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Cost and Efficiency in Government Outsourcing: Evidence from the Dredging Industry†

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This paper investigates the how government outsourcing affects efficiency and expenditures by considering how outsourcing decisions are determined along two dimensions: (i) cost differences between private firms and government suppliers of public goods and (ii) dynamics arising from cost complementarities and capacity constraints. I formulate and estimate a dynamic model of government outsourcing using project-level data from the dredging industry. Model estimates indicate substantial cost savings due to outsourcing but also that government presence in the market yields cost reduction. A counterfactual policy featuring direct competition between government and private sector firms finds a total expenditure reduction of 15.7 percent. (*JEL* D44, H41, H57, L84)

The role of the private sector in the provision of public goods and services is a topic of ongoing debate. Government agencies searching for the lowest-cost providers often leads to outsourcing, or contracting out, projects and tasks to the private sector, counting on productive efficiencies of private firms and the competition generated by procurement mechanisms to secure lower prices.[1] The consequences of these decisions are large. Outsourcing contracts in the United States span education, healthcare, regulatory compliance, public infrastructure, and many other industries, with total expenditures of $597 billion in 2019 (Bloomberg Government 2020).

Given the widespread nature of outsourcing, assessing its costs and benefits is important in evaluating the functions of government. Numerous theories have arisen aimed at clarifying the private sector's role in the provision of government services. Shleifer and Vishny (1994) illustrate how inefficiencies can arise within government firms, while Hart, Shleifer, and Vishny (1997) and Williamson (1999) detail environments in which government provision is optimal. However, existing empirical evidence on government outsourcing is largely descriptive and does not assess

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[1] Outsourcing is distinct from privatization in that it does not involve the transfer of ownership or control of government assets.

direct outcomes such as efficiency effects.[2] Measuring the differences in costs faced by government and private sector firms is necessary not only to assess the performance of outsourcing but also to inform how government should participate in these markets.

In this paper, I use data from the US dredging industry on a history of in-house and outsourced public infrastructure projects as well as procurement auction outcomes to estimate a structural model of outsourcing. A structural approach allows for new empirical insights through disentangling the impacts of productive efficiency, competition, and dynamic effects on outsourcing. This allows me to quantify the extent to which outsourcing is driven by the "cost effect," or efficiency advantages of private sector firms over government, versus by the "competition effect," or the competition between firms generated by the procurement process. When multiple outsourcing decisions are made over time, there are often future cost implications from current outsourcing decisions.[3] By estimating a multiperiod model in which cost complementarities across projects and capacity restrictions impact future costs, I am able to capture these dynamic effects.

Understanding the interactions between cost, competition, and dynamic effects guides how government should participate in procurement markets. Counterfactual simulations demonstrate how government presence in the market leads to substantial benefits when the level of competition is low. This is due to using government costs, including the impact of in-house provision on future costs, as the outside option of not outsourcing. The ability to credibly threaten to take projects for which there are few competitors and high bids leads to increased allocative efficiency and lower total expenditures. Given the low levels of competition generally present in procurement markets,[4] these results suggest an increased government presence in public service provision may prove beneficial.

The empirical setting used is the US dredging industry, from which I use data on project-level outsourcing decisions made between 1999 and 2013. Dredging projects are maritime construction projects chiefly aimed at keeping waterways navigable and are completed by large vessels called dredges. The dredging industry lends itself to the study of outsourcing as each year the US Army Corps of Engineers (USACE) splits the completion of government dredging projects between USACE owned and operated dredges and private sector dredging companies. The USACE operates 12 dredges that complete approximately half of all projects. The remainder are contracted out via procurement auctions in which the awards total between $700 million and $1.1 billion annually. Projects often vary considerably in size and scope across sectors.

In addition to the size of a project contributing to the cost of completion, there are two factors that lead to future cost considerations for the government. First, projects may be hundreds of miles apart, and transporting large dredging vessels and other equipment necessary to complete the projects is costly. Second, project

[2] Examples include Snyder, Trost, and Trunkey (2001), Stevens (1978), and Bel and Rosell (2016).

[3] For example, a municipality deciding whether to renew a contract for emergency medical services may consider an upcoming contract renewal decision for fire prevention and suppression in its decision, as fixed costs of establishing an in-house ambulatory service might be shared with that of a fire department.

[4] See, for example, Kang and Miller (2021) on US procurement markets.

dates routinely overlap and dredges themselves must remain on the project site until the work is completed; as such, assignment of a government dredge to work on one project may preclude keeping a future project in-house.

I specify and estimate a dynamic model of government outsourcing decisions that allows for both cost differences between private firms and government that vary with project characteristics and dynamic effects arising from travel distance costs and capacity restrictions. Based on its own expected project cost and dynamic considerations, the government decides each period to keep a project in-house or to outsource via a first-price sealed-bid auction. If a project is outsourced, potential bidding firms play a two-stage auction with entry game in which a first-stage entry game determines auction participants with participating bidders submitting bids in a first-price sealed-bid auction in the second stage.

By focusing attention on the role of cost differences, competition, and dynamics, this paper is complementary to much of the existing literature on outsourcing and make-or-buy decisions. Previous empirical work has focused on the role of transaction costs and property rights. The transaction costs economics framework of Williamson (1975, 1979) emphasizes the costs that are incurred by engaging in market transactions, including the well-known hold-up problem. Holmstrøm and Roberts (1998) provide a theoretical overview of firm make-or-buy decisions and Lafontaine and Slade (2007) survey empirical work on these models.

The property rights model of Grossman and Hart (1986) and Hart and Moore (1990) focuses on defining the boundaries of the firm by ownership of assets and the role of asset specificity in determining which tasks are completed within the firm and which are contracted out. I abstract from the asset specificity and ex post contract renegotiation that are central to property rights and transaction cost models as these are not a major concern in the dredging industry.[5] This paper also considers the make-or-buy decision within a dynamic context, while the empirical literature to date has focused on the static case.

Identification of the distribution of government costs in a dynamic discrete choice model is complicated by the presence of the future value component in the decision problem and the fact that outsourcing decisions do not directly reveal government cost. Two steps allow these issues to be circumvented: first, nonstationarity of state transitions yields a subset of "temporarily static" periods in which the future value components cancel and so dynamic considerations play no role in the decision of whether or not to outsource the project. Second, heterogeneity in competition across markets generates variation in the expected winning auction bid that identifies quantiles of the government cost distribution. I establish identification of the random, unobserved component of utility in the dynamic model, in contrast to much of the literature on dynamic discrete choice models in which this distribution is assumed to be known.

Results from the structural model indicate substantial cost differences between private firm and government provision, with a government cost advantage for smaller

[5] Dredging typically does not require specific investment for any one project, and there is no pattern of higher costs after contract adjustment that would indicate ex post renegotiation due to incomplete contracting. The online Appendix contains additional details.

projects while larger projects favor private firms. I estimate that for outsourced projects, which tend to be larger than those kept in-house, average private firm costs are 23 percent lower than government costs. However, in-house provision remains cost efficient for many smaller projects, and government presence in the market remains an important cost reducing force. Counterfactual simulations in which the size of the government fleet is reduced reinforce this, showing that while small reductions would have little impact, substantial cuts to the government's fleet would noticeably increase expenditures.

Using the model estimates, I implement an alternate procurement mechanism in which the government uses the in-house option to impose discipline on private firms in the procurement market. In this mechanism, the government directly participates in the auction by setting a dynamically optimal reserve price that takes into account both current and future costs of in-house completion. I find that total expenditures would be reduced by 15.7 percent through such a policy, indicating that there is scope for the government to further leverage its own resources in the procurement process to improve outsourcing outcomes. This policy is related to recent empirical work on the performance of procurement auction mechanisms, including Krasnokutskaya and Seim (2011), Lewis and Bajari (2011), and Decarolis (forthcoming). The main innovation of this paper is to identify the government's own in-house completion costs as the outside option of not outsourcing and to use these costs in setting the auction reserve rate to enhance allocative efficiency.

Understanding when direct government competition against private sector firms leads to cost reduction and welfare gain can be applied to many other industries that feature both a public and private sector presence. In health care, private health insurance companies regularly compete against the US government's Medicare program (Curto et al. 2014). The USACE operates as part of the US Department of Defense; in other areas of the Department of Defense, projects that could have been completed in-house are regularly contracted out (Snyder, Trost, and Trunkey 2001) and these procurements often have low competition (Kang and Miller 2016). In education, private schools and public schools operate side-by-side and compete for student enrollments (Epple and Romano 1998). Local governments must often decide which public services to provide in-house and which should be contracted out; for example, Levin and Tadelis (2010) study local government decisions to contract out public services such as water treatment and public park landscaping.[6] The results of this paper suggest ways in which government resources can be positioned to best take advantage of this mixed market structure.

The rest of the paper is structured as follows: Section I introduces the empirical setting and data. Section II describes the structural model of government outsourcing decisions. Section III discusses identification of the model, while estimation and results are given in Section IV. Section V gives the results of counterfactual simulations. Section VI concludes.

[6] In particular, they use three project measures—difficulty of measurement, need for flexibility, and holdup potential—as indicators for outsourcing candidates. The low potential for holdup, as evidenced by small ex post changes to contract price (see online Appendix), and the fact that the USACE has well-established systems for monitoring dredging projects indicates that it is a good candidate for outsourcing along this scale.

I. Empirical Setting and Data

The data analyzed in this paper come from dredging projects overseen by the United States Army Corps of Engineers (USACE). Dredging consists of excavation and transportation of underwater material. Dredging projects are carried out by large vessels known as dredges; a typical dredge has built-in machinery that excavates material from beneath the water as well as a storage container that will hold the dredged material until a disposal area is reached. The primary purpose of most dredging projects is the maintenance of shipping lanes and harbors to insure the safe passage of commercial vessels. Proper care of these passages is crucial to the US economy as much of US domestic and international trade involves transport of goods along these waterways. Each dredging project occurs in one of 34 USACE districts, which are located along the coasts and inland waterways of the United States.[7]

A series of laws, the first of which passed in 1824, tasked the USACE with maintaining navigable waterways throughout the United States. All dredging projects related to these tasks were performed directly by the USACE until 1978 when Congress passed Public Law 95-269, otherwise known as the Minimum Fleet Act. In this act Congress instructed the Corps to contract out to private dredging companies all work that could be done "at reasonable cost." Since that time, federal dredging work in the United States has been split between projects contracted out and those completed in-house, with the aim of completing all projects at the lowest cost. The role of Corps dredges in the market is thus to minimize government expenditures on dredging projects, and Congress periodically reassesses the level of involvement of Corps dredges in order to insure the lowest cost.[8]

The market operates as follows. Prior to the start of each fiscal year, the Corps publishes the schedule of projects to be completed over that year. This schedule includes all projects across all districts. The schedule of projects is made on a yearly basis because (i) the sites that will require dredging work are typically not known more than one year in advance and (ii) the navigation budget issued to the Corps is decided each year by Congress, and so the total budget available for dredging projects is not known until several months before the start of the fiscal year. Emergency dredging work is rare, and constitutes only a small fraction of total dredging. Project start dates are determined by a number of regulatory and seasonal factors, including environmental regulations for fish, birds, and sea turtles, weather considerations, and limiting disruption of public land usage such as beaches.

