been huge procurement of military aircraft and related R and D through much of the period'.[18] In their infancy, for example, the automobile, tyre, and television industries all had much stronger civilian demand and never experienced government demand that was as substantial as in the commercial airframe industry.

Shakeout theory

In this section we illustrate the potential effects of government demand on the commercial airframe market using Klepper's shakeout model.[19] The model assumes K_t potential entrants in each period. An entrant i chooses quantity (Q_{it}) and R&D expenditure (r_{it}) to maximize profits given by:

$$\Pi_{it} = [p_t - c_t + a_i g(r_{it})] Q_{it} - r_{it} - m(\Delta Q_{it}) \quad (1)$$

where p_t is the market price common to all firms, c_t denotes a cost component common to all firms, and $a_i g(r_{it})$ is the reduction in average cost due to R&D expenditure. Firm i enters the market in period t if $\Pi_{it} \geq 0$. So long as profits are weakly positive, the firm remains in the market. If $\Pi_{it} < 0$ in any period, the firm exits the market permanently.

Following entry decisions, firms incur a cost shock, $\varepsilon_{it} \geq 0$, which is independent and identically distributed across firms and periods. This captures random variation in costs due, for example, to management practices. Thus, average costs are given by $c_{it} = c_t - a_i g(r_{it}) + \varepsilon_{it}$. Firm-specific R&D productivity, a_i, is fixed over time and can take either value a_M or a_L, with $a_M > a_L$. To capture diminishing returns to R&D expenditures, $g' > 0$ and $g'' < 0$. To ensure that even low productivity (a_L) firms attempt at least some cost innovation, $a_L g'(0) Q_{min} > 1$. At the end of each period, all firms costlessly imitate the last period's lowest cost, so $c_t = c_{t-1} - \max\{a_i g(r_{it})\}$. Finally, there are costs associated with changing capacity, $m(\Delta Q_{it})$, where and $\Delta Q_{it} = Q_{it} - Q_{it-1}$ and for all output choices.

In the model, shakeout is driven by heterogeneity in firms' ability to translate R&D expenditures into lower average costs. Over time, more productive firms expand their output and $p_t - c_t$ decreases. This determines the profitability of new entrants and the survival of firms currently in the market. The first-order conditions for quantity (Q_{it}) and R&D expenditures ((r_{it})), respectively, are given by:

$$p_t - c_t + a_i g(r_{it}) = m'(\Delta Q_{it}) \quad a_i g'(r_{it}) Q_{it} = 1$$

The first expression equates the marginal benefit of expanding output with its marginal cost. Because firms with $a_M > a_L$ require less R&D expenditure for a given marginal cost of expanding output, they are more likely than firms with a_L to earn non-negative profit, and thus are more likely to enter the market and to survive. The second expression equates the marginal benefit of R&D with its marginal cost. Because g' is decreasing in r_{it}, firms with the same a_i but greater Q_{it} attempt more R&D.
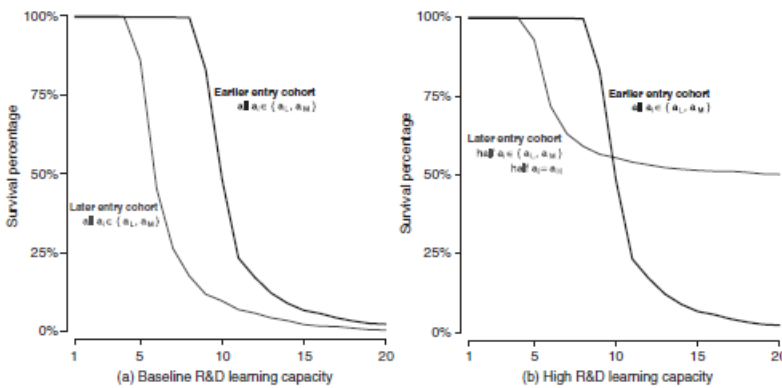

Figure 2. Model simulation results (a) Baseline R&D learning capacity. (b) High R&D learning capacity.

Notes: Panel A graphs the average firm survival percentage in 100 computer simulations of Klepper on firm age. The parameters used for panel A are used for the panel B simulations, except half of the 'later entry cohort' in panel B have high R&D productivity as described in the text.

To use the model to understand the role of government demand in the commercial airframe shakeout, we start by connecting its specific features to the determinants of the evolution of the commercial airframe industry. First, as can be seen from equation , a commercial airframe manufacturer that charges a high price for a plane increases their profit and thus their probability of survival. Unfortunately detailed data on prices for different aircraft over time are unavailable. Instead, our empirical analysis focuses on the commercial market share for the universe of manufacturers and controls for an extensive set of plane characteristics that adjust for differences that translate into differential abilities of firms to exercise market power.

The model assumes a cost component, c_t, common to all firms. In each period, existing entrants and potential new entrants can costlessly imitate the lowest cost from the previous period. In this section, we maintain this cost spillover assumption. In appendix I, we drop the assumption to allow for learning-by-doing and learning-by-using which are important phenomena in the airframe industry. To capture differences in costs of changing productive scale across firms, firm-specific $m(\cdot)$ functions can also be included.

The model captures firm-specific differences in R&D productivity through a_i. Additional differences in R&D productivity can be incorporated through firm-specific $g(\cdot)$ functions. Cost innovation productivity differences may arise if manufacturers with experience producing airframes prior to, or concurrently with, entry into the commercial market (for example, military or cargo) are more efficient at cost innovation. The coefficient a_i and the function $g(\cdot)$ can be interpreted as capturing a firm's learning capacity, or its ability to assimilate and exploit technological knowledge.[20] All else being equal, firms with more learning capacity require less R&D expenditure to lower their average costs.

