Whose Frac is It, Anyway? Using Sources of Productivity Gains to Explain Industrial Organization in Oilfield Services*

Timothy Fitzgerald† Charles F. Mason‡

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Abstract

We analyze the the relative roles played by sellers and buyers of frac jobs on experimentation, innovation, and diffusion of knowledge about hydraulic fracturing. An historically-concentrated sector has experienced substantial entry and erosion due to vertical integration by buyers. This changing industrial organization affects and is affected by the changing relative technical proficiency of service companies and their operator clients. We document how a proxy for the technical prowess of the oilfield service sector has changed substantially over time, consistent with weakening. It is not clear from the evidence brought to bear what the direction of causation is.

JEL Codes: L14, L71, O33, O34
Keywords: technological change; technological diffusion; oilfield service company; hydraulic fracturing; patents

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†Rawls College of Business, Texas Tech University; timothy.fitzgerald@ttu.edu

‡H.A. "Dave" True, Jr. Chair in Petroleum and Natural Gas Economics, Department of Economics & Finance, University of Wyoming; bambuzlr@uwyo.edu

1 Introduction

Hydraulic fracturing has evolved in productivity-enhancing ways through experimentation, innovation, and diffusion. This evolution has had important implications for the oil and gas sector as well as global consumers. In this paper we analyze the effect of this process on the relative roles played by sellers and buyers of frac jobs. Until recently, there were a small number of sellers—oilfield service companies—raising the possibility that would exercise market power. The well servicing industry has historically been highly concentrated. Rogers (2011) reports a 75 percent market share for the three largest service companies in the pressure pumping market. Indeed, one motivation for innovation in hydraulic fracturing was the high markups on gels, which were furnished by service companies at markups as high as 1000 percent (Steffy, 2019). On the other hand, in certain locations there are also a small number of buyers—well operators—raising the possibility of bilateral oligopoly. The ultimate resolution of this strategic interaction is ambiguous *ex ante*. Recent years have seen substantial entry into the oilfield services sector and a reorganization of the tasks it historically performed. This change affects the incentives for further experimentation with hydraulic fracturing as a source of productivity gains.

It might seem counterintuitive to think that a service company acting as a contractor would influence the path of productivity gains; the operator of a well is ultimately responsible for all activity and bears legal liability. For this reason it is natural to presume that the operator will maintain operational control over all aspects of operations. However, operators vary in their technically proficient in certain aspects of operations, and may therefore choose to employ specialized contractors for operations such as drilling or fracturing. We observe that all operators engage one or more specialists for hydraulic fracturing, which raises the question about which firm asserts more control over this dimension of the production process. The opportunity for hidden action exists, and contracts explicitly acknowledge and provide incentives for experimentation by service companies. Because of the high degree of technical specialization, contracts governing relationships between contractors can be quite complex. One high-profile illustration of this is the interconnectedness between BP (operator), Anadarko (partner), Halliburton (service company), and Transaocean (driller) during the drilling of the Macondo well, which ended in a blowout that destroyed the rig and led to a massive oil spill in the Gulf of Mexico. Ownership and control over aspects of operations are at the crux of the issues (Fama and Jensen, 1983), in particular how that separation might affect incentives to innovate.

Fetter et al. (2018a) is a recent study addressing the social diffusion of hydraulic fracturing expertise via public disclosure, using data from Pennsylvania. Addressing the issue of disclosure of hydraulic fracturing chemicals, the paper documents the diffusion of the most productive frac recipes to other operators, and an attendant reduction in new experimentation that was previously led by the firms with the highest-producing wells. While there are several potential channels for diffusion, Fetter et al. (2018b) assert that operators maintain control over fracs. In contrast, Fitzgerald and Mason (Forthcoming) reports significant differences in frac recipes across service companies.

Zborowski (2019) summarized some of the major changes observed in application of hydraulic fracturing in the United States during 2010–2017: the mean amount of proppant per treated foot more than tripled, the fluid volume pumped increased by 2.5 times, and the number of feet per treated stage fell by over 40 percent. In short, fracturing became more intensive. To facilitate that intensification, innovations were needed in a variety of dimensions—logistical chains both on and off the wellpad, downhole perforating and measurement, more pumping power, and improved fluid chemistry to sustain higher proppant loads.

Who deserves credit for the technological advances that have vaulted hydraulic fracturing into the common lexicon? How has changing market structure affected the contribution to and credit for continuing advance in productivity? Those are the questions that we try to answer, using different pieces of evidence.

