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Auctioning IT Contracts with Renegotiable Scope

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Abstract. Motivated by challenges facing IT procurement, this paper studies a hybrid procurement model in which a reverse auction of a fixed-price IT outsourcing contract may be followed by renegotiation to extend the contract's scope. In this model, the buyer balances the needs to incentivize noncontractible vendor investment and to curb the winning vendor's information rent by choosing the initial project scope and the buyer's investment in the quality of the project. We find that a buyer may benefit from inducing ex post renegotiation to motivate vendor investment, especially when the winning vendor has high bargaining power and the quality uncertainty is low. Broadening the initial scope reduces information rent but leaves little room for ex post renegotiation and, hence, discourages vendor investment, whereas increasing the buyer's investment has opposite effects. Interestingly, the two measures can be strategic substitutes or complements depending on the likelihood of the renegotiation and the two parties' bargaining powers. The buyer may strategically set a low initial project scope and high investment to incentivize renegotiation and vendor investment, which may explain why many IT outsourcing projects start small and allow expansions. Our findings also generate several testable predictions for IT outsourcing.

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Keywords: IT outsourcing • renegotiation • specific investments • reverse auctions • incomplete contracts

1. Introduction

Organizations often use external providers for a wide range of IT services, such as application and software development, technical support, infrastructure, system migration (e.g., to cloud computing), and process automation. Surveys report that 31% of IT services were outsourced in 2016 (Deloitte 2016). The global IT outsourcing (ITO) market was valued at USD 520.74 billion in 2019 with an estimated compound annual growth rate of 7.7% from 2020 to 2027 (Grand View Research 2020). A cost-effective way of procuring IT services is through competitive tendering, also known as reverse auctions, in which the buyer invites multiple prequalified vendors (sellers) to bid for a fixed-price service contract and awards the contract to the bidder with the lowest price.[1] Compared with negotiation-based outsourcing, reverse auctions can result in significant cost savings, improved speed, access to a larger pool of vendors, and increased transparency (e.g., Reece 2004, Mishra and Bureau 2012, Wilson 2016). Reverse auctions are used in almost all Fortune 1000 companies (Wyld 2011) and are especially popular in the public sector (e.g., Bajari et al. 2008, Wyld 2011) and among young procurement professionals (Bowman 2019).

Despite the aforementioned strengths, reverse auctions may be inadequate for dealing with a few challenges in IT outsourcing. The first challenge is quality uncertainties associated with IT outsourcing, which may result from unexpected technical difficulties, changing demand and expectations, and changing regulatory requirements, such as new data privacy laws (Susarla 2012, Bhattacharya et al. 2014). With such uncertainties, it is nearly impossible to specify all contingencies for the IT outsourcing contract. Consequently, IT outsourcing contracts are often *incomplete.* Furthermore, buyers may lack knowledge about vendor expertise at the beginning. This information asymmetry problem could result in *suboptimal* contracts. With incomplete and suboptimal contracts, organizations often find it necessary to renegotiate the terms of the contract (e.g., changing requirements, adding/removing requirements, and even terminating the contract) ex post. For instance, Korea Exchange and IBM extended the scope of a system maintenance service contract after IBM's excellent service delivery (IBM 2009). A Gartner survey of 200 executives of midsize and large companies reported that 55% of IT infrastructure outsourcing contracts had been renegotiated (Pinsent Masons 2005). Moreover, there are reports of IT outsourcing projects starting small and gradually extending into full operational systems (Hertzum et al. 2012).