In the model, when both earlier and later market entrants have the same distribution of R&D productivity coefficients, earlier entrants have higher survival rates. To illustrate this, we simulate equation one hundred times under the assumptions outlined above. Panel A of figure shows the average cumulative survival percentage of the simulations when cost shocks are randomly drawn and firms are randomly assigned R&D productivity coefficients of either a_M or a_L, with $a_M > a_L$. The black line is the average cumulative survival for an earlier-entering cohort; the grey line is for a later-entering cohort.

Section I notes that Boeing and Convair had small commercial airframe market shares for several years before finally breaking through after the Second World War. In terms of the shakeout model, we are interested in whether the survival probability changes if a subset of later entrants have high R&D productivity. Panel B of figure shows the average cumulative survival percentage of one hundred simulations using the same random assignment of cost shocks as in panel A. The random assignment of R&D productivity coefficients is also the same as in panel A with one exception: half of the later entry cohort are given R&D coefficients of a_H, where $a_H > a_M > a_L$. Again, the black line is for the earlier entry cohort and the grey line is for the later entry cohort.

When half of the later-entering cohort have a relatively high R&D coefficient, their own cohort's survival probability increases. However, the survival probability of the earlier cohort is unaffected when the later entrants have higher learning capacity ($a_i = a_H$). In appendix I, we report simulations with the cost spillover assumption relaxed. The survival probability of the earlier entry cohort falls in these additional simulations. The next section shows how key features of the model can be understood in the historical context of the early commercial airframe industry.

Specifics of the commercial airframe shakeout

This section draws on airframe industry history to highlight the determinants of the commercial airframe shakeout. In addition to considering the crucial role of government demand throughout the 1930s and 1940s, we survey other drivers of the industry's evolution, such as integration through holding companies.

Holding companies

Following a large expansion in aircraft production during the First World War, the market for airframes collapsed and remained small throughout the 1920s; airlines carried fewer than 10,000 revenue-passengers per year prior to 1928. In addition, demand from military contracts was almost completely absent. In the face of this uncertainty, market participants were reluctant to expand. Starting in the 1930s passenger traffic increased substantially and the number of commercial airframe manufacturers peaked, among them postwar industry leaders such as Boeing and Lockheed.

Prior to the stock market crash in October 1929, many airframe manufacturers organized under one of several holding companies. Under this form of business organization, stock of subsidiary companies was exchanged for stock in the parent company.[21] These affiliations potentially affected access to working capital, and thus the probability of firm survival. In particular, manufacturers obtained working capital predominantly from retained earnings or equity.[22] Holding companies that coupled commercial airframe makers with other aviation firms may have increased commercial airframe firms' probability of survival through cross-subsidization or by increasing revenue from stock issues.

For example, figure shows a time series of working capital for several major holding companies and the independent Douglas. William Boeing's United Air & Transport was the most integrated holding company with strong subsidiaries in engines and parts, commercial and military airframes, and airlines.[23] Curtiss-Wright also had strong military sales from its engine and aircraft subsidiaries. Aviation Corporation had two aircraft subsidiaries but focused on the transport of mail, passengers, and freight, and had no notable military sales.
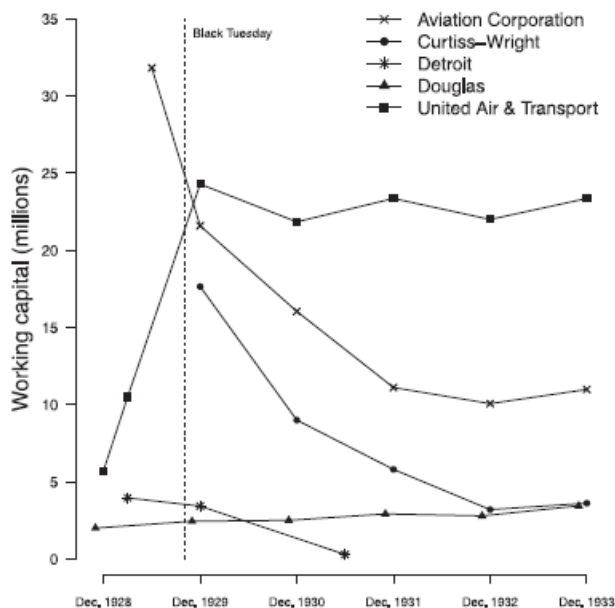
Figure 3. Working capital, by holding company
Notes: This figure shows working capital (current assets minus current liabilities) from Dec. 1928 to Dec. 1933 for several major holding companies and one independent firm, Douglas Aircraft. The holding companies were disbanded by the Air Mail Act in June 1934. The dashed vertical line indicates the 'Black Tuesday' stock market crash of Oct. 1929.
Source: Moody's Investors Service, Moody's manual of industrials.

Both Detroit Aircraft and Douglas had similar levels of working capital. Detroit's explicit goal was to become the General Motors of aviation. Through conscious choices by its founders, the company had little access to government demand; it had no subsidiary airlines with Air Mail revenue and manufactured no military planes in quantity. On the other hand, 91 per cent of Douglas's plane sales went to the military during this period. Thus, although holding company affiliation may have aided survival, it was not decisive. The composition of holding companies mattered.

When the Air Mail Act of 1934 forcibly separated airframe manufacturers from airlines, quasi-vertical integration via holding companies was ended and revenues from Air Mail disappeared. At this point, government demand through military contracts became increasingly important. In the empirical analysis, we control for holding company affiliation and examine the relationship between access to government contracts and success in the postwar commercial market.