We conduct three empirical exercises. First, we examine the timing of the diffusion of expertise about hydraulic fracturing and how the oilfield service sector reacted to those changes. Second, we apply to a similar dataset the methodology of Fetter et al. (2018a) for comparing similarity of frac jobs. We find noticeable different patterns than Fetter et al. (2018a), which suggests that their results may not apply in all places and time periods. Third, we explore an alternative pathway for diffusion of developing knowledge—academic publications. We find strong evidence that authors from service companies made outsized contributions to the public body of knowledge, especially early in the development of hydraulic fracturing. Over time, as information asymmetries evened out and the oilfield service sector became more competitive, the publication leadership waned.

The results of these empirical exercises suggest that oilfield service companies previously had a more important role in driving productivity gains in hydraulic fracturing.

2 Background

2.1 Hydraulic Fracturing Evolution as Technological Change

Hydraulic fracturing as a technology can be traced to 1947 and perhaps even as early as the 1860s (Montgomery et al., 2010). The mechanics of the technology are well-explained elsewhere. While used for decades to stimulate conventional reservoirs, the more recent knowledge about how to use the technology to exploit deposits of source rock like shales has lead to a diffusion of the technology of particular relevance. The adaptation of an existing technology to a new problem is not novel. When the realization that hydraulic fracturing could be reengineered and repurposed was made around 2000, only a couple operators and service companies grasped what could be about to occur. A resource bonanza ensued, with tens of thousands of wells providing a perfect setting for experimentation, potential learning-by-doing, and realizing economies of scale.

Gallegos and Varela (2015) trace the adoption of hydraulic fracturing from 1947–2010. After two decades of consistent but unchanging usage, in a five year period between 1997–2001, the number of frac treatments in the United States doubled. By 2007 they had doubled again. This evidence suggests that the period of initial technological diffusion was perhaps earlier than often presumed (often dated to 2008 and after). Within the industry, the cat was getting out of the bag much earlier.

Paragraph here about input changes and setting up the input substitution point in next graph Fukui et al. (2017) (Covert, 2014; Fitzgerald, 2015) Contrast with Agerton (2020), which attributes gains to geological variation and not inputs

Weijers et al. (2019) cite an important example of input substitution. Documenting the rapid growth in overall proppant used by the industry after 2010, "use of higher-quality proppants such a Resin-Coated Sands (RCSs) and ceramics have been marginalized and now the industry is focusing on even lower-cost locally-sourced, poorer quality sands." Whereas RCSs and ceramics had a roughly 25 percent market share in 2009, by 2005 the share was less than 5 percent (Weijers et al., 2019). This suggests that these high-quality proppants are inferior inputs (Epstein and Spiegel, 2000; Weber, 2001).

Another reason for entry into the traditional realm of service companies has been the dramatic increase in demand for pumping horsepower. Weijers et al. (2019) document a near tripling in the mean intensity of pressure pumping (0.16–0.42 bpm/ft) from 2010–2017. This required a massive increase in the amount of pressure pumping and frac spreads available to the industry, a large share of which was met through entry.

The bottom line is what ultimately matters to oil and gas producers, and the technological improvement in hydraulic fracturing has delivered substantial cost decreases. Weijers et al. (2019) report that service companies have achieved substantial cost reductions that they can pass along to their customers, reducing the price per pound of proppant placed downhole by a factor three to five. Details of the source of these reductions point towards gains from greater specialization, moving away from a more traditional service company role providing a bundle of services.

2.2 The Structure of Oilfield Services

There are many dimension of adjustment in well completions, including perforations, stages, pressure, and the particular combination of inputs that are injected into the well. Not surprisingly, we observe firms that specialize in the different activities of drilling boreholes, performing frac jobs, and the production and marketing of oil and natural gas. The last group, oil and gas operators, hire technical assistance from an array of contractors including drillers, pipeliners, and service companies. Platt and Platt (1989) showed the strong interrelationship between oil and gas producers and oil and gas field service companies—not surprising given that the service industry relies on upstream investment by developers. As unconventional resources grow more important to the U.S. reserve base, service companies have assumed an important role in well completions and hydraulic fracturing.

Given the interdependence between the two types of firms, and the potentially strategic environment, the governance of the relationship between these firms is an important consideration. Operators and service companies interact in repeated games. Corts and Singh (2004) studied the use of alternative contracts between developers and drillers in an offshore context; their results suggest that transaction costs are minimized by using weaker (day rate) contracts, but that repeated interaction is important to the success of the relationship. Kellogg (2011) found similar results in the onshore drilling context. Strong productivity gains from repeated interaction help explain the prevalence of long-term weak contracts between drillers and developers. Fitzgerald (2015) provides some evidence that strong productivity gains are not as likely between developers and service companies, which would help explain the use of strong contracts.