The Corps allocates projects on a rolling basis throughout the year.[9] Once a project has been allocated to the private sector and the auction procedure has been initiated, this decision is final; only in extreme circumstances will a project be allocated to a Corps dredge after an auction has been held. The USACE also does not use its own dredging resources to participate in the auction. The Corps does specify a

[7] A list of districts and a summary of their dredging activity can be found in the online Appendix.

[8] For example, a 2005 report to Congress (United States Army Corps of Engineers 2005) outlines several options for Corps dredging fleets and evaluates the total costs.

[9] While the schedule published at the start of the year estimates which projects will be completed in-house and which will be outsourced, the Corps regularly makes changes prior to final allocation.

reserve price in each auction. However, this reserve price is based on engineering guidelines and historical contracting prices and does not reflect an estimate of the Corps' own cost of completing the project.[10]

The USACE district in which a project will be completed holds a first-price sealed-bid auction to contract out the project to a private firm or arranges for the Corps dredge charged with overseeing that district to complete it. Auctions occur on a rolling basis, with the bid opening date typically falling about two months prior to the start of the project, while the contract is awarded about three to four weeks prior to the scheduled start date for the project. When a project is allocated to a government dredge, the vessel moves to the district in which the project is located and completes the project. Project completion times range from several days to several months.

While private sector firms and Corps dredges have access to the same dredging technologies, there are several operational differences across the two sectors. USACE vessels have regulated crew requirements that stipulate the number of crew members required for operation. The crew requirements for USACE dredges are larger than would typically be employed on a private sector dredge. These workers are full-time employees who receive wages based on federal pay scales and overtime pay.[11] Corps dredges must also meet regulations on the size of crew accommodations, amount of stored fuel on board, and other equipment requirements that are not present for private sector firms. These requirements increase the size and weight of vessels, which impacts costs through fuel expenditure and maintenance. These same requirements can facilitate faster project commencement; private sector dredging companies must assemble and train crew on the specifics of each project. Corps dredges can also utilize the infrastructure capabilities of the USACE for logistics support, particularly for the mobilization phase of a project during which the necessary materials and equipment are transported to the project location.

Private dredging companies are located throughout the United States and perform dredging for private firms and individuals, governments and the state and local level, as well as federal dredging contracts through the USACE. While USACE projects represent an important source of demand for dredging services, these projects are a relatively small fraction of the overall number of projects completed in the United States each year. Completion of dredging work by contracted firms is closely monitored by the USACE through several channels. Many contracts have provisions that the contracted firm supply office space on the project site for USACE engineers to supervise the project. Samples of dredged material are required to be sent for testing at various stages of the project to check compliance with environmental regulations. Images of the completed work are often compared with computer-generated plans to ensure the completed work matches contract specifications.[12]

[10] Guidelines for Corps cost estimation are contained in USACE Engineer Regulations (ER) 1130-2-500 and 37-2-10.

[11] For example, Pacific Northwest Waterways Association (2002) notes that for two similar-sized dredging vessels, one in the private sector and one operated by the Corps, the private dredge was manned by 28 crew members on average while the USACE dredge crew was 43. The report also notes that USACE crews are full-time and generally receive higher wages than private crews.

[12] Data on ex post adjustments to winning bids, summarized in the online Appendix, reveal that approximately half of all payment adjustments are negative, i.e., firms receive less than the winning bid for completing

A. *Data*

The main source of data comes from the United States Army Corps of Engineers Navigation Data Center (USACE Navigation and Civil Works Decision Support Center 1999–2013), and includes information on all USACE projects contracted out to private dredging companies and daily activities for all dredges operated by the USACE from 1999 to 2013. Data are collected at the district level and then published on a yearly basis on the Navigation Data Center web page. I supplement this dataset with between-port distances obtained from the National Oceanic and Atmosphere Administration (National Oceanic and Atmospheric Administration 2012). Data for the in-house projects consist of the identity of the vessel completing the project, project characteristics such as volume and number of working days, and the district in which the project is completed. Outsourced projects are allocated by first-price sealed-bid procurement auctions. Procurement auction data consist of the winning bid and identity of the winning bidder, district where work was performed, number of bidders, and project characteristics.

There were 2,178 projects awarded to private firms and 1,940 projects taken by USACE dredges over the 15-year period in the data. The final sample removes observations for which key data were missing, large, multiyear projects which require resources beyond USACE capabilities, and projects from three districts in which Corps dredges don't operate; additional information on the data and sample construction can be found in the online Appendix. Table 1 contains summary statistics for the projects contained in the sample. The distance measured in the table is between each district's USACE headquarters location. There were $472.7 million worth of contracts issued to private firms each year on average. Although the number of projects completed by the USACE is comparable to the number of projects outsourced, the USACE projects tend to be much smaller; the mean USACE project excavates less than 25 percent of the material excavated by the mean project completed by a private firm. The government engineering estimate for outsourced projects is higher than the average winning bid. Officially, this estimate determines the reserve price, which is 125 percent of the engineering estimate. However, approximately 7 percent of winning bids are above this reserve price in my sample, suggesting that it is not strictly enforced in practice.

Overall, 177 firms were awarded at least one contract over the sample period. Most firms are active in a small number of areas: the mean number of districts in which a firm is active is approximately two, while the median is one. This suggests that most firms confine their dredging operations to their local geographic area. Additionally, private sector dredging capacity far exceeds government dredging resources, with an average of six dredging companies per district. As such, capacity does not appear to be a limiting factor in auction participation: regression results indicate no statistically significant effect of the number of currently ongoing projects in a district on

the project. As payments are structured in terms of price per cubic yard of material dredged, this is consistent with substantial monitoring and only paying firms for work observed to have been completed.

Table 1—Summary Statistics

	Mean	SD
Panel A. Procurement auctions		
Project volume (thousands of cubic yards)	1,176.90	(1,575.41)
Project working days	125.82	(135.99)
Winning bid ($, millions)	4.03	(3.83)
Government engineer's estimate ($, millions)	4.47	(4.34)
Number of bidders	2.46	(1.33)
Panel B. USACE dredges		
Project volume (thousands of cubic yards)	276.22	(921.50)
Project working days	22.25	(52.19)
Miles traveled to reach in-house projects	123.17	(298.92)
Miles to nearest USACE dredge for all projects	261.59	(422.65)

Notes: This table gives summary statistics of projects overseen by the USACE over the sample period 1999–2013. Cubic yards per project is the volume of material (sand, silt, etc.) excavated. The distance statistics capture how far a USACE vessel did travel (in the case of in-house projects) or would have to travel (for all projects) to reach the project location. Winning bid per project gives the winning bid in the procurement auction for each contracted-out project. The government provides an engineering estimate of project cost for outsourced projects; officially the reserve rate is 125 percent of this estimate, although this is frequently not enforced in practice.

auction participation. This result indicating an absence of capacity constraints also holds when private sector dredging projects are considered.[13]

Competition in the auctions is low, with a mean of 2.46 bidders per auction and a median of 3. Auctions with higher numbers of bidders are rare, with only 18 percent of auctions attracting four or more bidders. Over 20 percent of auctions attract only a single bidder. The level of competition varies across districts, with districts in the inland waterways and along the Pacific coast having the fewest competitors while districts in the Gulf and Atlantic coastal regions having higher levels of competition. For example, the auctions in the Galveston district average one full bidder more per auction (3.2) than those held in the Vicksburg district (2.2). This difference in the number of competitors is highly correlated with the number of projects completed in each of these areas and appears to be more closely related to overall demand for dredging and the importance of commercial shipping in these regions than any particular geographic features. As shown in Figure 1, the private sector dredging industry is stable, with relatively small variation in the number of bids received per auction and project concentration (measured by the average number of projects per firm) across the years in the sample.[14]

In order to examine the importance of project locations and distance traveled on the outsourcing decision, I regress the government's outsourcing decision on observable project variables and distance measures. Table 2 gives coefficient estimates for linear probability models of in-house government completion. "Project volume"

[13] Online Appendix B.4.1 uses data on dredging permits issued from the USACE ORM Jurisdictional Determinations and Policy Decisions database (United States Army Corps of Engineers 2010–2013) to investigate how bidder participation and winning bid levels are affected by local private sector demand for dredging services. Neither the number of participating bidders nor the average winning bid are significantly impacted by increases to issued dredging permits within the same district.

[14] Additional details on firm activity and competition can be found in the online Appendix.

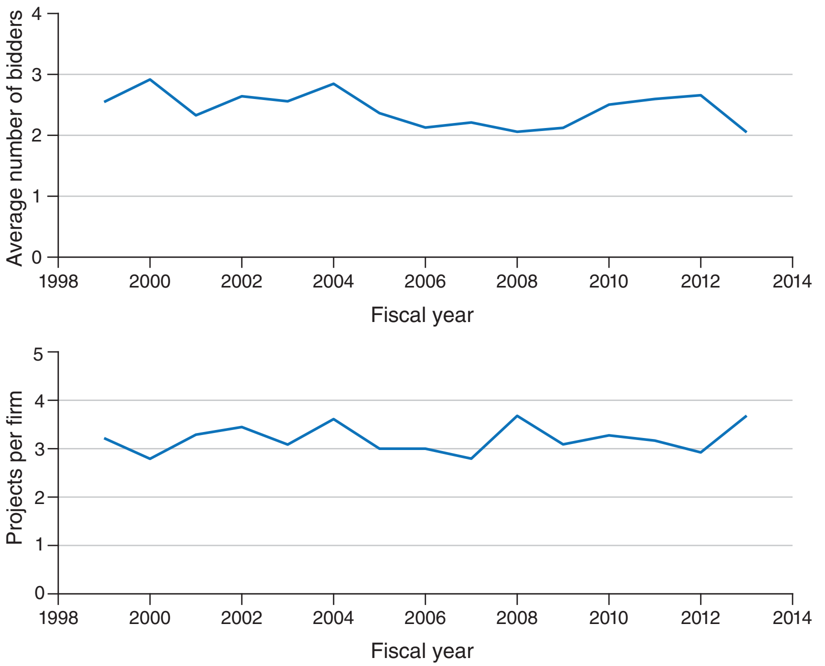

Figure 1. Level of Competition and Concentration over Time

Table 2—Government Project Selection Probability

	(1)	(2)	(3)
Project volume (cubic yards)	−0.102	−0.097	−0.098
	(0.004)	(0.005)	(0.005)
Working days	−0.013	−0.011	−0.010
	(0.001)	(0.001)	(0.001)
Distance	−0.036	−0.023	−0.023
	(0.002)	(0.002)	(0.002)
$t + 1$ distance saved	0.002	0.002	0.002
	(0.001)	(0.001)	(0.001)
Constant	1.938	1.666	1.809
	(0.048)	(0.123)	(0.059)
District	No	Yes	Yes
Year	No	No	Yes
Observations	3,509	3,509	3,509

Notes: This table displays the regression results for the probability that a project is kept in-house. Larger projects and those located farther away from a government dredge's current location are more likely to be outsourced. However, if taking a project will bring a government dredge closer to a subsequent project (represented by the variable "$t + 1$ distance saved"), then that project is more likely to be kept in-house.

measures the amount of dredged material for a project in cubic yards, "Working days" gives the number of days required to complete the project, and "Distance" gives the distance to project district in nautical miles. The variable "$t + 1$ distance saved" gives the reduction in distance to the next project on the schedule should the current project be taken; that is, it measures how much closer or farther the vessel will be to the next project to be allocated if the current project is kept in-house.