Dominant designs, patents, and innovation spillovers

The rise in concentration in the late 1930s was driven by one plane: the Douglas DC-3 (see panel C of figure 1). Introduced in 1936, the DC-3 synthesized previous technological innovations to such an extent that airlines were forced to buy it, or one of its imitators. Following the introduction of this plane, one-time commercial leaders such as Fairchild, Ford, Fokker, and Stinson either were acquired, exited the commercial market, or shuttered completely. The DC-3 thus fits the definition of a dominant design as discussed by Utterback and Suarez.[24]

While the DC-3 was undoubtedly revolutionary in lowering operating costs for the airlines, it did not embody technology that unilaterally 'triggered' the industry's shakeout. The number of firms in the commercial airframe market peaked prior to Douglas's entry. Moreover, despite the increase in market concentration in the 1930s shown in panel C of figure 1, the number of firms remained relatively constant as shown in panel A of figure 1.

The development of the DC-3 illustrates the scattered nature of technological advance in the pre-Second World War period. It was derived from Douglas's earlier DC-2 and DC-1 planes. In turn, the DC-1 drew technology from Boeing's 247 and from Northrop Corporation's Alpha and Gamma commercial planes. Boeing had drawn on prior experience with their B-9 bomber for the 247. In turn, the B-9 drew on the 221, a commercial plane. Phillips concludes that 'unlike the post-World War II period … it cannot with generality be contended that military aircraft were antecedent to commercial planes of the same general performance and technical characteristics'.[25]

From 1917 to 1975, the airframe industry enjoyed a series of patent cross-licensing agreements under the auspices of the Manufacturers Aircraft Association (MAA).[26] The patents of each MAA member were available to every other member. As a result, unlike Alcoa's early dominance in aluminium, the evolution of the early commercial airframe industry is not explained by the patent protection of a dominant design.

The shakeout may have been affected by design spillovers within multi-market airframe firms. Companies that designed military airframes or flying boats in addition to commercial airframes may have had an advantage relative to firms that only produced commercial, land-type planes. Smith argues that flying boats embodied major aeronautical advances.[27] The leaders in the field were Sikorsky, Martin, and Boeing. At the same time that typical land-type planes had two engines and weighed less than 30,000 pounds, typical flying boats had four engines and weighed over 50,000 pounds. For the empirical analysis, we use detailed information on plane characteristics to separate the importance of specific design attributes from the contribution of government demand.

Technological change and scale economies

It is possible that airframe manufacturers who produced both commercial and military planes had scale economies advantages over commercial-only producers. Scale advantages are a key determinant of survival in the model presented in section II. However, an implicit assumption of the model is that technology is relatively fixed.

The pace of technological change in the airframe market in the 1930s has been described as 'violent' by Holley.[28] Unlike airframe firms, aircraft engine makers could mass-produce and the market was essentially a duopoly between Curtiss-Wright and Pratt-Whitney. The contrast between airframe and aircraft engine manufacturers in the mid-1930s is instructive:

> The engine manufacturers are on firmer economic ground than the airplane manufacturers. The former are more nearly manufacturers in the true sense, with a fairly steady market for a relatively slowly changing product. The latter are really contractors, offering a product that is constantly changing which seldom affords them opportunity to settle down and manufacture steadily and efficiently.[29]

In such a market, airframe manufacturers could not expand output up to the point at which their marginal profit from doing so vanished.

Indeed, because technology was changing so rapidly, civil aircraft average unit costs increased from $4,854 in 1928 to $8,413 in 1937.[30] Military aircraft average unit costs, driven by military performance requirements, were greater in magnitude and rose even more over the same period. In the commercial airframe market, panel D of figure indicates that the expected return for new commercial planes was not low enough to dissuade plane makers from sinking costs into developing (often unsuccessful) planes throughout the 1930s.[=31]

Government contracts

Government contracting with commercial airframe firms took two forms: Air Mail contracts and military airframe contracts. Commercial airframe manufacturers with Air Mail contracts potentially enjoyed a survival advantage over their competitors without such contracts. For example, while Boeing Aircraft was part of the United Air & Transport holding company with United Air Lines, Bellanca Aircraft had no similar relationship with an Air Mail carrier. However, any cross-subsidization that may have aided survival in the commercial airframe market was short-lived; the Air Mail Act of 1934 forcibly separated airline and airframe firms. In our empirical analysis, we account for firms who were part of a holding company with Air Mail revenue.

It is possible that producing certain types of military planes before and during the Second World War gave some firms an advantage in the commercial airframe market at the end of the war. Planes procured in the era included light bombers (with an A- designation), medium and heavy bombers (B-), transports (C-), and fighters (P-). Of these, the B- and C-designated planes were the most similar to commercial airframes. Eight airframe manufacturers produced large bombers with a B-designation. Of these, three firms (Bell, Ford, and North American) did not attempt to enter the commercial airframe industry after the war. The other five (Boeing, Convair—formerly Consolidated, Douglas, Lockheed, and Martin) were the only firms with a positive share in the commercial market from 1946 until 1955 (when Vickers-Armstrong entered with its 770 plane).

The development of the heavy bombers used by the US in the Second World War began in the second half of the 1930s. In the fall of 1935, the Boeing 299 beat Douglas and Martin aircraft for a military contract. This airframe eventually became the B-17, of which 12,692 were produced during the war.[32] The other large bombers with substantial wartime production were Consolidated's B-24 (18,190 produced), North American's B-25 (9,816), Martin's B-26 (5,157), and Boeing's B-29 (3,898). Douglas did not design any of these, but was a competitor for each contract.[33] In addition to the five firms just mentioned, the set of serious competitors for the contracts

included Lockheed. In Britain, Vickers (later Vickers-Armstrong) designed the Wellington bomber, of which 11,461 were manufactured.