The oilfield services sector has seen substantial entry and more competition in recent years, a trend that some observers expect to continue (Jacobs et al., 2019). One important factor has been an increased focus on cost reduction by operators facing lower oil prices since 2014. The competitiveness of U.S. producers against conventional producers like OPEC has relied in large measure on reducing completion costs while continuing to increase productivity.

The space traditionally occupied by oilfield service companies has fragmented, and the dominant position of occupant firms identified by Rogers (2011) has eroded. Measuring market share by pressure pumping capacity, by the end of 2018 the same three firms had less than 60 percent share (Rystad 2018). Coras (2016) tells a much grimmer story with a 31 percent market share, but also highlights another important industry change. Operating firms, traditionally the clients for the oilfield service companies, had 13 percent of the deployed pumping capacity. This suggests that in addition to increased competition within its own sector, oilfield service companies faced vertical integration of one of their products by their customers. Using pressure pumping capacity as a proxy for the market share of oilfield service companies may undercount the capacity of larger firms to provide a greater scope of services.

3 Measuring Technological Diffusion

Posit four pathways for technical diffusion: specific knowledge within a partnership, diffusion via employees, diffusion via private knowledge made public, and diffusion via publicly-intended knowledge.

In the first part of the analysis, we apply the methodology of Fetter et al. (2018a) to the data of Fitzgerald and Mason (Forthcoming) to try to resolve the differing results. The data are drawn from an earlier time period with far fewer operators. While the earlier time period may advantage service companies, the small number of operators should lead to more concentrated gains.

Frac recipes that have dozens of additives, chosen from a choice sets of hundred of possible chemicals, pose a measurement challenge. Fetter et al. (2018a) use a innovative method to measure the similarity or divergence in these recipes; the Jaccard index collapses a high-dimensional vector with potentially many zeros to the unit interval. Figure 1 depicts the smoothed distribution of these scores for wells with the same or different operators for 4,944 wells in Pennsylvania. While the same operator distribution first order stochastically dominates the different operator distribution, both exhibit a substantial degree of variability, ranging from 1 (perfectly similar) to 0 (no ingredients in common).

Using data described in Fitzgerald and Mason (Forthcoming), we used a similar methodology but found a markedly different result. Figure 2 shows the smoothed distribution of Jaccard similarities for 352 wells in Sublette County, Wyoming. The tighter distribution of most frac jobs (Jaccard similarities above 0.8) suggests that a different process is at play. Wells in the Wyoming sample appear to have converged more strongly than the sample in Fetter et al. (2018a). It is important to note that hydraulic fracturing has been used in Sublette County since the early 1990s, giving a long history to learn from.

A number of factors could explain the more concentrated distributions that we observe. It is possible that Wyoming is further along the frac learning curve. While a single county in Wyoming does not have as many wells as the entire state of Pennsylvania, a longer time period of experience with unconventional wells may have given the industry more time to fine-tune its frac recipe. A second possibility is that there are fewer or smaller relevant differences in the geology across one county than there are across a state. One reason for slightly different frac recipes across Pennsylvania is that the geology may differ slightly, requiring different recipes to maximize well productivity. A third explanation could have to do with the structure of the industry. Fetter et al. (2018a) underscore the competitive nature of the industry in Pennsylvania, both for operators and for service companies. As a new province relatively far from established centers, new entry in Pennsylvania might be efficient. We note, however, that our setting in Wyoming has a highly concentrated structure, both for operators (four firms) and for service companies (three). This raises the possibility of market power as a motive force for the different result. The only way to get further convergence in Wyoming is via a merger or acquisition—different operators and service companies use and provide different input mixes. A joint firm might use multiple different recipes, perhaps because of differing geology, or it might select a single optimal input mix and collapse the distribution to one (optimal) input mix.

4 Conceptual/Theoretical Model?

If Chuck has something, or if there is some relevant literature. Might want a model that includes

5 Other Pathways for Diffusion

In measuring the diffusion of technological advances, economists have analyzed patents (MacGarvie, 2005; Johnstone et al., 2010; Moser, 2013). An alternative measure is academic citations. While all measures all have their own weaknesses (Nelson, 2009), we examined the affiliations of authors in the *Journal of Petroleum Technology* between 2000–2019. We downloaded 18,959 papers including the keyword “hydraulic fracturing” published in JPT from 2000-2019 and extracted the reported affiliation of each author. These affiliations were matched to a handful of affiliation types, detailed in table 1.