Another challenge lies in the "hold up" problems in IT outsourcing—that is, a vendor can make a noncontractible investment that benefits the buyer, but once such an investment is made, the buyer can hold up the value of the vendor investment. Specifically, IT outsourcing usually requires the vendor to invest in quality improvements (e.g., technology R&D and security enhancements), which are often *noncontractible* because they are nonverifiable by a third party (Snir and Hitt 2004, Bhattacharya et al. 2014). For example, General Services Administration "encourages" vendors to incorporate upgrades and innovations when procuring its next-generation telecommunication services (Miller 2017). Reverse auctions with a fixed-price contract provide strong incentives for vendor investments in cost reduction (e.g., Bajari and Tadelis 2001), but not for noncontractible quality improvements. Consequently, reverse auctions may be inadequate for ensuring the quality of IT outsourcing.

The aforementioned challenges suggest the importance of combining reverse auctions and renegotiations. Renegotiation following a reverse auction (henceforth, *ex post renegotiation*) can complement the reverse auction in two ways: first, the ex post renegotiation lets the two parties adjust the contract to leverage new information about the vendor and the project. Second, renegotiations may be useful for motivating the vendor's noncontractible investment in project quality because, with renegotiations, vendors can capture a share of the surplus generated by their investment. Reverse auctions with renegotiation make the most sense in a two-phased IT outsourcing project, in which the first phase is a reverse auction and the second phase is a renegotiation that expands the scope of the project. Such two-phased implementations seem popular: a survey of large Australian and United Kingdom organizations shows that 81% and 87%, respectively, of respondents award pilot contracts for information system implementation before full-scale implementation (Hertzum et al. 2012).

Although renegotiation frequently occurs after IT outsourcing auctions (e.g., Snir and Hitt 2004, Deloitte 2013, Kujala et al. 2015), the literature is absent on the joint use of reverse auction and ex post negotiation. Many interesting issues arise in such a context, including the following:

- How would vendors behave in reverse auctions in anticipation of likely ex post renegotiation?
- Can reverse auctions with renegotiation alleviate the information asymmetry and hold-up problems in IT outsourcing?
- When and how should buyers induce (or suppress) ex post renegotiation after an IT outsourcing auction?

This research addresses the aforementioned questions by examining a two-phased IT outsourcing project: in the first phase, a buyer awards a fixed-price IT outsourcing contract to a winning bidder via a reverse auction; the winner makes a noncontractible investment in quality enhancements (henceforth *vendor investment*) and fulfills the contract; in the second phase, after observing the first-phase quality outcomes, the two parties can renegotiate the contract to extend the project's scope.[2] We capture three important features of IT outsourcing in our model: the two parties can learn new information about the project implementation quality after the initial phase, the buyer does not know vendors' true expertise ex ante ("information asymmetry"), and the vendor investment is noncontractible (the *hold-up* problem). We use this model to analyze vendors' bidding and investment decisions and the buyer's decisions.

We focus on two kinds of buyer decisions. First, the buyer can choose the scope of the initial contract for auctioning (i.e., *initial scope*). Second, the buyer can choose the *up-front investment* (e.g., developing detailed project requirements and securing more financial and managerial resources for the project) that affects vendors' productivity and, thus, their bidding and investment behaviors in IT outsourcing.

Overall, we find that a vendor may face three renegotiation cases: *never*, *always*, or *opportunistically renegotiate* (that is, renegotiate only when the implementation quality in the first phase is favorable). The winning vendor has incentives to make an up-front quality investment only when a renegotiation is possible, and the investment incentive and information rent increase if renegotiation is more likely to happen. Broadening the initial scope undermines vendor investment and also curtails vendor's information rent although increasing buyer investment has the opposite effects. Interestingly, the two measures may be either strategic substitutes or complements for the buyer, depending on the renegotiation scenarios and the vendor's bargaining power in the renegotiation. The buyer strategically chooses the initial project scope and the upfront investment to balance the gains from the initial contract (for which the two measures are complements) and the renegotiation one (for which the two measures are substitutes). The buyer optimally induces more renegotiation as the quality uncertainty decreases and the vendor's bargaining power increases. In the extended analyses, we show that the main results hold qualitatively when we allow for an optimal reserve price, costly learning of project quality, and buyer investments in cost reduction.