Transports were also large, commercial-like military planes. In fact, they were modified directly from existing commercial planes. They included the C-45 made from Beech's Beechcraft 18, the C-46 made from Curtiss-Wright's CW-20, the C-47 from Douglas's DC-3, the C-54 from Douglas's DC-4, and the C-60 from Lockheed's L-18. Other transport manufacturers included Fairchild, Cesna, Convair, and Lockheed. Because transports were modified versions of existing commercial airframes, their effect on the postwar market was minimal. In our empirical analysis, we test for potential spillovers from military airframe production to postwar commercial success.

Empirics of the commercial airframe shakeout

The previous section proposes several hypotheses that we test using information on the planes introduced to the commercial market between 1926 and 1965 drawn from Phillips.[34] For each plane the data include information on whether and when it was adopted for use in the commercial market, the market share, and additional characteristics, such as the number of engines and seats, speed, and range. A particularly useful feature of these data is that they provide the universe of all planes that could have possibly been used in the commercial market *and* indicate which planes were actually used in said market. In sum, the dataset contains 118 planes produced by 49 manufacturers.

Table 1 shows summary statistics for planes used in the empirical analysis. Panel A summarizes the characteristics of all planes; panels B and C stratify the sample by planes adopted and not adopted by the commercial market, respectively. In general, the patterns in the table are as expected. Planes adopted in the commercial market tended to be more powerful (for example, 9,625 versus 2,711 horsepower), larger (37 versus 21 passengers), and faster (258 versus 167 miles per hour). We include these characteristics in the empirical analysis to control for the role of specific design features in the postwar presence and market share of these planes.

Table 1. Summary statistics for plane characteristics

		Panel A: All			Panel B: Used			Panel C: Not used	
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Entry year	1938	1926	1965	1941	1926	1965	1936	1927	1958
Speed	212.3	95	610	258.1	95	610	167.2	102	400
Capacity	28.32	4	216	36.98	4	142	20.52	5	216
Engines	2.18	1	8	2.41	1	4	1.97	1	8
Engine type	0.9	0	1	0.78	0	1	1.00	0	1
Power	6,018	200	72,000	9,625	300	72,000	2,711	200	30,000
Load	12.23	7.3	20.3	11.49	7.3	14.5	12.77	8.2	20.3
Range	1,413	420	6,300	1,469	420	6,000	1,348	450	6,300
Service	22,590	2,000	41,000	24,430	2,000	41,000	20,180	12,000	41,000
Climb	1,180	650	2,460	1,247	675	2,460	863.1	650	1,695
Observations		118			56			62	

Notes: Panel A contains all models; panels B and C, respectively, stratify by whether a plane was adopted and not adopted by the commercial market. The variables in the table are the year a plane entered domestic service (panel B) or the year a plane became available (panel C), no. of engines, engine type (piston equal to 1 and turbo-prop, turbo-jet, and turbo-fan equal to 0), maximum power at take-off, typical passenger capacity, gross weight in pounds per horsepower or load, typical cruising speed, full load cruise range, service ceiling (in feet), and initial climb rate (in feet per minute), respectively, in the rows.

Our main interest lies in quantifying the postwar impact of prewar and war-related relationships with the government through contracts for Air Mail and military airframes. We measure these relationships using indicator variables for whether the firm producing each plane had contracts to deliver Air Mail, contracts to deliver planes of all types to the Army or Navy in the 1930s, and contracts to produce the B-series bomber during the Second World War.[35] Because the historical record highlights the importance of holding companies, we include holding company affiliation in our analysis. For outcomes, we focus on market presence and market share in the postwar period. We are primarily interested in whether access to government contracts delayed the shakeout of some firms and allowed others to continue production despite low initial market share.

Table 2 shows the relationship between the variables we use to capture access to government contracts and success in postwar markets. Panel A shows that of all planes introduced between 1926 and 1965, 21.2 per cent were produced by firms with some presence in postwar markets. Panel B gives the share of planes manufactured by firms with a postwar presence, stratified by whether the firm had any type of government contract (that is, Air Mail, Army/Navy, or bomber). Of these, 31.0 per cent were present in the postwar market, compared with 6.4 per cent that received no government contract. The entries in panel C show that the difference apparent in panel B is driven by access to Army/Navy and bomber contracts; Air Mail contracts appear unimportant for postwar market presence.

Table 2 Summary statistics for postwar market presence

	Obs.	Mean	Std. dev.
Panel A			
All	118	0.212	0.410
Panel B			
Any contract			
Yes	71	0.310	0.466
No	47	0.064	0.247
Panel C			
Air Mail			
Yes	23	0.217	0.422
No	95	0.211	0.410
Army/Navy			
Yes	56	0.357	0.483
No	61	0.080	0.275
Bomber			
Yes	44	0.500	0.506
No	74	0.041	0.199

Notes: This table provides summary statistics for the share of all planes introduced between 1926 and 1965 with postwar market share (panel A), stratified by whether the firm had any type of government contract (panel B), and specific types of contracts including Air Mail, Army/Navy, and Second World War bomber contracts (panel C).