The estimates are consistent with the summary statistics in that government dredges are less likely to take larger volume projects and those that require more days to complete. Additionally, greater distance to a project decreases the chance that the project is kept in-house while additional distance saved to the next project will increase it: one standard deviation increase in distance saved increases government selection probability by 2 percent. Taken together, these results suggest that travel distance incurs costs to government dredges and that the government is forward-looking with regard to total travel distance.

II. Model

Motivated by the empirical facts presented in the previous section, this section presents a model of sequential project allocation in which a government makes outsourcing decisions in each period in order to minimize the expected cost of completing a known schedule of projects.[15] When making the outsourcing decision, the government considers the expected winning bid in a procurement auction and its own cost for the project, which it learns at the beginning of each period. Because vessels must be moved between project sites in order to complete projects and this travel is costly, the impact that vessels locations will have on future travel distances also affects the government decision. Lastly, availability of vessels to complete projects is also considered, as current project allocation decisions may affect the ability to complete future projects in-house. If the project is contracted out, a first-price sealed-bid auction is held in which firms make entry decisions prior to bidding and the contract is awarded to the lowest-bidding firm.

A. *Model Setup*

A risk-neutral government must complete a known schedule of projects over the course of one year. The schedule of projects is a list, ordered by project start date and containing all the information relevant to each project. There are K districts in which projects must be completed. Time is discrete with a finite horizon T. The start of each period corresponds to the start date of a project, so that the duration of a period is the time elapsed between project start dates. Each period, the government makes a decision to either outsource the project or keep it in-house. The state variables are denoted $z_t \equiv (\delta_t, x_t, \bar{N}_{k_t}, w_t, y_t)$, where δ_t represents the distance from the government dredge to the current project district and x_t is a vector of project characteristics (e.g., project size). The district in which the project is to be completed is k_t, with $\bar{N}_{k_t} \in \mathcal{N}$ denoting the number of firms in district k_t.

[15] Other models of government preferences assume budget-maximizing objectives (e.g., Niskanen 1968, 1971), in which a "Sponsor" allocates the budget and has an inferior bargaining position relative to the bureau due to an informational disadvantage regarding the social value of the bureau's projects. In my setting, I assume that the "Sponsor" can compare costs of dredging for Corps dredges and private sector dredging and prefers the lower-cost option, even if the total number of dredging projects exceeds the social optimum.

Projects can last for a number of periods and may overlap with other projects; w_t indicates the number of projects whose dates overlap with the project starting in period t. If a dredge is allocated to complete the project in period t, then it will be committed to that project for w_t periods and will be unable to complete other projects during that time. The state variable y_t indicates the availability of the government vessel, with $y_t = 0$ indicates that the vessel is currently available at the start of period t and $y_t = c$ for $c \in \mathbb{N}$ indicating that there are c periods until the vessel is available to take another project.[16]

The timing of the model is as follows: at the start of each period, the government learns its cost for completing the project in that period. It then forms expectations about the winning bid if the project were to be contracted out and makes the outsourcing decision. If the project is kept in-house, the government vessel allocated to the project moves to the project's district and begins the project. If the project is outsourced, a first-price sealed-bid auction is held to determine which firm is awarded the contract.

While the model is agnostic as to the source of cost differences between government in-house work and contracted firms, reasons why private firms may have cost advantages over government agencies for certain tasks include use of high-powered incentives as in Holmstrøm and Milgrom (1994), reduction of inefficient bureaucratic policies, and more flexible labor practices. Conversely, a full-time staff of skilled in-house employees may mitigate fixed costs associated with projects.

In describing the model, I work backwards from the auction stage, first obtaining an expression for the expected winning bid in the auction conditional on a project being outsourced. I then write the government's payoffs and value function given expectations over the expected winning bids derived in the first section and characterize optimal outsourcing decisions.

B. *Auction Stage*

When a project is outsourced, firms active in the district in which the project is located have the opportunity to bid for the project's contract. I assume that firm bidding behavior is myopic: given that many firms are active in only one or two districts and that the number of ongoing projects does not affect bidder participation, the main two factors driving dynamics in the government decision—distance to project sites and availability of dredges—are unlikely to be a strong factor in firm bidding decisions. As such, participating firms compete in a static first-price sealed-bid auction for the contract. The decision to contract the project out is final and precludes assignment to a government vessel.

In the first stage, potential bidders play an entry game to determine who participates in the auction based on the model of Levin and Smith (1994). Prior to learning their private costs for completing the project, bidders receive independent entry cost

[16] If $y_t = 0$ at the start of the period, then a decision to keep the project in-house will mean that $y_{t+1} = w_t$ and it must wait w_t periods before it can be assigned any other projects. If the project is outsourced, $y_{t+1} = 0$.

draws e from a common distribution ζ with support $[\underline{e}, \bar{e}]$.[17] Each potential bidder is aware of his/her own entry costs but not the entry costs of other potential bidders. Entry costs are independent of project completion costs. After learning their entry costs, bidders make entry decisions based on the expected payoff from entering the auction. Bidders that choose to enter the auction then receive their private cost draw from the cost distribution and learn the number of other bidders competing in the auction.

Formally, suppose there are $\bar{N}$ potential bidders. Let e_i indicate the private entry cost drawn from ζ for bidder i, and let $\mathbf{e}_{-i}$ represent the entry costs of the other potential bidders. A pure strategy for player i is defined as a function $\sigma : [\underline{e}, \bar{e}] \rightarrow \{0,1\}$ that maps each entry cost to an entry decision. Let $E[u_i | N]$ represent the expected profit for bidder i upon entering an auction with N total bidders. Then there exists a threshold cost level e^* given by

$$e^* = \sum_{n=1}^{\bar{N}} \Pr(N = n | e^*) E[u_i | N = n],$$

where any $e_i < e^*$ leads to entry and $e_i > e^*$ means that bidder i does not enter the auction. This can be reexpressed using the distribution of entry costs as

$$e^* = \sum_{n=1}^{\bar{N}} \binom{\bar{N}}{n} \zeta(e^*)^n \left(1 - \zeta(e^*)\right)^{\bar{N}-n} E[u_i | N = n]. \tag{1}$$

Since the left side of (1) is increasing in e^* and the right side is decreasing in e^*, as higher entry costs lead to lower entry probabilities, the equilibrium cutoff point e^* exists and is unique.

After bidders have made their entry decisions, they draw costs and submit bids in a first-price sealed-bid auction. The number of bidders n is assumed known. Each bidder i receives an i.i.d. project cost drawn c_{fi} from a common distribution $F(c_f | x)$ conditional on project characteristics x with positive support on $[\underline{c}_f, \bar{c}_f]$. Because many winning bids in the data are above the USACE's stated reserve price, I assume that there is no binding reserve price in auctions with two or more bidders. Finally, I assume that bidders play a symmetric, pure strategy Bayesian Nash equilibrium with bids that are increasing in costs.

The conditionally independent private values assumption implies that after conditioning on observed project characteristics x each bidder's private cost is independent.[18] This assumption is motivated by the heterogeneity in dredging equipment and technologies across firms: dredges are individually produced, and each dredge

[17] To test for the presence of selective entry, in which potential bidders receive a signal of their costs prior to entry, I use the nonparametric test of Marmer, Shneyerov, and Xu (2013). I fail to reject the Levin and Smith (1994) model at the 5 percent confidence; the online Appendix contains additional details on the construction of the test statistic.

[18] Other studies of procurement for construction contracts using the independent private values paradigm in auction models with entry include Li and Zheng (2009), Krasnokutskaya and Seim (2011), and Groeger (2014).

can be built to use a number of different dredging methods.[19] Variation in dredging methods, vessel size and crew requirements, vessel weight and speed, and storage capacity for dredged material introduces idiosyncratic cost components across bidders. Each firm's cost is determined by how the details of a project align with the particular capabilities of its dredging vessels, which is idiosyncratic to that firm.

For ease of notation, I suppress the conditioning on project characteristics x and the time subscript in what follows. Given the above assumptions, the bid function can be written as

$$b^*(c_i) \ = \ \max_b \Pr\big(b \ \leq \ b_j \, \forall j \ \neq \ i\big) \times \big(b - c_i\big),$$

which has a closed-form expression given by

$$(2) \qquad b\big(c_{fi}\big) \ = \ c_{fi} + \int_{c_{fi}}^{\infty} \frac{\big(1 - F(u)\big)^{n-1}}{\big(1 - F\big(c_{fi}\big)\big)^{n-1}}\, du.$$

The expected winning bid is the auction feature determining government outsourcing decisions. Define $m(c_{fi})$ to be the expected payment received by bidder i. Then $E[m(c_{fi})|N \ = \ n]$ is the ex ante expected payment received by each bidder when there are n bidders in the auction. For auctions that feature only one bidder, I assume that the firms compete against the government by the government announcing a maximum acceptable contract price, which the firm agrees to provided it is above their cost for the project.[20] Because N is unknown to the government at the time the outsourcing decision is made the government takes the expectation of $E[m(c_{fi})|N \ = \ n]$ over the number of bidders when assessing the expected winning bid. Each district k has $\bar{N}_k$ potential bidders. The probability distribution over the number of bidders is given by η_k, with η_{kn} the probability that there are n bidders in the auction. Defining $R(\bar{N}_k)$ to be the expected ex ante winning bid of an auction held in district k, we have

$$R\big(\bar{N}_k\big) \ = \ \sum_{n=1}^{\bar{N}_k} \eta_{kn} \cdot nE\big[m\big(c_f\big)|N \ = \ n\big].$$

C. *Outsourcing Decision*

At the beginning of each period t, the government learns its cost c_{gt} for completing the project, which is drawn from a distribution that has conditional cdf $G(\cdot|x_t)$. The distance cost associated with traveling to the project district is given by $\omega(\delta_t)$ and is assumed to be additively separable from the project completion cost. Define $d_t \ \in \ \{0,1\}$ to be the decision variable in period t, where $d_t \ = \ 0$ represents that the project has been kept in-house and $d_t \ = \ 1$ indicates that the project

[19] For example, suction dredging uses a pipe extended beneath the vessel to excavate using suction, while bucket-chain dredging uses containers attached to a conveyor belt as its means of excavation. The depth of excavation, slope, and distance to disposal sites often makes one method more suitable than others.