Our research contributes to the IT outsourcing and procurement auction literature in two ways. First, we advance the understanding of the buyer and vendors' strategic considerations in real-world procurement auctions that are often renegotiated. Our hybrid procurement model, motivated by observations from IT outsourcing, captures both information asymmetry and moral hazard problems. In contrast, prior literature on reverse auctions with renegotiation has only dealt with information asymmetry issues. In our hybrid procurement model, renegotiation is not a passive coping mechanism but a strategic tool, used in conjunction with the reverse auction, for dealing with moral hazard problems. Second, we provide new insights on how organizations should use the initial project scope and buyer up-front investment as strategic levers in a hybrid IT outsourcing environment. The extant literature has not provided insights on such issues. For example, it is not yet clear why some organizations start with a small pilot project before scaling it up (e.g., Fenton 2016) and others start big (e.g., European Services Strategy Unit 2017). Although prior research examines the buyer's investment decision (e.g., Roels et al. 2010, Lee et al. 2013), it is unclear what roles it plays in the hybrid procurement mechanism or how it should be coordinated with the initial scope.

Though the procurement literature has long recognized the prevalence of ex post renegotiation in contexts such as the construction industry, it characterizes renegotiation as a passive and costly adaptation mechanism (Gil and Oudot 2009, Bajari et al. 2014, Miller 2014, Jung 2016) and focuses on strategies of avoiding such renegotiation (e.g., Herweg and Schmidt 2020). Only a handful of papers recognize the strategic value of ex post renegotiation. Herweg and Schwarz (2018) suggest that renegotiation and resulting cost overruns in the construction industry can be optimal for the buyer. Agrawal and Oraiopoulos (2020) find that renegotiation can be a powerful way of aligning the interests of the firms and, therefore, maximizing the value from a codevelopment initiative. Still, there is very limited research on how to set up the reverse auction in anticipation of ex post renegotiation, especially in a complex IT outsourcing environment with both information asymmetry and moral hazard problems.

The remainder of the paper is organized as follows: we next review the related literature, followed by the research model. We then analyze the model and its extensions. The last section concludes the paper.

2. Relation to Existing Literature

There is a large body of research on ITO. Several comprehensive reviews (e.g., Lacity et al. 2009, Liang et al. 2016) summarize this body of research. Most ITO studies are empirical work with very different foci from this paper. They, however, lay a foundation for this research. For example, existing research shows that contracting for IT services is inevitably incomplete (e.g., Susarla et al. 2010) because it typically involves unforeseen contingencies (e.g., Aubert et al. 2004), noncontractible investments and behaviors (e.g., Susarla 2012), and immeasurable performance (e.g., Fitoussi and Gurbaxani 2012). These studies inform our choice of model elements. In the following, we focus on existing work on procurement design for ITO and other related contexts with an emphasis on analytical modeling papers.

This research is generally related to the literature on vendor selection problems in ITO. Nam et al. (1995) and Chaudhury et al. (1995) study the winner-determination problem in ITO auctions when bidders have asymmetric cost structures. Tunca and Zenios (2006) study the choice between auctions and relational contracts when the suppliers' quality is nonverifiable. Cao and Wang (2007) study a two-stage vendor selection model, in which the buyer sponsors multiple vendors in the first stage and picks the best for the second stage of the project. Their focus is on how to allocate the buyer's budget between the first and second stages. Unlike this research, these papers do not study how to motivate noncontractible vendor investments after vendor selection.

Our paper is also related to the economics literature on the hold-up problem; the risk of the buyer holding up the vendor's noncontractible investment can undermine the vendor's incentives to invest (Che and Sákovics 2008). Tirole (1986) shows that a vendor generally underinvests in a two-period procurement model in which the vendor invests in the first period and the vendor and the buyer acquire private information about their cost and valuation, respectively, before entering a renegotiation. This stream is devoted to alleviating the hold-up problem using strategies such as vertical integration (Williamson 1979), shifting property rights (Grossman and Hart 1986), and allocating control rights (Aghion and Bolton 1992). Our model is most similar to the property-right approach in that the buyer can use the buyer's decisions to alter the renegotiation surplus claimed by the winning vendor.