To examine further the impact of prewar and wartime relationships with the government, we estimate the following specification:

$$y_j = \alpha_1 bomber_j + \alpha_2 army/navy_j + \alpha_3 airmail_j + \alpha_4 holding_j + X_j \beta + \varepsilon_j \text{ (2)}$$

where y_j is an indicator for whether plane j had positive market share in the postwar period (1946–65). The first three variables on the right-hand side of equation are indicators equal to one if the firm producing j had bomber, Army/Navy, or Air Mail contracts, respectively. The variable $holding_j$ is an indicator for whether plane j was produced by a firm belonging to a holding company prior to 1934. The vector of plane characteristics, X_j, adjusts for the role of the design features given in table 1. Multidimensional clustering is used to adjust standard errors for both within-firm as well as within-year-of-entry correlations of the residuals.[36]

The results of estimating equation (2) are shown in table 3. Column 1 includes only the variables associated with our main hypotheses from section III, column 2 adds controls for speed and capacity, and column 3 includes additional controls for number of engines, engine type, maximum power at take-off, gross weight pounds per horsepower or load, full load cruise range, service ceiling, and initial climb rate. These variables are standardized by subtracting the mean and dividing by the standard deviation so that the coefficient gives the change in the outcome for a one standard deviation change in the corresponding plane characteristic.

Table 3 Government contracting and market structure

		Postwar market presence	
	(1)	(2)	(3)
Bomber	0.530	0.208	0.209
	(0.095)	(0.073)	(0.081)
Army and Navy	−0.023	0.047	0.036
	(0.071)	(0.038)	(0.044)
Air Mail	0.090	0.034	−0.018
	(0.043)	(0.030)	(0.083)
Holding company	−0.084	−0.022	−0.018
	(0.048)	(0.045)	(0.058)
Capacity		−0.018	−0.011
		(0.054)	(0.063)
Speed		0.259	0.303
		(0.063)	(0.143)
Engines			0.088
			(0.049)
Engine type			−0.048
			(0.093)
Power			−0.109
			(0.072)
Load			−0.035
			(0.057)
Range			0.000
			(0.071)
Service			0.012
			(0.136)
Climb			−0.128
			(0.094)
Observations	118	118	118
R^2	0.411	0.594	0.658

Notes: This table shows the results from estimating equation (2). The dependent variable is an indicator for whether a plane had positive market share in the postwar period (1946–65). The results in col. 1 include indicators for whether a firm had bomber, Army/Navy, or Air Mail contracts, or belonged to a holding company. Col. 2 adds controls for capacity and speed;

col. 3 includes additional controls for the no. of engines, engine type, power, load, range, service, and climb. See the notes to tab. for a description of these variables. Standard errors (in parentheses) adjust for within-firm as well as within-year-of-entry correlations of the residuals using multidimensional clustering.

In the absence of controls for plane characteristics in column 1, the coefficients on the indicators for bomber and Air Mail contracts are positive and statistically significant. Interpretation of the coefficients' magnitudes suggest that bomber and Air Mail contracts increased the probability of a postwar market presence by 53 and 9 percentage points, respectively. The coefficients on $army/navy_j$ and $holding_j$ are negative, although only the latter is statistically significant. Across the specifications including controls for plane characteristics (columns 2 and 3), only the coefficients on speed and number of engines are statistically significant. When plane characteristics are included, the magnitude of the coefficient on $bomber_j$ is reduced by half, although it remains economically large: bomber contracts increase the probability of a postwar market presence by almost 21 percentage points. In columns 2 and 3, the coefficients on the other aspects of government contracting are closer to zero and are not statistically significant. Our analysis suggests that postwar survival was aided by the production of large, military airframes as opposed to holding company affiliation or earlier manifestations of government contracting.

The results in table use an indicator for presence in any postwar year up to 1965. To examine variation over time, we re-estimate equation (2) separately for each postwar year and plot the coefficients for the primary variables of interest in figure .[37] The first panel shows the results for the coefficients on bomber contracts. The results are consistent with a higher probability of survival in the commercial market throughout the early postwar period. Note the decrease in the bomber coefficient (panel A) after 1960. This is due to consolidation in the industry so that by the early 1960s most of the remaining airframe manufacturers had held contracts to produce bombers during the Second World War.

Discussion

The shakeout model in section II makes clear that survival is more likely for firms that enter early relative to those that enter late, but this effect can be partially offset through experience. Several shakeout episodes support this theoretical result. Entrants with previous experience in the radio industry were more likely to survive the television shakeout.[38] Likewise, entrants with previous experience in carriage, bicycle, or engine markets were more likely to survive the automobile shakeout.[39] The commercial airframe shakeout provides an additional interpretation of what it means to be an 'experienced' entrant.

We find that survival in the commercial airframe shakeout is explained not only by past experience in a related industry, but by concurrent experience in a related industry, namely, the military airframe industry. We partially concur with Sutton, who writes: '[T]he war years generated a major shock to the industry's structure. As the exigencies of wartime enhanced production capabilities and design experience of all firms involved in military aircraft, so it provided a window of opportunity for these firms to enter the manufacture of civil aircraft in the postwar years'.[40] Our empirical results suggest that not all firms enjoyed this window of opportunity, but that commercial airframe survival was specifically aided by producing large, military airframes for the Second World War.
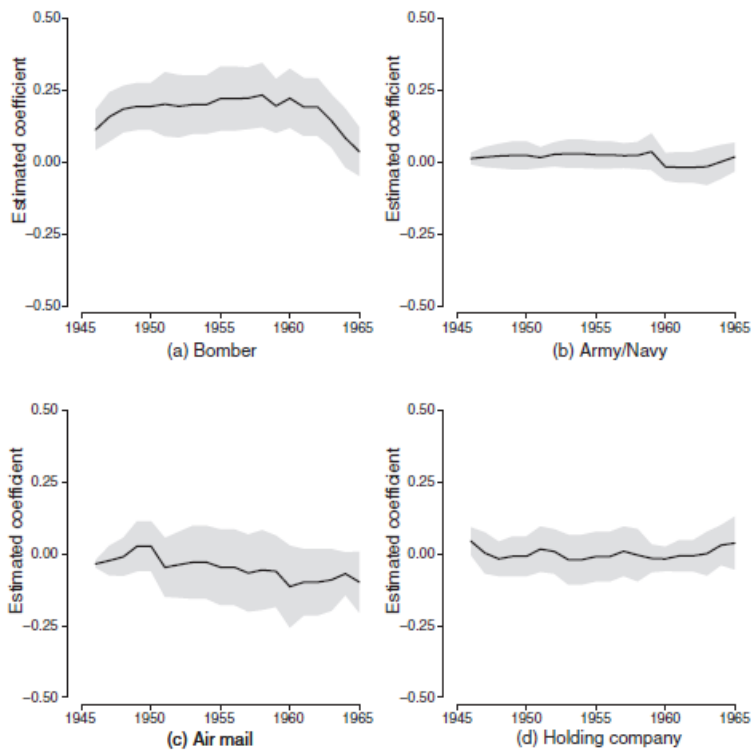
Figure 4. Government contracting and market structure, by year (a) Bomber. (b) Army/Navy. (c) Air Mail. (d) Holding company.