[20] This is similar to the method used in Li and Zheng (2009) and reflects the USACE policy to negotiate with firms in the event that only one bid is received.

has been contracted out. Letting $\pi_j(z_t)$ denote the per-period payoff for state z_t when $d_t = j$, the per-period payoffs have a simple expression of the form

$$\pi_0(z_t) = -\omega(\delta_t) - c_{gt}, \tag{3}$$

$$\pi_1(z_t) = -R(x_t, \bar{N}_{k_t}), \tag{4}$$

where $R(x_t, \bar{N}_{k_t})$ is the expected winning auction bid. The only random component of the government's payoffs enters through the government's cost draw c_{gt}; hence, this cost should be interpreted as the cost of completing the project relative to the cost of contracting the project out.[21]

The schedule of projects is known for each year, meaning that the project characteristics x_t and district-level competition $\bar{N}_{k_t}$ are known in advance for each project. Distance to future projects is determined by the current location of the government's work crews; when the government sends a vessel to a project location the distance to the subsequent project will be known with certainty. Hence, all state transitions are deterministic, with transitions for two of the states (project characteristics and district characteristics) determined exogenously by the project schedule while the transitions for distance and vessel availability are determined by the government's outsourcing decision and the schedule of projects. While state transitions are deterministic, they are nonstationary as they will depend on the sequence of upcoming projects.

The government discounts future payoffs according to an annual discount factor $\tilde{\beta} \in (0,1)$. Each period has a different duration in calendar time, as the length of each period is the time until the next project allocation decision must be made and project start dates are not equally dispersed throughout the year. The discount factor in each period corresponds to the duration of that period. Specifically, I assume that the period t discount factor is given by $\beta_t = \tilde{\beta}^{days_t/365}$, where $days_t$ is the duration of period t.[22]

Define $q_{jt}(z_{t+1}|z_t)$ to be the state transitions after making choice j in period t. If we again consider the schedule of projects as a list, ordered by project start date and containing all the information relevant to each project, the state transitions can be thought of as crossing one project off of the list and moving to the next one, updating the locations and availabilities of the government vessels each period. Current choices affect future states through the dependence of the state variables y_t and δ_t on the current period choice. A project that is far away from the remaining projects on the schedule for the fiscal year and has a long completion time will affect future payoffs by both (i) increasing the distance necessary to complete future projects and (ii) potentially rendering the vessel unavailable for the subsequent projects, taking away the potential for the government to save costs by keeping the project in-house.

[21] As any pair of choice-specific utility shocks that lead to the same differenced distribution are observationally equivalent, normalizing one of the utility shocks to zero is necessary for identification.

[22] The online Appendix contains estimates for the model under the assumption that all periods are discounted equally regardless of calendar time per period.

With these factors in mind, the value function for choice j in period t can be written

$$(5) \qquad V_{jt}(z_t) = \pi_j(z_t) + \sum_{\tau=t+1}^{T}\left(\prod_{t'=t}^{\tau-1}\beta_{t'}\right)E\left[\pi_{j_\tau^*}(z_\tau)\right],$$

where j_τ^* is the optimal choice in period τ. Define the ex ante value function $\bar{V}_t$, which represents the expected value for the optimal period t choice j_t^*, by

$$(6) \qquad \bar{V}_t(z_t) \equiv p_{0t}(z_t)E\left[V_{0t}(z_t)\,|\,j_t^* = 0\right] + p_{1t}(z_t)E\left[V_{1t}(z_t)\,|\,j_t^* = 1\right]$$

with $p_{0t}(z_t) = \Pr(V_{0t}(z_t) > V_{1t}(z_t))$. Now define $v_{jt}(z_t)$ to be the value functions conditional on choice j without the random cost c_{gt}; note that removal of this term affects only the in-house payoff. These conditional value functions can be expressed

$$(7) \qquad v_{0t}(z_t) = -\omega(\delta_t) + \beta_t \sum_{z\in\mathcal{Z}} \bar{V}_{t+1}\, q_{0t}(z|z_t),$$

$$(8) \qquad v_{1t}(z_t) = -R\left(x_t, \bar{N}_{k_t}\right) + \beta_t \sum_{z\in\mathcal{Z}} \bar{V}_{t+1}(z)\, q_{1t}(z|z_t).$$

This allows for expression of the conditional choice probability of in-house provision as

$$(9) \qquad p_{0t}(z_t) = \Pr\left(c_{gt} < v_{0t}(z_t) - v_{1t}(z_t)\right).$$

Capacity affects payoffs through the elimination of the in-house decision option when no dredges are available. In particular, this means that the value function is

$$V_t(z_t) = \begin{cases} \max_{j\in\{0,1\}} \pi_j(z_t) + \beta_t \sum_{z_{t+1}=1}^{Z} \bar{V}_{t+1}(z_{t+1})\, q_{jt}(z_{t+1}|z_t) & \text{if } y_t = 0, \\ \pi_1(z_t) + \beta_t \sum_{z_{t+1}=1}^{Z} \bar{V}_{t+1}(z_{t+1})\, q_{1t}(z_{t+1}|z_t) & \text{otherwise.} \end{cases}$$

If a project would occupy a government dredge for the next $\bar{t}$ periods then the government must trade off potential gains from keeping the project in-house in the current period against the expected losses that might be incurred through the inability to complete projects in-house for the next $\bar{t}$ periods.

III. Identification

This section describes the identification of the model primitives, which are the government cost distribution G, distance costs $\omega(\delta)$, entry cost distribution ζ, and firm cost distribution F, from the observables z_t, d_t, n_t, and the winning auction bids.

A. *Overview*

Identification of the government cost primitives uses the nonstationarity of state transitions to isolate "temporarily static" periods in which all future value terms cancel. This removes the primary obstacle to identification of the distribution of choice shocks in dynamic models, as the future value terms themselves depend on this distribution. I then combine these static periods with an exclusion restriction that government costs are independent of the number of active firms within a district. The full distribution of government costs is identified by variation in the number of active firms using an exclusion restriction in a similar manner to static nonparametric identification of binary choice models (e.g., Lewbel 2000).

Identification of private sector firm costs uses results from the auction literature for auctions with only winning bids known (for example, in Athey and Haile 2002). Firm costs are then used to identify the expected bidder profit conditional on the number of bidders. Combining this with the empirical distribution over the number of bidders in the auction gives the expected auction profit conditional on entry. This generates an equilibrium cutoff condition for each number of potential bidders $\bar{N}$. Hence, quantiles of the entry cost distribution are identified through variation in the number of potential bidders.

B. *Government Cost Primitives*

Identification of G is established in two steps. The first step is to eliminate the future value component of government choices, as this is the main barrier to identification of the unobserved component of payoffs.

In this setting, such a situation arises when an available dredge is located in the same location as the period t project and the project will conclude before the period $t+1$ project is set to begin. Then, regardless of the choice to take the project or not, the two factors affecting the future value function—distance to project and availability—are unaffected: the vessel remains in the original district and is available in both cases.

Formally, consider a project in period t located in district k. There is an available government vessel located in district k at the start of period t; further, suppose that the period t project will conclude prior to the start of the project in period $t+1$. Then the state is $z_t \equiv (\delta_t, x_t, \bar{N}_{k_t}, w_t, y_t) = (0, x_t, \bar{N}_{k_t}, 0, 0)$ and the current decision will not affect availability for the next period project. The project characteristics x and market competition $\bar{N}$ have exogenous transitions that are due to the schedule of projects and hence are unaffected by the choice of the government. The distance to the next project δ_{t+1} will remain fixed regardless of the outsourcing decision, as the vessel has not changed districts. Then the state variables at the start of period $t+1$ are $(\delta_{t+1}, x_{t+1}, \bar{N}_{t+1}, w_{t+1}, 0)$ whether the previous period's project was kept in-house or not.[23]

It is straightforward to demonstrate that these circumstances result in static decisions:

$$
\begin{aligned}
v_{1t}(z_t) - v_{0t}(z_t) &= \pi_1(z_t) - \pi_0(z_t) + \beta_t \sum_{z \in \mathcal{Z}} \left(\bar{V}_{t+1}(z)\, q_{1t}(z|z_t) - \bar{V}_{t+1}(z)\, q_{0t}(z|z_t)\right) \\
&= \pi_1(z_t) - \pi_0(z_t),
\end{aligned}
$$

[23] As a concrete example, suppose there is a project to be completed in New York on July 1 that takes 10 days to complete. There is an available Corps dredge already in New York, and so no travel is required to reach the project. Furthermore, the next project is in the New England district and starts on July 15, after the current project will already have finished. Regardless of whether the project is assigned to the Corps dredge, the dredge will be available to complete the New England project and will have to travel the same distance in either case.

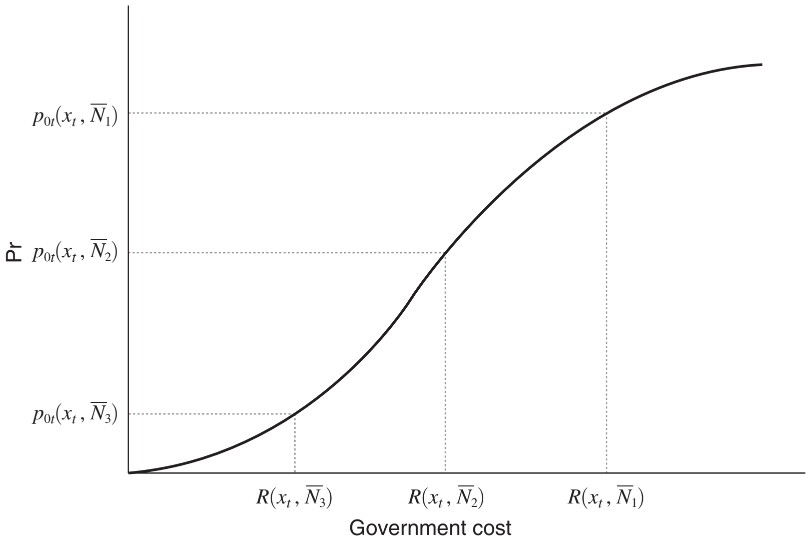

Figure 2. Identification of Government Cost Distribution

Notes: Holding the contract characteristics x_t fixed, the distribution function of government costs evaluated at the expected contract price for each level of competition n maps exactly to the conditional choice probability for that state.

since $q_{1t}(z|z_t) = q_{0t}(z|z_t)$. Hence, when the state transitions are the same for both choices, the ex ante value function terms for the next period cancel and the differenced conditional value function can be expressed solely in terms of the current period flow utilities.

After obtaining a set of temporarily static observations using the method above, the distribution of G is identified using an exclusion restriction. Specifically, I assume that $\bar{N}$ affects the expected winning bid, and hence the probability of the outcome variable d, but is independent of C_g after conditioning on characteristics x. This allows variation in $\bar{N}$ to change the probability that $d_t = 1$ in a way that identifies the distribution of C_g. This is illustrated for fixed project characteristics x in Figure 2.