The first column identifies different types of affiliations of authors. The second column counts the total number of papers published by *any* author reporting that affiliation. Coauthorship across affiliation types accounts for why there were more papers by affiliation than total number of papers. The final column tabulates *all* authorships by affiliation. One interpretation of the total is that the mean paper has 72,966/18,959 = 3.85 coauthors. The affiliation categories correspond to specialized contractors, independent operators, major operators, national oil companies, academic researchers, service companies, and a remainder category of all other affiliations. In addition, some authors do not identify an affiliation.

Figure 3 displays the evolution of authorships of these papers. This effectively counts each author as equal, and therefore overweights papers with more coauthors. Four trends are immediately evident in the figure. First, the gross number of authorships on the topic of hydraulic fracturing has expanded dramatically, from around 1100 annually during 2000–2004 to around 7000 annually from 2015–2019. This could be accounted for by a spurious correlation due to increasing numbers of coauthors over time. Second, the largest share of authorships by affiliation is academic and research institutions across the entire time period. Third, the share of authorships from academic and research institutes is growing over time. Fourth, the second-largest categorized affiliation, service companies, lost authorship market share over time. That is clearer in figure **??**, which traces the share of authorships over time.

An alternative measure to authorships is paper-equivalents, which assumes that each of several coauthors made an equal contribution. Figure 5 shows a similar trend in overall growth in the number of publications each year, expanding by approximately four times over the two decades we analyzed. By either the authorship of the paper-equivalent metric, the deterioration in the share accounted for by service companies is striking. In 2005, for example, service companies accounted for 25 percent of authorships and 27 percent of paper-equivalents. By 2019 those shares had fallen to 10 percent of authorships and 12 percent of paper-equivalents. The absolute contribution fell as well, from 1469 authorships in 2015 to 893 in 2019, and from 326 paper-equivalents in 2015 to 179 in 2019—the lowest level in a decade. Figure 6 shows the evolution of paper-equivalent shares over time.

Other types of affiliations exhibit time-invariant patterns in the data. First, the independent producers, who drill most of the wells in the United States, do not invest much into research publication. Larger operators, including major integrated oil companies, have larger research departments and expert geology and engineering staffs, so it is not surprising that they contribute, even though they drill fewer wells. National oil companies, which largely do not employ hydraulic fracturing, are similarly equipped with technically-proficient personnel who can contribute to scientific literatures. A substantial fraction of authors and publications emanate from places not otherwise classified. Some authors come from major corporations with substantial research expenditures, while many others come from boutique consultancies or other opaque organizations. Many of these affiliations are individually responsible for only a handful of authorships.

Two interpretations of the changes in publication shares by service companies over time are relevant. First, service companies appear to have had a substantial informational advantage, especially early in the propagation of hydraulic fracturing. The greater experience and expertise translated into more publications and a greater share of the overall contribution to knowledge. Second, the systematic differences between researchers at different kinds of

One final important metric is to weight papers by their citation in subsequent wok. While this methodology may be biased against more recent papers, it can help identify where contributions deemed important or significant by other researchers emanated from. To account for the potential bias towards older work, the citation weights are calculated as a share of citations of all papers in the publication year. Figure 7 reveals the results. Here again, the historically important position enjoyed by service companies has been substantially eroded in recent years.

6 Linking Diffusion of Technology and Industry Structure

What can we say about direction of causality?

Rosenberg (1982) draws a distinction between learning by doing, in which producers learn, and learning in which buyers provide feedback. It seems that the case of the hydraulic fracturing moved from the one of learning by doing, in which oilfield service companies were learning by doing, through a stage of learning by using, during which operators gained considerable technical expertise. This technical knowledge was likely gained through a combination of relationship-specific experience and the migration of personnel with specific knowledge between service companies and operators and vice versa. Once operators learned by using, then the opportunity presented itself to vertically integrate and for operators to assume many of the tasks previously contracted out to service companies. As this happened, the competitive pressures on the servicing sector increased.