Notes: Each panel of the figure plots the coefficient associated with each type of contract (panels A to C) and whether the firm belonged to a holding company (panel D), for each postwar year (1946–65). The dependent variable is an indicator for whether a plane had positive market share in the postwar period. All specifications included controls for plane characteristics (as in col. 3 of tab. 3). The no. of observations is 118.

In affecting the course of the commercial airframe shakeout through contracts made in the military airframe industry, the government's role in commercial airframes was less direct than in the penicillin industry where the government hand-picked 20 producers. Yet the government's role in shaping survival was crucial in both industries. In the penicillin market, four of the 20 firms selected by the government to produce penicillin accounted for 70 per cent of that industry's post-shakeout sales. Likewise, three of the eight airframe firms with heavy bomber contracts (Boeing, Douglas, and Lockheed) accounted for 79 per cent of commercial plane sales from 1955 to 1965.[41]

Government contracting directly affected survival in the penicillin industry; in commercial airframes, such contracting indirectly affected survival via the military airframe market. The firms that acquired heavy bomber contracts gained advantages in learning capacity.[42] While the jet engine was the product of government-funded R&D, only a few firms had the technological know-how or learning capacity to incorporate this non-proprietary knowledge into a commercially viable jet airplane.[43] As Mowery and Rosenberg write: 'After World War II, the development of jet-powered strategic bombers and tankers allowed airframe makers to apply knowledge gained in military projects to commercial aircraft design, tooling, and production'.[44]

Our empirical results suggest that the advantages in learning capacity gained from bomber contracts were a necessary, though not a sufficient, condition to survive the commercial airframe shakeout. Converting technological advances in aviation from the military to the commercial realm was neither easy nor costless. Rosenberg et al. estimate that under 60 per cent of aviation advances from the military market made their way into the commercial market.[45] In 1948, Glenn L. Martin wrote of the difficulties of absorbing and applying

basic aeronautical research to specific commercial craft: '[D]ata as is made available from [publicly-funded, basic research]… cannot be put to immediate use by the aircraft designer. These data must be analyzed in relation to the specific design project and then perhaps become the subject of further specific tests and study before their usefulness can be fully realized'.[46]

The postwar experiences of Republic Aviation and the Curtiss-Wright Corporation illustrate the difficulties that firms faced in surviving in the commercial airframe market. Republic attempted entry into the commercial market for the first time in the postwar period. Having converted surplus C-54 transports into airliners for American Airlines immediately following the war, the company attempted *ex novo* entry into the commercial airframe market with its Rainbow plane.[47] By 1946, the number of engineers at Republic devoted to the Rainbow project exceeded 420.[48] Though this team developed the fastest piston-engine aircraft in our sample, Republic scrapped the Rainbow project in early 1947.

Unlike Republic, Curtiss-Wright had a storied history in the airframe industry as the merged product of its two earliest entrants. During the 1940s, the firm increased its research staff and its R&D expenditures in line with its competitors.[49] However, much of this research effort was directed at engines rather than airframes. As the company's main source of profit, Curtiss-Wright's management favoured the Wright engine division at the expense of the Curtiss airframe division. More generally, the company's dividend payout ratio (dividends over net profit) was three times that of Boeing and Douglas from 1946 to 1950.[50]

On the other hand, Boeing was so committed to airframe research that the company built its own wind tunnel in 1947, thereafter greatly aiding its competition with Douglas and Lockheed.[51] Donald Douglas, the founder of Boeing's chief postwar competitor, indicates just how extensive his company's airframe R&D commitment was:

> [E]xperience has repeatedly taught that no single experimental airplane or dozen experimental airplanes are a sufficient number to eliminate the major bugs in the design and manufacture of new commercial aircraft or aircraft of any advanced type. In the case of the DC-6, despite great similarity to the Army's C-54 … the Douglas Company is continuing to spend vast sums to improve the airplane after approximately eighty of them have been delivered … In the broad sense development costs never cease, only diminish as production continues during the lifetime of an airplane model.[52]

In the commercial airframe shakeout, as our simulation results in section illustrate, experience mattered. In the first decade after the Second World War, the ex novo commercial airframe entrants were Hughes, Republic, Chase, Martin, and Britain's Vickers-Armstrong. Martin and Vickers-Armstrong were the only members of this group to enjoy any postwar success. Not coincidentally, both companies designed bombers for the war; Martin the B-26 and Vickers the Wellington bomber in England.[53] For markets with government demand, or markets closely related to those with government demand, we emphasize that for entrants, it is better to be early, *best* to be experienced.