After identification of G is complete, identifying $\omega(\delta)$ follows from the representation results of Arcidiacono and Miller (2011) after a normalization of $\omega(\delta)$ for one value of the state δ. These results are formalized in the proposition below.

PROPOSITION 1: *Suppose the following assumptions hold:*

(i) $G(c|x,\bar{N}) = G(c|x)$ *for all* $x \in \mathcal{X}$.

(ii) *There exists a set of periods* $\mathcal{T}$ *such that for each* $\tau \in \mathcal{T}$ *there exists a subset* $Z_\tau \subset \mathcal{Z}$ *for which the state transitions do not depend on the government's choice*: $q_{1,\tau}(z_{\tau+1}|z_\tau) = q_{0,\tau}(z_{\tau+1}|z_\tau)$ *for all* $\tau \in \mathcal{T}$ *and* $z_\tau \in Z_\tau$.

(iii) $G(c|x)$ *is strictly increasing for all* $x \in \mathcal{X}$.

(*iv*) *For each fixed* x, $R(x,n)$ *is strictly decreasing in* n *so that* $R^{-1}(n;x)$ *exists.*

(*v*) $\omega(\delta_0) = 0$ *for some* $\delta_0 \in \Delta$ *and the discount factor* β_t *is known for all* t.

Then $G(c|x)$ *and* $\omega(\delta)$ *are identified for all* $x \in \mathcal{X}$ *and* $\delta \in \Delta$.

Assumption (i) is the exclusion restriction which allows for variation in $\bar{N}$ to identify quantiles of the government cost distribution.[24] Assumption (ii) ensures the existence of a set of periods and states for which all future value terms cancel. Assumption (iii) is required to apply the inversion theorem of Hotz and Miller (1993). Assumption (iv) guarantees a one-to-one mapping between $\bar{N}$ and expected winning bids for a given x, implying that higher levels of competition are associated with lower expected winning bids. Finally, assumption (v) is a normalization that enables identification of $\omega(\delta)$ for all $\delta \neq \delta_0$.

C. *Auction Game*

Identification for the distribution of firm costs follows the arguments of Guerre, Perrigne, and Vuong (2000) and Athey and Haile (2002) applied to auctions in which bidders have independent private costs and only the winning bid is observed. The number of bidders n is known. Let $W(\cdot)$ denote the distribution of winning bids. The costs for winning bidders can be expressed in terms of the submitted bid and winning bid distribution as $c_f^W = b - \left(n[1 - W(b)]/\left((n-1)w(b)\right)\right)$, where $w(\cdot)$ is the density associated with the distribution $W(\cdot)$. This gives the distribution of winning costs $F_W(c_f)$, and an order statistic transformation yields the distribution of all firms' costs.

Identification of the entry cost distribution follows a similar argument to that of the identification of the government cost distribution. For a fixed vector of project characteristics x in market k with the number of potential bidders denoted $\bar{N}_k$, the equilibrium entry cutoff $e_k^*(x)$ can be obtained by using the observed participation decisions for the probability distribution over the number of bidders in (1):

$$e_k^*(x) = \sum_{j=1}^{\bar{N}_k} \eta_{jk}(x) E\left[u_i | n = j, x\right], \tag{10}$$

where $\eta_{jk}(x)$ is the observed probability of j bidders in an auction with characteristics x in market k. Variation in the number of potential bidders across districts generates different values for $e^*(x)$.[25] This means that

$$\sum_{j=1}^{\bar{N}_k} \zeta\left(e_k^*(x)\right)^j \left(1 - \zeta\left(e_k^*(x)\right)\right)^{\bar{N}_k - j} E\left[u_i | n = j, x\right] = e_k^*(x) \tag{11}$$

[24] Table 18 in the online Appendix provides empirical evidence on contract costs across districts that motivates the use of this assumption.

[25] Specifically, a lower number of potential bidders increases the expected profit and raises the equilibrium entry cutoff, while a higher number of potential bidders has the opposite effect.

holds for each market $k \in \mathcal{K}$. Then the quantiles of the distribution ζ associated with each value of $e_k^*(x)$ are identified from (11).

IV. Estimation and Results

Estimation of the model primitives proceeds in three stages. In the first stage, nonparametric estimators for the number of potential bidders in each district and the expected auction price are obtained. These are then used to estimate the government cost distribution and distance costs following the strategy laid out in the previous section. Finally, the observed distribution over the number of bidders is used with the estimated number of potential bidders to estimate the entry cost distribution, and firm costs are estimated from the auction data.

While the identification results from the previous section are nonparametric, in practice the number of observations and the size of the state space make nonparametric estimation impractical. Hence, I make the following parametric assumptions in estimation: government costs are assumed to be drawn from a Weibull(α, ρ) distribution, the winning bids distribution is parameterized as Log-Normal(μ, γ),[26] and entry costs are drawn from Exponential(λ). All parameters are log linear in the project characteristics (and the number of bidders in the case of μ and γ). Travel distance costs are assumed to be linear: $\omega(\delta) = \theta\delta$. Finally, I fix the yearly discount factor $\tilde{\beta} = 0.94$.[27]

The model's parameters are estimated via maximum likelihood. As the Corps operates dredges in several nonoverlapping geographic regions, these regions are treated as distinct during estimation.[28] The winning bid distribution parameters (λ, γ) are estimated directly from the winning bid observations for auctions with two or more bidders. This winning bid distribution is then used to estimate the cost distribution. The government cost distribution is estimated by maximizing likelihood of the observed outsourcing decisions over the temporarily static periods, where the likelihood for each observation is a Bernoulli likelihood in which the probability of keeping a project in-house is determined by the government cost parameters (α, ρ) and the expected winning bid $R(x_t, \bar{N}_{k_t})$. Similarly, firms' entry likelihood is a binomial likelihood in which the entry probability is determined by the probability of being below the equilibrium entry cutoff, which is computed using the firm cost distributions and empirical probabilities over the number of bidders. Finally, the travel cost parameter is estimated by backwards induction of the value function using the estimated government cost distribution. Confidence intervals are obtained via subsampling following the procedure

[26] For the government costs and winning bids distributions, each of the following distributions were tested: Normal, Log-Normal, Weibull, and Logistic. The distributions used in the final estimation were chosen based on fit as determined by AIC.

[27] The results are robust to different values for $\tilde{\beta}$. Online Appendix B.2.3 shows results for $\tilde{\beta} = 0.9$ and $\tilde{\beta} = 0.99$.

[28] I assume the range of each Corps dredge to be the set of districts it is observed to visit in the data, and combine the ranges of each dredge to generate the nonoverlapping regions used in estimation. In regions that include multiple USACE dredges, I assume that the closest vessel is allocated to the project; the online Appendix provides additional details.

Table 3—Estimates

	Estimate	95 percent CI
Panel A. Government costs		
α		
Constant	0.8189	[0.7180, 1.2885]
Project size	0.0019	[−0.0005, 0.0021]
Working days	0.4665	[0.4549, 0.7358]
ρ		
Constant	3.3371	[3.1053, 5.0762]
Project size	0.0000	[−0.0004, 0.0001]
Working days	−0.0320	[−0.0877, −0.0295]
θ		
Distance (100s of miles)	0.0222	[0.0152, 0.0460]
Panel B. Entry costs		
λ		
Constant	−3.9377	[−4.1680, −2.2831]
Project volume	0.3288	[0.1803, 0.3256]
Working days	−0.0751	[−0.1294, 0.0990]
Panel C. Winning bid distribution		
μ		
Constant	2.3533	[2.3297, 2.3783]
Project size	0.0266	[0.0248, 0.0283]
Working days	0.0009	[0.0006, 0.0012]
Number of bidders	−0.0035	[−0.0054, −0.0016]
γ		
Constant	0.7473	[0.4610, 1.0664]
Project size	−0.0878	[−0.1107, −0.0685]
Working days	0.0018	[−0.0009, 0.0056]
Number of bidders	0.0120	[−0.0140, 0.0411]

of Politis, Romano, and Wolf (1999). Online Appendix B.2 contains additional details on the estimation procedure.

A. *Estimates*

The estimates for the government cost distribution and the distance cost are contained in Table 3. Larger projects and projects that take longer to complete increase expected cost, while also increasing the expected winning bid in the auction market. Results from the dynamic model demonstrate that distance costs are substantial, with each additional 100 miles adding \$23,400 to total costs. The average contribution of travel costs for projects taken by the government is 3 percent for all projects and 7 percent for projects that involve changing districts.

Simulated results using the model estimates are listed in Table 4. To obtain the model predictions the model was simulated 500 times using the estimated values. The model matches the percentage of government projects outsourced and the total contract costs from outsourcing well. Total accumulated distance by government vessels is slightly overestimated by the model. Average project characteristics for both in-house projects and outsourced projects also fit model predictions well.

Table 4—Model Fit

	Data	Predicted (95 percent CI)
In-house projects (percent)	0.5226	0.4933 (0.4836, 0.5013)
Annual contract costs (millions)	$472.7	$493.4 (488.0, 499.1)
Government distance traveled per project	146.7	137.3 (129.3, 145.4)
Government cubic yards per project (thousands)	276.2	239.0 (219.3, 259.5)
Firm cubic yards per project (thousands	1,177	1,160 (1,134, 1,186)
Working days per project (government)	22.25	20.09 (18.64, 21.81)
Working days per project (firms)	125.8	122.0 (119.1, 124.4)

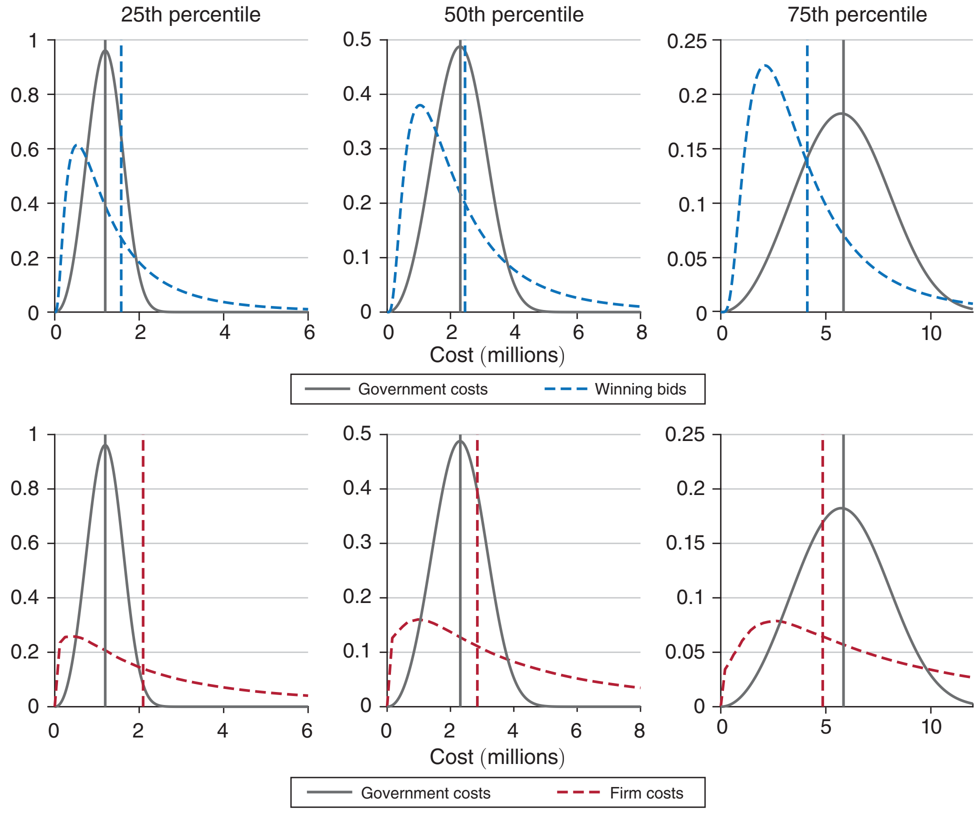

Figure 3. Distributions of Government Costs, Winning Bids, and Firm Costs

Notes: This figure compares the distribution of government costs with winning bid and firm cost distributions for the 0.25, 0.50, and 0.75 quantiles of project size. The three graphs in the top panel display government costs distributions plotted with the winning bid distributions for auctions with three bidders, while the bottom three graphs shows firm cost distributions. Means associated with each distribution are displayed as vertical lines.