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Table 1: Author Affiliation Classifications

Category	Examples	Share of authorships (%) (all years)
Contractor	FracGeo, MicroSeismic, Petro-Geotech	2.92
Independent Producer	Devon, Encana, Pioneer, Southwestern	2.67
Integrated Oil Company	Exxon, Chevron, BP	6.06
National Oil Company	Saudi Aramco, Pemex, Equinor	10.84
Academic/Institute	Universities, National Labs	33.38
Service Company	Halliburton, Schlumberger, Weatherford	20.12
Other	Battelle, Dow Chemical, Dupont, 3M	22.32
None Given		1.69
Baker Hughes		1.61
Halliburton		3.46
Schlumberger		7.47
Subtotal		12.54

Notes:

Table 2: JPT Authorship by Affiliation, 2000–2019

	# papers (author-weighted)	# authorships (all authors)
Contractor	1,003	2,129
Independent	839	1,950
Major	1,682	4,425
NOC	2,750	7,906
Academic	8,721	24,357
Service Co.	4,948	14,680
Other	6,557	16,285
Unreported	820	1,234
Total	18,959	72,966

Notes: Based on sample of 18,959 papers published in JPT from 2000-2019. The first column identifies different types of affiliations of authors, as explained in table 1. The affiliation categories correspond to specialized contractors, independent operators, major operators, national oil companies, academic researchers, service companies, and a remainder category of all other affiliations. The second column counts the total number of author-weighted papers. This assumes all coauthors contribute equally. One interpretation of the total is that the mean paper has 72,966/18,959 = 3.85 coauthors coauthors. The final column reports the total number of authorships by author affiliation.

Figure 1: Distribution of Jaccard Index Describing Similarity of Hydraulic Fracturing Additives in PA, from Fetter et al. (2018a)

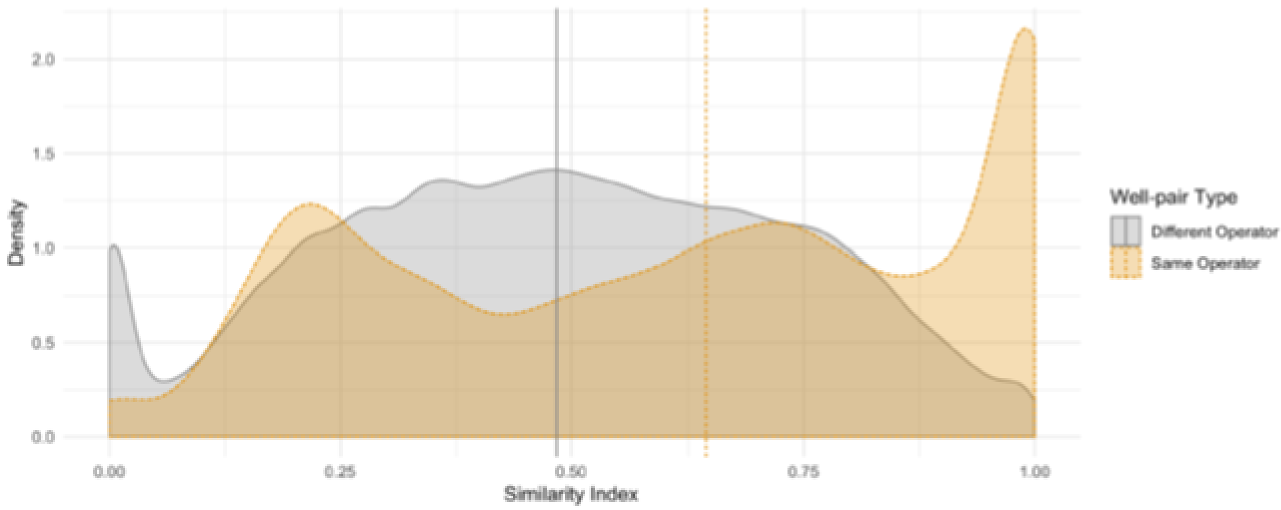

Figure 2: Distribution of Jaccard Index Describing Similarity of Hydraulic Fracturing Additives in Sublette County, WY