Conclusion

This article has used industry history to reinterpret a standard model of shakeout to incorporate government demand, and has shown how this demand channel moulded commercial airframe market structure from the late 1920s to the early 1960s. Theoretical and empirical work on shakeout has emphasized how market forces produce shifts in entry and exit that instigate evolution to oligopoly. In the automobile, tyre, and television industries, this standard story fits. However, in other industries, such as commercial airframes, it lacks explanatory power. Using newly digitized data on plane characteristics and market share for all commercial airframe manufacturers from 1926 to 1965, we have highlighted the critical role of government demand through Second World War-era bomber contracts on the commercial airframe shakeout.

Our results show that government demand must be added to the standard shakeout story in the case of the early commercial airframe industry. Recent evidence suggests that military production had a limited impact on aggregate productivity growth in the immediate post-Second World War period.[54] We have focused on the postwar impact of military production on market structure—on who survived instead of how much was produced—and have identified a large impact of government demand on firm survival. We found that large bomber design and production permitted some airframe firms to gain relative advantages in R&D learning capacity. Such learning capacity differentials then allowed a select group of manufacturers greater access to the postwar commercial airframe market.

We have focused on the period from the origin of the commercial airframe market to the early days of jet airliners. In subsequent years, Boeing acquired Douglas, and Lockheed exited the commercial airframe market.[55] In addition, beginning in 1967, the British, French, and German governments subsidized Airbus, and by the late 1980s the company was profitably competing with Boeing. Today, the commercial airframe market is essentially a duopoly between Boeing and Airbus (along with smaller, commuter plane makers including Bombardier and Embraer). We have argued that in the pre-jet age, governments affected firm survival primarily through indirect military airframe contracts. The 20-year ascension of Airbus was the result of more direct government involvement in the commercial airframe market.[56] So while the channels through which governments affect the evolution of the commercial airframe market have changed over time, government demand continues to shape the industry's market structure.

Notes

1 Authors' Affiliations: Taylor Jaworski, Queen's University, Department of Economics; Andrew Smyth, Marquette University, Department of Economics.

2 We thank the Special Collections staff at Honnold/Mudd Library of the Claremont Colleges for help with primary sources and Carl Kitchens for comments that improved the article. Katrina Brazzell and Will Crouchene provided excellent research assistance. All remaining errors are our own.

7 Aeronautical Chamber of Commerce of America, Aircraft yearbook (1948), p. 35.

8 Jovanovic and Lach, 'Entry, exit, and diffusion'; Jovanovic and MacDonald, 'Life cycle of a competitive industry'; Klepper, 'Entry, exit, growth'; Jovanovic, 'Selection'.

9 Klepper and Graddy, 'Evolution of new industries'; Utterback and Suarez, 'Innovation'; Jovanovic and MacDonald, 'Life cycle of a competitive industry'; Klepper and Simons, 'Making of an oligopoly'; Klepper, 'Firm survival'; Klepper and Simons, 'Industry shakeouts'.

10 David, 'Clio'; Arthur, Increasing returns; Saxenian, Regional advantage; Krugman, 'History and industry location'.

11 We distinguish between the commercial airframe market, or 'those firms developing and manufacturing aircraft intended for use by the domestic trunk lines' (Phillips, Technology and market structure, p. 23), and the military airframe market. Some airframe manufacturers produced planes for only one of these two markets (Grumman, North American, Vought), others for both (Boeing, Lockheed).

12 Gordon, '$45 billion'; Cain and Neuman, 'Planning for peace'; Higgs, Crisis and Leviathan; Field, Great leap forward.

13 Prior to 1925, peacetime civilian aircraft production (including commercial, cargo, and private planes) did not exceed 100 planes per year. Several factors in the 1920s made commercial aviation viable, including the Kelly Mail Act (1925), the Air Commerce Act (1926), and Charles Lindberg's 1927 cross-Atlantic flight. See Rae, Climb to greatness; and Pattillo, Pushing the envelope.

14 Rae, Climb to greatness, p. 48.

15 Quoted in Mowery and Rosenberg, Technology, n. 18, p. 182.

16 Calculated from data in Phillips, Technology and market structure.

17 Sutton, Technology and market structure, p. 426.

18 Phillips, Technology and market structure, p. 127.

19 Klepper, 'Entry, exit, growth'; idem, 'Firm survival'.

20 Cohen and Levinthal, 'Innovation and learning'. The model can be more closely connected to the learning capacity literature by incorporating Cohen and Levinthal's technological and scientific knowledge (z_i) function in place of a_i and $g(\cdot)$. In Cohen and Levinthal, z_i increases in R&D expenditure and in learning capacity.

21 Pattillo, Pushing the envelope. The amount of control exercised by aircraft holding companies over their subsidiaries varied, with United Air & Transport exercising the most control.

22 Holley, Buying aircraft, pp. 33–42. Debt financing was not prevalent.

23 Barron's magazine contemporaneously praised United's management for diversification; 'Net of $2 expected for United Aircraft: despite expansion, operating at a profit in time of general depression—government orders big factor', Barron's, 22 Sept. 1930, p. 21.

24 Utterback and Suarez, 'Innovation'.

25 Phillips, Technology and market structure, p. 119.

26 Bittlingmayer, 'Property rights'.

27 Smith, 'Intercontinental airliner'.

28 Holley, Buying aircraft, p. 28. The models by Klepper were motivated by the automobile and similar industries. The models explain the life cycle in those industries well because, in contrast to the airframe industry, contemporary automakers engaged in the large-scale production of relatively fixed car designs. Superficial similarities of automotive and airframe manufacturing belie major differences. In 1937, 3,100 aircraft were produced compared to 4,732,553 automobiles. As late as 1941, when a Ford executive visited Consolidated's B-24 bomber plant, he noted, 'The nearer a B-24 came to its final assembly the fewer principles of mass production there were as we at Ford had developed and applied over the years. Here was a custom-made plane, put together as a tailor would cut and fit a suit of clothes', as quoted in Rae, Climb to greatness, p. 136.