B. *Comparing Government and Firm Costs*

Using the estimates from the structural model I analyze the relative effects that competition and costs have on project allocation. Figure 3 displays the cost distribution for the government plotted against the winning bid distribution for auctions with three bidders and the distribution of firm costs for three levels of project size quantiles. The quantiles are for both project volume and length: the 0.25 quantile corresponds to a project with the 0.25 percentile for cubic yards of material dredged and the 0.25 percentile for working days. As can be seen from the top three graphs in Figure 3, the mean government cost of project completion is lower than the expected winning bid for the 0.25 project size quantile, while being approximately even at the median project size and substantially greater than the winning bid at the 0.75 quantile.

The relationship between firm costs and government costs is similar, although as is to be expected the firm cost distribution has both a higher mean and variance than the winning bid distribution. This leads to a government cost advantage on average for median-sized projects, while the expected winning bid is almost exactly equal to government costs. The high variance in firm costs and the two-stage nature of the outsourcing process can lead to inefficient allocation of projects; I will quantify the extent to which this occurs in the following section.

These results suggest that the role of government in this market varies with the type of project being considered. For smaller projects that require less time and use of capital resources, government vessels act as the main source for project completion. Indeed, most of the projects that are smaller in scope are kept in-house. In contrast, for larger projects the government acts essentially as a fringe competitor: given the large difference in average costs for projects above the seventy-fifth percentile, a cost draw that would lead the government to forgo contracting the project out to a private firm would be rare.

Reports on dredging costs from government and industry sources offer several explanations for these cost patterns.[29] Primarily it is suggested that operational differences between the USACE and private firms generate differences in costs across project sizes. As discussed in Section II, USACE vessels typically have larger crew sizes and all crew are full-time employees, meaning that for longer projects the number of workers cannot be adjusted over the project's duration. Private dredging companies often use smaller crew sizes and utilize the part-time nature of their employees by adjusting the number of workers to suit the current stage of the project. This additional labor flexibility lowers costs associated with larger projects. Other Department of Defense regulations for USACE vessels, such as expanded on board crew accommodations and increased storage capacity for fuel, increase weight and hence daily operating costs through fuel expenditures and maintenance costs. Conversely, the full-time employment of the USACE vessel crews lowers fixed costs associated with dredging projects. Mobilization, or getting the necessary equipment and materials to the project site, is reported as a substantial cost for many projects. USACE crews are able to efficiently mobilize due to the full-time crew of experienced dredging specialists, possibility to jointly mobilize for future projects that have already been allocated, and receiving logistical support from USACE district headquarters.

[29] These reports include *The Case for the Federal Hopper Dredge Fleet on the Pacific Coast* (Pacific Northwest Waterways Association 2002) and United States Army Corps of Engineers (2005).

Internal cost reporting from the USACE provides anecdotal evidence that Corps dredges are better equipped to handle smaller projects, particularly those that require fewer working days to complete. Corps estimates of cost per working day are higher for USACE-operated dredges than comparable industry dredges, while cost per cubic yard estimates place Corps dredges below the average reported private sector rates. These trends in the internal cost reports suggest that Corps vessels should be assigned to projects that require few working days and have a high ratio of cubic yards to the number of working days. Both of these trends are present in the data. As detailed in Section II, Corps dredges are assigned to projects that have shorter duration than private sector dredging projects, and the average cubic yards per day for USACE projects is 15,291 compared to 9,356 for private sector projects. As my estimates are based on the allocation patterns present in the data, they also reflect these trends: the number of working days is an important component of government costs, while the project volume is of greater importance for private sector costs.[30]

The estimated cost distributions represent the marginal costs of additional project completion. One limitation of the results is that it is not possible to separately identify long-term fixed cost components, including costs of capital investments and regularly scheduled maintenance, from marginal cost components such as fuel and labor. While the USACE and private sector firms face many of the same fixed costs, differences in fixed cost structure, particularly if the Corps faces larger fixed costs due to pre-commitment to full-time employees or national defense capability requirements, might indicate that these allocation patterns are due to high fixed cost but low marginal cost for Corps vessels rather than an absolute cost advantage for smaller projects. The USACE's choice to allocate generally smaller projects to its own vessels is indicative of a lower marginal costs for these projects; however, this may not represent an inherent operational advantage over private sector firms if the fixed costs of the Corps are high.

C. *Cost versus Competition Effect in Outsourcing*

Previous reduced-form studies (e.g., Stevens 1978; Snyder, Trost, and Trunkey 2001) have aimed to quantify the extent to which government outsourcing decisions are driven by differences in cost between public sector provision and private firms and to what extent they are driven by outsourcing decisions inducing competition among firms. I estimate the cost and competition effects by comparing the estimated government cost against the expected outsourcing cost when there is one bidder and the expected outsourcing cost for the standard competition level. I define the competition effect to be the difference in costs between the one-firm case and the baseline competition, while the cost effect is the difference between the government's cost and the cost in the one-firm case.

I find that 79 percent of the cost savings between government and private sector firms for outsourced projects is due to the cost effect, while 21 percent is due to the

[30] Online Appendix B.2.6 contains additional discussion of the results and a comparison of my estimates to other cost measurement data from Corps estimates (USACE Institute for Water Resources 2018) and the Government Accountability Office (GAO 2003).

competition effect. This result is intuitive given the relatively low level of competition and the large cost differences between public versus private provision for large projects. It should be noted that the cost effect varies substantially for outsourced projects according to project size. In general, a mixed-delivery approach is likely to be most beneficial when the competition effect is small and there is variability in the cost effect, so that the government can take (or at least credibly threaten to take) projects that might otherwise only have a single competitor.

V. Counterfactual Simulations

This section presents the results of two counterfactual policy simulations. First, I investigate the effect of reductions to the government's dredging fleet in order to determine the importance of government dredging on total expenditures. Second, I implement an alternate procurement mechanism. In this mechanism, the government directly participates in the auction by setting a dynamically optimal reserve price that takes into account both current and future costs of in-house completion.

A. *Reduction in Government Capacity*

In order to investigate the effect that government presence in the market has on total expenditures I perform a counterfactual policy simulation in which I reduce the government's capacity. Lessening the ability to complete projects in-house will indicate how important direct public sector involvement in project completion is for minimizing government expenditures. Additionally, fixed costs of maintaining dredges are high; the USACE estimates that annual costs for keeping a dredge operational are at least $2 million. Retiring underutilized dredges may thus save costs through eliminating their associated fixed costs.[31]

The counterfactual is run by simulating the model a sequence of times. For each iteration the vessel that was active for the fewest working days is removed from the government's fleet. The simulations track the number of projects kept in-house as well as total expenditures on dredging projects.

The results of the simulations are summarized in Figure 4. Small reductions in government fleet size have little effect on expenditures: reducing the fleet size by one increases annual outsourcing costs by $0.22 million and a reduction of 2 vessels increases annual outsourcing costs by $1.33 million. However, further reductions are more influential. When four vessels are removed, annual government costs increase by over $7 million per year, and a five-vessel reduction corresponds to a $13.5 million per year increase. These results suggest that while government may be slightly overinvested in dredging capacity, government dredges nevertheless remain important in lowering total expenditures.

[31] As discussed in the results section, the fixed costs associated with Corps presence in the market are not known. In particular, the extent to which fixed costs vary with fleet size cannot be directly ascertained. While fixed costs may decline due to saving on maintenance costs, the Corps may have to increase spending in other areas to maintain national defense and emergency response capabilities.

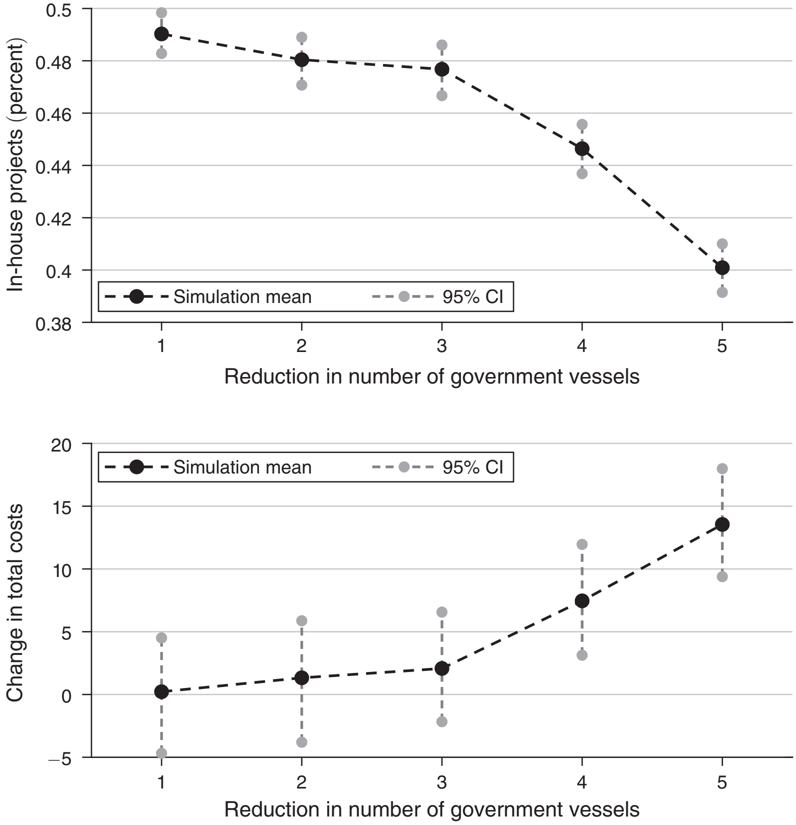

Figure 4. Vessel Reduction Simulation Results

Notes: This figure summarizes the results of the capacity reduction counterfactual simulation. On the *x*-axis is the number of vessels subtracted from the baseline model. The *y*-axis on the two figures corresponds to the percentage of projects kept in-house and the annual project costs (in millions of dollars), respectively.