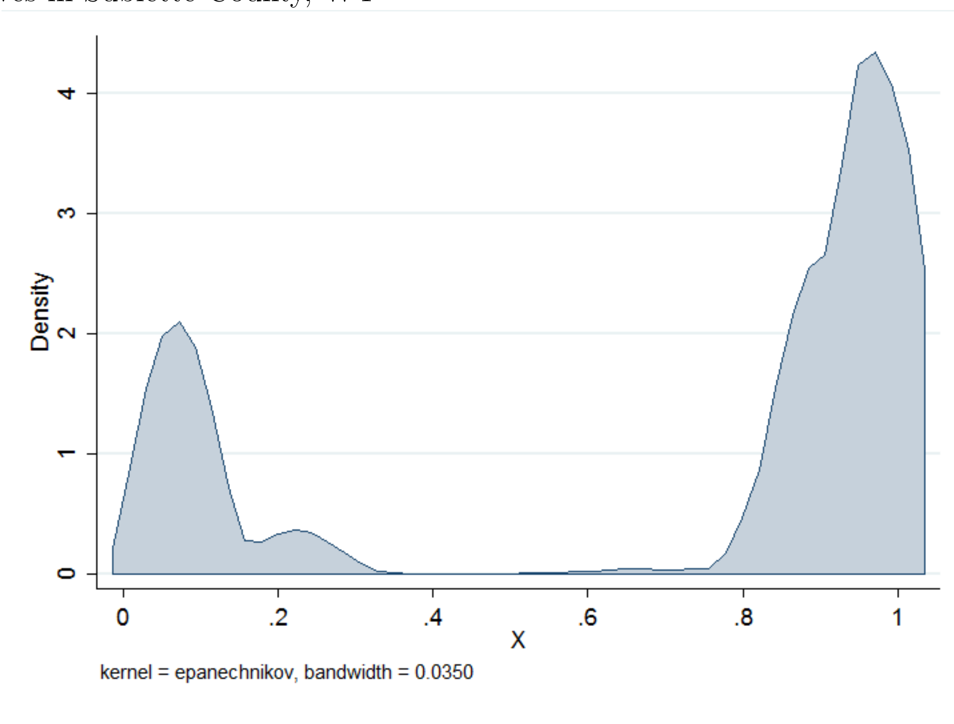

Figure 3: JPT Authorships by Author Affiliation, 2000–2019

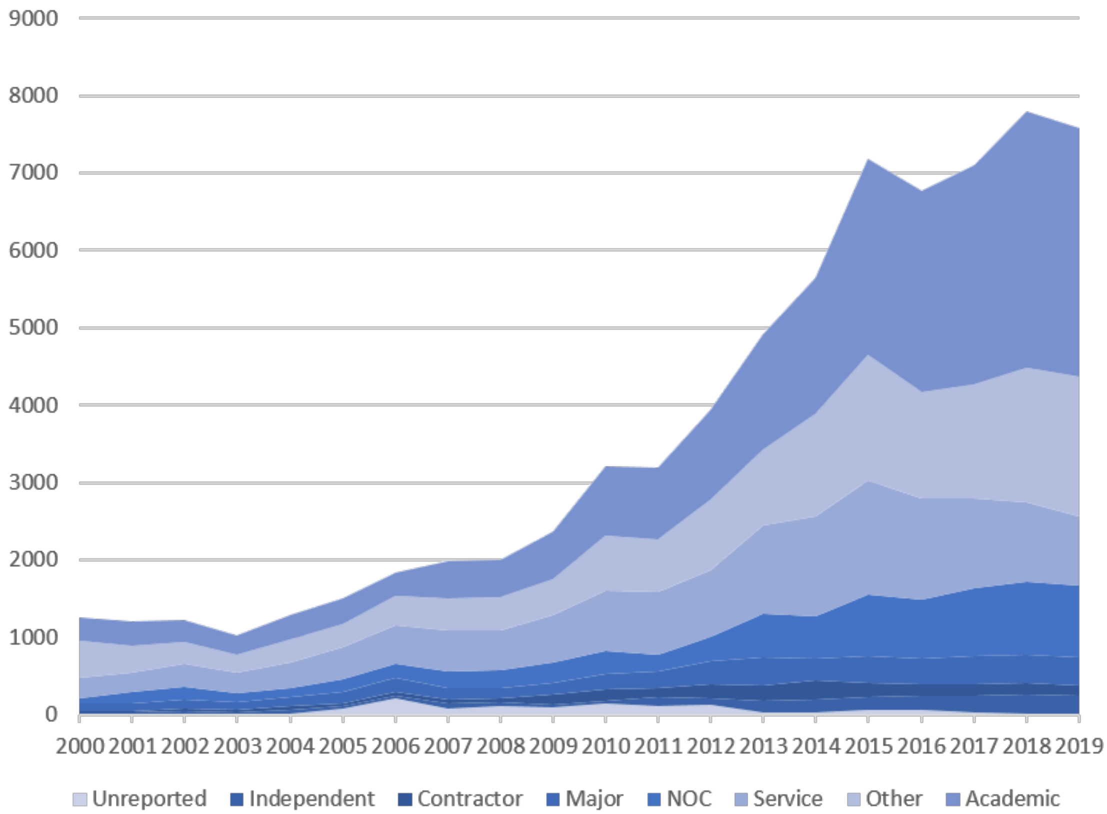

Figure 4: JPT Authorship Share by