29 US Congress, Delaney Hearings, 2 Feb. 1934, p. 454.

30 Holley, Buying aircraft, p. 20.

31 Lockheed's quick revival as an independent firm after emerging from Detroit Aircraft's bankruptcy in 1934 is further evidence that scale economies were not a crucial shakeout determinant at this point in the industry's life cycle.

32 Calculated from data in Holley, Buying aircraft, app. B, pp. 576–9.

33 Douglas also produced the B-18, which, while obsolete by the war, was the US's standard bomber in the late 1930s with roughly 350 produced.

34 Phillips, Technology and market structure.

35 Air Mail data were collected from various editions of the Aircraft yearbook. Data on Army and Navy contracts were collected from US Congress, Rodgers Hearings and Delaney Hearings, respectively. Finally, data on B-series bomber contracts were collected from Holley, Buying aircraft.

36 Cameron, Gelbach, and Miller, 'Robust inference'. Also note that pre-1934 holding company affiliation, Army or Navy plane contracts from the 1930s, and Second World War bomber contracts potentially affected postwar market presence (y_j) but the reverse is not possible.

37 Our results are robust to using market share in each year (rather than market presence) as the dependent variable.

38 Klepper and Simons, 'Making of an oligopoly'.

39 Klepper, 'Pre-entry experience'. Earlier, in 'Firm survival', Klepper suggested that experience mattered relatively little in automobiles, that essentially every entrant in penicillin was experienced, and that tyres were so different from other rubber products that no tyre entrants were experienced. Though there was no shakeout in merchant shipbuilding, experience mattered for survival according to Thompson, 'Selection and firm survival'.

40 Sutton, Technology and market structure, pp. 428–9.

41 Calculated from data in Phillips, Technology and market structure.

42 Kotha, 'Spillovers'.

43 Mowery and Rosenberg, 'Technical change'.

44 Mowery and Rosenberg, Technology, p. 185.

45 Rosenberg, Thompson, and Belsley, 'Technological change', p. 50.

46 Aeronautical Chamber of Commerce of America, Aircraft yearbook (1948), p. 147.

47 The C-54 was derived from the Douglas DC-4.

48 Aeronautical Chamber of Commerce of America, Aircraft yearbook (1948), p. 14.

49 Mowery and Rosenberg, Technology and the pursuit of economic growth; Gholz, 'Curtiss-Wright Corporation'.

50 *Calculated from data in Gholz, 'Curtiss-Wright Corporation', tab. 4.*

51 *Kotha, 'Spillovers'.*

52 *Aeronautical Chamber of Commerce of America, Aircraft yearbook (1948), p. 229.*

53 *The learning capacity acquired by Martin in producing massive flying boats (the M-130 'Clipper') should not be underestimated. See Smith, 'Intercontinental airliner'.*

54 *Field, 'Impact of the Second World War'; idem, Great leap forward.*

55 *Sutton, Technology and market structure.*

56 *More recently, the Chinese, Japanese, and Russian governments have heavily subsidized commercial airframe entry attempts.*

57 *See the quotation from Glenn L. Martin in section V.*

58 *Wright, 'Factors affecting the cost of airplanes'; Alchian, 'Reliability of progress curves'.*

59 *Rosenberg et al., 'Technological change'.*

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PHOTO (COLOR): Stylized facts of the commercial airframe shakeout (a) Firms, entry, and exit. (b) No. of passengers. (c) Market concentration. (d) New planes by usage. Notes: Panel A shows the no. of commercial airframe firms (US and foreign), entrants, and exits on time. Panel B shows the no. of airline passengers in the prewar period. Panel C shows commercial airframe market concentration on time. The vertical lines indicate the release dates of major Douglas Aircraft planes. Panel D shows the moving average of new commercial planes, both used and unused, on time. Source: Phillips, Technology and market structure; Aeronautical Chamber of Commerce of America, Aircraft yearbook.

PHOTO (COLOR): Model simulation results (a) Baseline R&D learning capacity. (b) High R&D learning capacity. Notes: Panel A graphs the average firm survival percentage in 100 computer simulations of Klepper on firm age. The parameters used for panel A are used for the panel B simulations, except half of the 'later entry cohort' in panel B have high R&D productivity as described in the text.

PHOTO (COLOR): Working capital, by holding company Notes: This figure shows working capital (current assets minus current liabilities) from Dec. 1928 to Dec. 1933 for several major holding companies and one independent firm, Douglas Aircraft. The holding companies were disbanded by the Air Mail Act in June 1934. The dashed vertical line indicates the 'Black Tuesday' stock market crash of Oct. 1929. Source: Moody's Investors Service, Moody's manual of industrials.

PHOTO (COLOR): Government contracting and market structure, by year (a) Bomber. (b) Army/Navy. (c) Air Mail. (d) Holding company. Notes: Each panel of the figure plots the coefficient associated with each type of contract (panels A to C) and whether the firm belonged to a holding company (panel D), for each postwar year (1946–65). The dependent variable is an indicator for whether a plane had positive market share in the postwar period. All specifications included controls for plane characteristics (as in col. 3 of tab.). The no. of observations is 118.

PHOTO (COLOR): Model simulation results (no cost spillovers) Notes: Panel A graphs the average firm survival percentage in 100 computer simulations on firm age. The parameters used for panel A are used for the panel B simulations, except half of the 'later entry cohort' have high R&D productivity. Whereas cost spillovers are allowed in the simulations in fig. , such spillovers are prohibited here.

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