A reduction to the USACE fleet of four vessels decreases the proportion of projects kept in-house by approximately 5 percentage points. This corresponds to 12 additional projects per year to be completed by the private sector. In the interpretation of the results given above it is assumed that private sector dredging companies do not respond to the decrease in USACE fleet size by entering the market. For example, an existing private dredging company that does not participate in USACE procurement auctions might make new capital investments to compete in the market for federal government contracts. Analysis of bidder participation and winning bid levels suggests that, in the short run, firms competing in the USACE procurement auctions are not capacity constrained and therefore could likely accommodate these additional projects without substantially increasing costs.[32] The long-run impact of this policy may result in respecialization of previously nonparticipating firms that

[32] Regression results for number of bidders and winning bid levels using measures of capacity can be found in online Appendix B.4.1.

would increase the potential bidders in USACE auctions and could ameliorate the estimated cost increase from the fleet reduction.

B. *Direct Government Competition*

I perform a counterfactual policy experiment that features direct competition between the government and private sector firms for each project that uses government costs as the outside option of not outsourcing to the private sector. As discussed in Section II, current USACE policy is to use engineering cost estimates and historical contracting data to determine a government estimate for the project. Not only does this estimate not reflect Corps costs of project completion in-house, but the reserve price based on this estimate is not strictly enforced in practice. In the proposed alternative mechanism, the government holds a second-price auction for every project with a reserve rate set by the government's cost for doing the project and the future value components.[33] This reserve rate ensures that the project is allocated to the supplier in the auction with the lowest cost, whether that is government or a private firm.

The reserve price policy is motivated by efficient allocation within the auction.[34] Under the current system used by the USACE, misallocation of projects can arise because either (i) an auction is held but the costs of the winning bidder are higher than government costs for the same project or (ii) the project is kept in-house, but were an auction to be held the resulting winning bidder would have costs below the USACE costs. By using the cost estimates from the model to simulate static costs for each project I estimate that 28 percent of projects are subject to misallocation along one of these two dimensions.

For each auction if no bids are placed below the government's reserve rate, the project is kept in-house. Otherwise, the project is contracted out to the lowest-bidding firm, with the contract price determined by the second-lowest cost (which may be the government's reserve price). Because bidder entry into the auctions may be affected by the presence of a reserve price, the entry equilibrium is recalculated for each auction and this is used to compute the government's value function. The procedure is described briefly below, and full details of the simulation can be found in Appendix A.

In the auction stage for a project in period t, the government has drawn a project cost c_{gt} with distance cost $\theta\delta_t$ and has expected future value terms $\bar{V}_{t+1}(z)$ for each $z \in \mathcal{Z}$. Then the maximum bid that the government is willing to accept in order to contract the project out is

$$r_t^* = c_{gt} + \theta\delta_t + \beta_t \sum_{z \in \mathcal{Z}} \left[\bar{V}_{t+1}(z_{t+1})\left(q_{1t}(z|z_t) - q_{0t}(z|z_t)\right)\right]. \tag{12}$$

[33] A publicly announced reserve price results in a lower expected cost to the government than a secret reserve that would be the case if the government were to submit a bid in the auction; see Elyakime et al. (1994).

[34] Alternative approaches could be considered, such as a reserve price policy that minimizes total dredging costs to the USACE. For instance, the Corps may find it optimal to set a lower reserve price to encourage entry and increase competition in the auction. I also assume that the government has no information advantage that it wishes to exploit, i.e., the Corps truthfully reports all relevant project characteristics. While the government may have information about the project that it could potentially withhold from bidders, this could lead to incomplete contracts and costly ex post renegotiation.

Hence, the value in (12) gives the reserve price set by the government in each auction. The reserve price will also affect bidder entry, as the presence of a reserve price changes the expected profit obtainable by potential entrants. Modifying equation (1) to account for a reserve price r yields the new equilibrium cutoff condition:

$$e_r^* = \sum_{j=1}^{\bar{N}} \binom{\bar{N}}{j} \zeta(e_r^*)^j \left(1 - \zeta(e_r^*)\right)^{\bar{N}-j} E[\tilde{u}_i | r, n = j], \tag{13}$$

where $E[\tilde{u}_i | r, n]$ is the payoff for player i in a second-price auction with n total bidders and a reserve price r. In order to account for the effect that the reserve price policy has on entry decisions into the auctions, I recompute the equilibrium entry cutoff for each auction. The timing is as follows: each period, the government draws its cost c_{gt} and sets the reserve price according to (12). Next, entry costs for each firm are drawn from ζ. Using the new equilibrium cutoff $\tilde{e}_{k_t}(x_t)$, firms with entry costs lower than $\tilde{e}_{k_t}(x_t)$ enter the auction. Auction entrants then learn their private costs c_f and bid in a second-price auction for the project contract. If no firm's bid is lower than the government reserve, the project is kept in-house. Otherwise, the project is awarded to the lowest bidder who receives the minimum of the reserve price and the second-lowest bid.

The results of the counterfactual policy experiment, obtained from 500 simulations of the model, are contained in Table 5. Direct competition of government vessels against private sector firms lowers total expenditures by 15.7 percent. One of the key reasons for this is that the reserve price binds in many cases when the project would otherwise have been issued at a higher cost: a low-cost bidder may submit a bid greater than the government's cost of completing a project and still win the auction if the level of competition is low. The government reserve caps the amount awarded to the winning firm for these auctions, and in many such cases the project would have been kept in-house under the baseline model of choosing to outsource before the auction result was known. The "wait and see" approach of the direct competition model allows the government to opportunistically outsource projects after seeing how bidding unfolds, facilitating lower total expenditures.

Endogenous Project Scheduling.—The schedule of projects has been treated as exogenous due to the predetermined nature of the projects to be undertaken in a given year: the USACE determines which projects are to be completed and the order in which they will be completed, and then assigns projects to either public or private sector completion on a rolling basis throughout the year. With a change to the procurement mechanism of direct government competition in the procurement auctions, the optimal scheduling procedure that takes place in the first stage may be affected. In principle, it might be possible to consider all feasible permutations of project orders within each fiscal year. In practice, consideration of all these permutations is infeasible for both institutional and computational reasons.

From an institutional standpoint, there are many restrictions on the starting times of projects due to environmental regulations, weather conditions, and other factors. Hence, considering an alternative schedule that moves a project originally scheduled for an August start date to a January start date may be infeasible for these reasons.

Table 5—Results of Direct Government Competition Counterfactual Simulation

	Predicted costs (millions)	Percent change from baseline model
Government	$101.1	−36.78
Outsourcing	$449.8	−8.8
Total	$550.9	−15.7

From a computational standpoint, the set of all possible project permutations is an incredibly large set and optimizing over this set in a brute-force manner is not possible as each schedule requires solving for the value function by backwards induction.

To accommodate endogenous scheduling in a way that takes into account both of these restrictions, I construct a restricted set of alternative schedules that reduces the computational burden and lessens concerns that these project orders would be infeasible based on institutional factors. This set of alternative schedules is constructed by allowing each project to be moved at most two places forward or backward on the schedule. That is, if a project was originally scheduled to be the seventh project completed in a given year, it can at most be moved up on the schedule to be the fifth project or moved down on the schedule to be the ninth project. This is done by swapping the start dates for projects, leaving all other project characteristics unchanged. This is a much smaller set of possible schedule alternatives, and the narrow window for start date adjustment means that institutional scheduling rules are less likely to be violated.

The counterfactual is run by taking a random sample of 100 schedules from this restricted set and simulating the market 200 times. After all simulations for each schedule have been completed, the schedule generating the minimum average total cost is selected. The results of the endogenous schedule simulations indicate that a further 3 percent reduction in costs from the government reserve counterfactual are achievable.

VI. Conclusion

This paper studied the outsourcing of dredging projects by the US Army Corps of Engineers. A dynamic binary choice model of outsourcing decisions is formulated and estimated using a novel identification strategy to identify the full distribution of the random component of government payoffs. I supply evidence of cost differences between the government and private firms that varies by project type, with in-house project allocation often proving optimal for smaller projects while larger projects are more likely to be contracted out. I find substantial private sector firm cost advantages for outsourced projects, averaging 23 percent lower costs than government provision, and also that government in-house provision remains optimal for a large share of projects.

The model estimates are used to perform two counterfactuals. In the first, the total capacity of the government is reduced in order to investigate the effect of government presence in the dredging market. I find that a reduction of up to one-sixth to government capacity would have little effect on total expenditures, while larger reductions prove more consequential. In the second counterfactual, I feature direct competition of government against private firms through a dynamically optimal reserve price determined by government costs. The result is a 17.1 percent decrease in total government expenditures. These results are primarily due to the facts that private firms and government face different cost structures that vary based on project characteristics and competition is low. Markets facing similar conditions can utilize direct government involvement in the market, combined with a procurement mechanism aimed at taking full advantage of government presence, to enhance efficiency and lower costs of public good provision.

Appendix A. Proofs and Simulation Details

A1. *Identification of Government Cost Primitives*

PROOF OF PROPOSITION 1:

The proof proceeds in three stages. First, the identification of G from the static observations is shown. Next, an expression for the value function that makes use of the distribution estimated in the first stage is derived. Finally, identification of $\omega(\delta)$ is established by using techniques similar to Arcidiacono and Miller (2011).[35]

First, take $\tau \in \mathcal{T}$. The conditional choice probability $p_{0\tau}(z_\tau)$ is

$$\begin{aligned} p_{0\tau}(z_\tau) &= \Pr\Big(-c_{g\tau} - \omega(\delta_0) + \beta\sum_{z\in\mathcal{Z}}\bar{V}_{\tau+1}(z)\,q_{0\tau}(z|z_\tau) \\ &\qquad \geq -R(x_\tau,\bar{N}_{k_\tau}) + \beta\sum_{z\in\mathcal{Z}}\bar{V}_{\tau+1}(z)\,q_{1\tau}(z|z_\tau)\Big) \\ &= G\big(R(x_\tau,\bar{N}_{k_\tau})|x_\tau\big), \end{aligned}$$

where the equality follows from the assumption that $\omega(\delta_0) = 0$ and $q_{0\tau}(z|z_\tau) = q_{1\tau}(z|z_\tau)$ for all $z \in \mathcal{Z}$ and $\tau \in \mathcal{T}$. Then all choices in the set $\mathcal{T}$ are effectively static and depend only on $(x_\tau,\bar{N}_{k_\tau})$, so that $p_{0\tau}(z_\tau) \equiv p_{0\tau}(x_\tau,\bar{N}_{k_\tau})\ \forall\tau \in \mathcal{T}$. By assumption, $R^{-1}(x_\tau,c) : \mathcal{X}\times[\underline{c},\bar{c}] \rightarrow \mathcal{H}$ exists. Hence,

$$G(c|x_\tau) = p_{0\tau}\big(x_\tau,R^{-1}(x_\tau,c)\big) \tag{A1}$$

completing identification of G.