Author Affiliation, 2000–2019

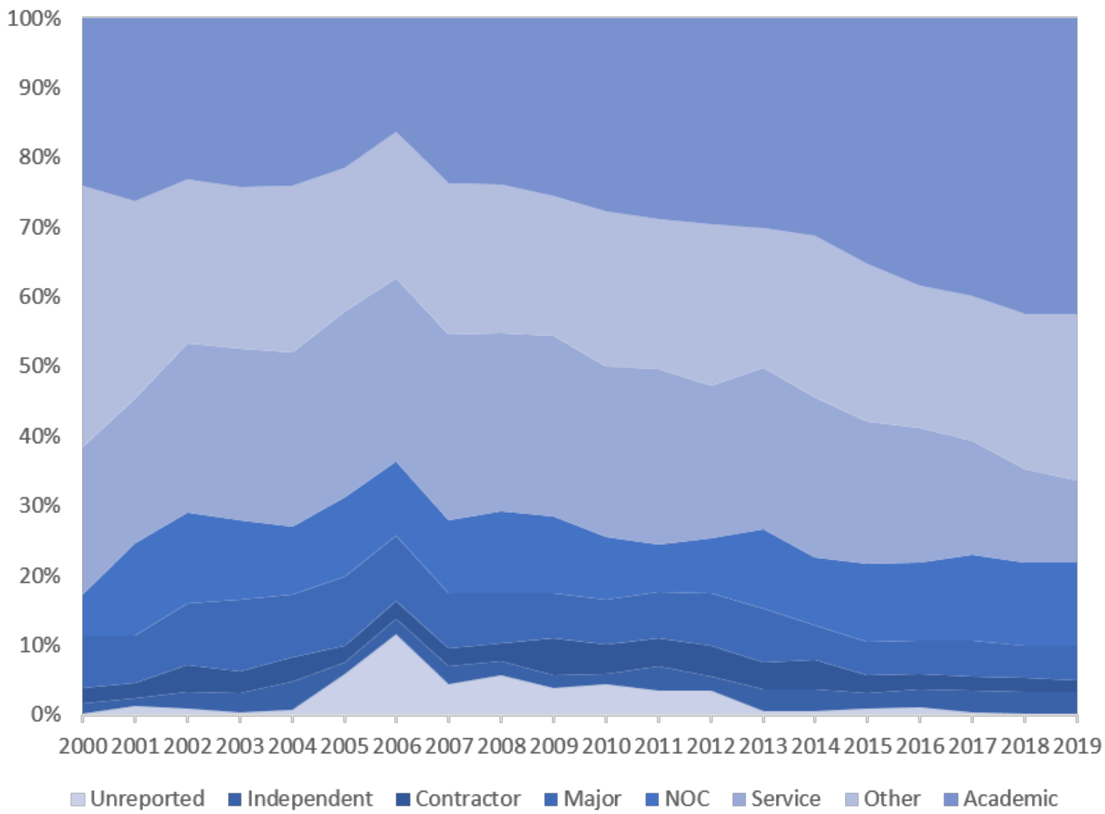

Figure 5: JPT Publications by Author Affiliation, 2000–2019

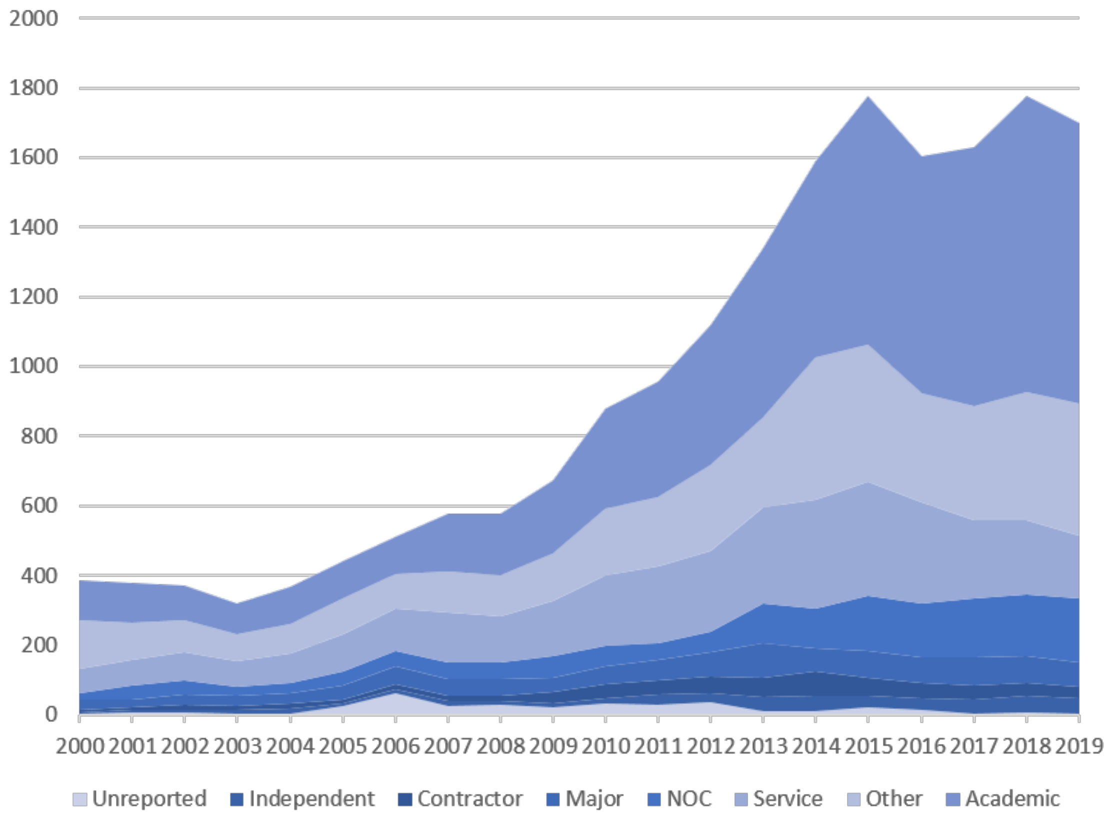

Figure 6: JPT Publication Share by Author Affiliation, 2000–2019

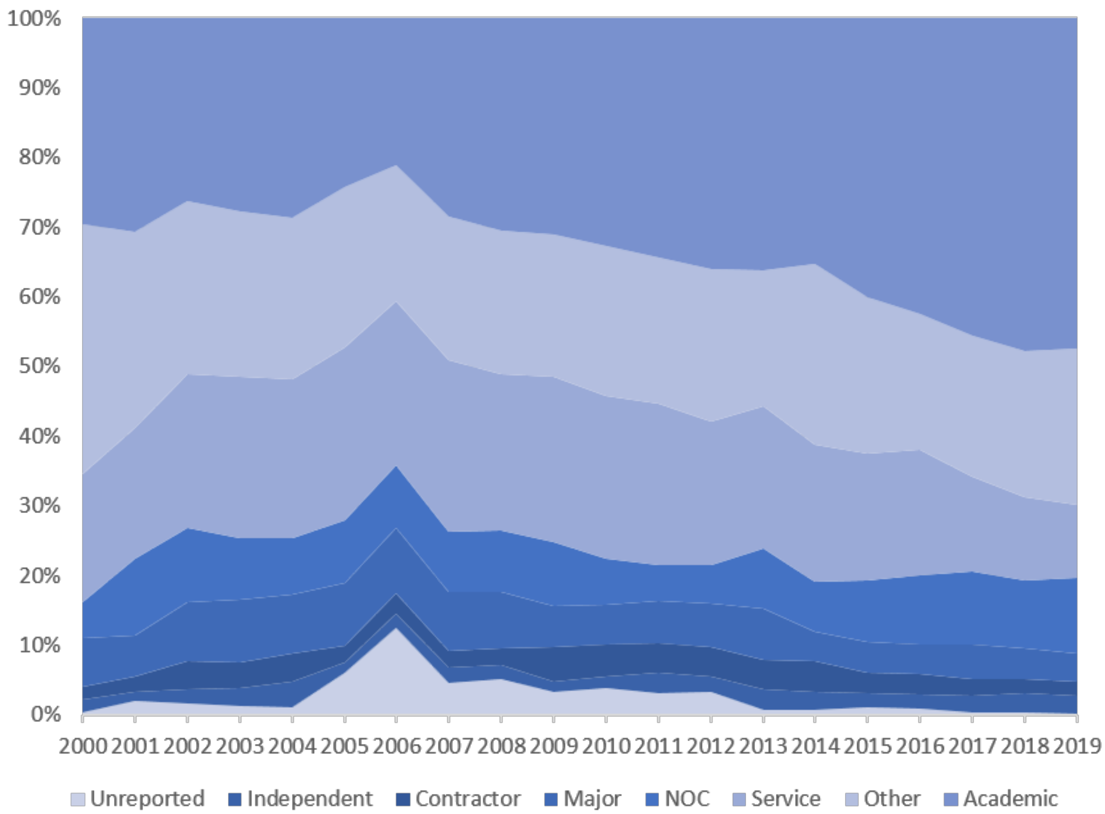

Figure 7: Citation-Weighted JPT Publication Share by Author Affiliation, 2000–2019