Identification of $\omega(\delta)$ proceeds by expressing the future value function in terms of observables. The first step is to use the inversion theorem of Hotz and Miller (1993) to establish the existence of a function $\phi(p_{0t}(z_t)) = v_{0t}(z_t) - v_{1t}(z_t)$. Because G is continuous and strictly increasing and $p_{0t} = \Pr(-c_{gt} + v_{0t}(z_t) \geq v_{1t}(z_t))$, it follows that $\phi(p_{0t}(z_t)) = G^{-1}(p_{0t}(z_t)|x_t)$.

[35] For notational simplicity, I assume that periods receive the same time discount factor (i.e., $\beta_t = \beta\ \forall t$), but the proof can be easily adapted to accommodate heterogeneous (known) discount factors.

Next, we establish an expression for the expected government conditional on keeping a project in-house:

$$E\left[c_{gt} \mid -c_{gt} + v_{1t}(z_t) \geq v_{0t}(z_t)\right] = E\left[c_{gt} \mid c_{gt} \leq v_{1t}(z_t) - v_{0t}(z_t)\right]$$
$$= E\left[c_{gt} \mid c_{gt} \leq -\phi\left(p_{1t}(z_t)\right)\right].$$

As the distribution of c_{gt} is known and ϕ is given by the inversion theorem, this expression is known. Let $\xi(p_{1t}(z_t))$ denote this term. Following Arcidiacono and Miller (2011), we can write the value function as follows:

$$V_t(z_t) = \sum_{j=0}^{1} p_{jt}(z_t)\, v_{jt}(z_t) + p_{1t}(z_t)\xi\left(p_{1t}(z_t)\right).$$

Subtracting $v_{1t}(z_t)$ from each side yields

$$\text{(A2)} \qquad V_t(z_t) - v_{1t}(z_t) = \sum_{j=0}^{1} p_{jt}(z_t)\, v_{jt}(z_t) + p_{1t}(z_t) \cdot \xi\left(p_{1t}(z_t)\right) - v_{1t}(z_t)$$
$$= \sum_{j=0}^{1} p_{jt}(z_t)\left(v_{jt}(z_t) - v_{1t}(z_t)\right) + p_{1t}(z_t) \cdot \xi\left(p_{1t}(z_t)\right)$$
$$= p_{0t} \cdot \phi\left(p_{1t}(z_t)\right) + p_{1t}(z_t) \cdot \xi\left(p_{1t}(z_t)\right)$$
$$\equiv \psi_1\left(p_t(z_t)\right).$$

Using a similar procedure, we define $\psi_0(p_t(z_t)) \equiv p_{1t} \cdot \phi(p_{1t}(z_t)) + p_{1t}(z_t) \cdot \xi(p_{1t}(z_t))$. Now that expressions for the ψ_j terms have been derived, we can appeal directly to the results of Arcidiacono and Miller (2011) for the remainder of the proof. Specifically, let $\{d'_\tau\}_{\tau=t+1}^{T}$ be any sequence of decisions from τ until T. Using the definition of $\psi_j(p_\tau(z_\tau))$ we can write the conditional value function for choice $d_t = 0$ as

$$\text{(A3)} \qquad v_{0t}(z_t) = \pi_{0t}(z_t) + \sum_{\tau=t+1}^{T} \sum_{z_\tau \in \mathcal{Z}} \beta^{\tau-t}\left[\pi_{d'_\tau \tau}(z_\tau) + \psi_{d'_\tau}\left(p_{d'_\tau \tau}(z_\tau)\right)\right]$$
$$\times \kappa_{\tau-1}\left(z_\tau \mid z_t, d'_t = 1\right)$$

with a similar expression for $v_{1t}(z_t)$. Noting that

$$v_{1t}(z_t) - v_{0t}(z_t) = \psi_0\left(p_t(z_t)\right) - \psi_1\left(p_t(z_t)\right),$$

we can insert plug in the expressions for $v_{1t}(z_t)$ and $v_{0t}(z_t)$ and set $d'_\tau = 1$ for all $\tau > t$ to obtain, upon rearrangement

$$\omega(\delta_t) = R\left(x_t, \bar{N}_{k_t}\right) - \psi_0\left(p_t(z_t)\right) + \psi_1\left(p_t(z_t)\right)$$
$$- \sum_{\tau=t+1}^{T} \beta^{\tau-t} \sum_{z_\tau \in \mathcal{Z}} \left[-R\left(x_\tau, \bar{N}_{k_\tau}\right) + \psi_0\left(p_\tau(z_\tau)\right)\right]\left(\kappa_{\tau-1}\left(z_\tau | z_t, 0\right) - \kappa_{\tau-1}\left(z_\tau | z_t, 1\right)\right).$$

This yields an expression for $\omega(\delta_t)$ in terms of functions of state variables which are known from normalizations $(R(x_\tau, \bar{N}_{k_\tau})$, the distribution of the unobserved term identified in the first stage $(\psi(p_\tau(z_\tau)))$, or observed in the data $(\kappa_{\tau-1}(z_\tau | z_{\tau-1}, d_t))$, completing identification of $\omega(\delta_t)$. ∎

A2. *Government Reserve Price Simulation*

To perform the counterfactual policy in which government sets a reserve price for each auction, it is necessary to recompute the value function for each state as auction entry and bidding (and therefore expected winning bid) are affected by the establishment of a reserve price policy. Ex ante value functions for each state are computed using the following sequence of steps, which is run for each fiscal year-region pair:

(1) Starting in period T, government draws cost c_{gT}, sets $r^*(c_{gT})$ to be

$$r^*\left(c_{gT}\right) = c_{gT} + \theta\,\delta_t.$$

(2) Expected profit conditional on reserve price $r^*(c_{gT})$ and j bidders for each $j \in \{1, \ldots, \bar{N}_{k_t}\}$ is calculated by simulating the auction 200 times.

(3) For each $n = 1, \ldots, \bar{N}_{k_t}$, the expected profit for each bidder conditional on entry is calculated by simulating auction outcomes 200 times for each number of bidders:

$$E\left[\tilde{u}_i | n, x_T, r^*\right] = \Pr\left(c_i < c_j \;\forall j \neq i\right)$$
$$\times E\left[b\left(c_i\right) - c_i | c_i < c_j \;\forall j \neq i, c_i \leq r^*\left(c_{gT}\right)\right].$$

(4) The expected profit and entry cost distribution are used to solve for the equilibrium entry cutoff $\tilde{e}_k(x_T)$:

$$\tilde{e}_k\left(x_T; r^*\left(c_{gT}\right)\right) = \sum_{j=1}^{\bar{N}_{k_t}} \left(\zeta\left(\tilde{e}_k\left(x_T; r^*\left(c_{gT}\right)\right)\right)^j \left[1 - \zeta\left(\tilde{e}_k\left(x_T; r^*\left(c_{gT}\right)\right)\right)\right]^{\bar{N}_{k_t} - j}\right)$$
$$\times E\left[\tilde{u}_i | j, x_T, r^*\left(c_{gT}\right)\right].$$

(5) Using the entry cost cutoff $\tilde{e}_k(x_T)$, the distribution over the number of bidders can be expressed

$$\Pr\left(n = j|\tilde{e}_k\left(x_T; r^*\left(c_{gT}\right)\right)\right)$$
$$= \zeta\left(\tilde{e}_k\left(x_T; r^*\left(c_{gT}\right)\right)\right)^j \left[1 - \zeta\left(\tilde{e}_k\left(x_T; r^*\left(c_{gT}\right)\right)\right)\right]^{\bar{N}_{k_t}-j}.$$

(6) Draw from the number of bidders distribution and simulate the auction outcome.

(7) Average over simulations s to obtain CCPs and conditional payoffs:

$$\tilde{p}_{0T}(z_T) = \frac{1}{200}\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 0\},$$

$$E\left[\tilde{V}_{0T}(z_T)\,|d_T = 0\right] = -\frac{\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 0\}\left(c_{gsT} + \theta\,\delta_t\right)}{\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 0\}}, \quad \text{and}$$

$$E\left[\tilde{V}_{1T}(z_T)\,|d_T = 1\right] = -\frac{\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 1\}\,b_s^1}{\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 1\}},$$

where b_s^1 is the winning bid in auction s.

(8) Ex ante value function computed as

$$\tilde{V}_T(z_T) = \tilde{p}_{0T}(z_T)E\left[\tilde{V}_T|d_T = 0\right] + \left(1 - \tilde{p}_{0T}(z_T)\right)E\left[\tilde{V}_T|d_T = 1\right].$$

(9) Iterating backwards from $t = T-1,\ldots,1$, draw 200 government costs c_{gst} for each t and z_t from $G(\cdot|x_t)$. Set reserve price $r^*(c_{gst}) = c_{gst} + \theta\delta_t + \beta_t\sum_{z\in\mathcal{Z}}\tilde{V}_{t+1}(z_t)(q_{0t}(z|z_t) - q_{1t}(z|z_t))$.

(10) Repeat steps 1 through 8, with

$$E\left[\tilde{V}_{0T}(z_T)\,|d_T = 0\right]$$
$$= -\frac{\sum_{s=1}^{200}\mathbf{1}\{d_{st} = 0\}\left(c_{gst} + \theta\delta_t - \beta_t\sum_{z\in\mathcal{Z}}\tilde{V}_{t+1}(z)\,q_{0t}(z|z_t)\right)}{\sum_{s=1}^{200}\mathbf{1}\{d_{st} = 0\}},$$

and

$$E\left[\tilde{V}_{1T}(z_T)\,|d_T = 1\right]$$

$$= -\frac{\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 1\}\,b_s^1 - \beta_t\sum_{z\in\mathcal{Z}}\tilde{V}_{t+1}(z)\,q_{1t}(z|z_t)}{\sum_{s=1}^{200}\mathbf{1}\{d_{sT} = 1\}}.$$

The simulation is run by beginning at the first project for each region and fiscal year, drawing cost c_{gt} and setting the reserve price using the simulated value functions, and simulating the entry process and auction outcome. If the lowest cost for private sector firms in the auction is lower than the reserve price, the project is outsourced. Otherwise, the project is kept in-house. Then the state variables are updated and the simulation proceeds to the next stage. The simulation is run 500 times for each fiscal year-region pair.

Endogenous Government Schedule.——For the setting in which the government reserve can be adjusted, I first determine the set of possible alternative schedules. This set consists of all permutations in which the maximum number of steps moved up or down the schedule is two. When a project moves up or down the schedule of projects, it assumes the start date of the project that previously occupied that schedule slot, but otherwise maintains all of its previous project characteristics. To conduct the counterfactual, I randomly draw from this set of schedules. Then, steps 1–10 are conducted in the same manner as above to establish the ex ante valuation for each time period, and the simulation is run by drawing from the government cost distribution and simulating the auction outcome to determine whether the project will be completed in-house or allocated to a private sector firm. The simulation is run 200 times for each schedule.

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