Bhattacharya et al. (2014) also study the hold-up problem in IT outsourcing. They show that gain-share contracts are superior to commonly observed cost-plus contracts. Benaroch et al. (2010) propose a real-option approach for determining when a buyer should include flexible contract terms for ex post renegotiation. Most recently, Agrawal and Oraiopoulos (2020) study a hold-up problem in codevelopment initiatives in which two parties can both make a noncontractible effort to affect future outcomes and can renegotiate after observing the market potential. They adopt a decision-right approach to alleviate the hold-up problem: one party may choose a menu of contracts ex ante, whereas the other may choose a specific contract ex post. Different from these hold-up papers, we study the hold-up problem jointly with a vendor-selection problem. As a result, there is a trade-off between alleviating the hold-up problem and extracting information rent. Our version of the hold-up problem is most similar to that of Agrawal and Oraiopoulos (2020) though their setting (of product codevelopment) and mitigation strategy are quite different from ours.

The issues of contract incompleteness and associated renegotiation are also investigated in other industries, such as building construction (e.g., Bajari and Tadelis 2001, Bajari et al. 2008) and weapons systems (e.g., Tirole 1986, Riordan and Sappington 1989). A few studies compare the effectiveness of different contract/procurement formats when ex post renegotiations are required. Bajari and Tadelis (2001) model ex post renegotiations in the construction industry as a result of an inadequate initial design. They show that cost-plus contracts, which permit two parties to reach efficient ex post designs but provide little incentives for cost-reduction efforts, are preferred to fixed-price contracts when a project is more complex. Herweg and Schmidt (2017) compare price-only auctions and negotiations in a context in which potential suppliers hold private information about possible design improvements. They show that negotiations are superior to auctions if design improvements are important, renegotiation is very costly, and the buyer's bargaining position is strong. A host of empirical studies examine the implications of auctioning incomplete contracts and associated renegotiation: Bajari et al. (2008) find that reverse auctions perform poorly when the project is complex and the initial contract is incomplete but may still outperform negotiations if there are many potential bidders. Miller (2014) finds that, relative to in-house projects, renegotiation significantly increases costs, distorts bidding strategies, and causes welfare losses. Bajari et al. (2014) show that bidders respond strategically to contractual incompleteness and incorporate adaptation costs into their bids. Our research departs from the aforementioned studies of renegotiation in that we study a more proactive approach of managing renegotiation: anticipating the likely renegotiation, the buyer can choose a smaller scope contract for auctioning and renegotiate additional scope as needed. Moreover, noncontractible vendor investments in quality improvements play a key role in our setting but are absent from the aforementioned studies. Interestingly, although a majority of empirical papers in the construction context paint a negative role of ex post renegotiation, Susarla (2012) demonstrates a positive role of renegotiation in ITO contexts: when the procurement contract includes delineations of decision rights for ex post contingencies, renegotiation can lead to Pareto improvements.

Our study belongs to a small literature that examines design issues in auction-renegotiation hybrid models. Herweg and Schwarz (2018) study whether a buyer should announce a standard or a fancier design in the initial auction for a construction project in anticipation of possible renegotiation to the ex post efficient design. They show that the buyer may prefer a simpler design plus renegotiation for its ability to compress vendors' information rent. Unlike their paper, we consider both rent-extraction and hold-up problems in our setting. Herweg and Schmidt (2020) focus on excessive renegotiation caused by vendors concealing their private information about initial design flaws. They propose a direct mechanism based on third-party arbitration that induces vendors to report design flaws ahead of the reverse auction. They focus on eliminating inefficient renegotiations without considering hold-up problems. Moreover, they study an efficient design, whereas we study a design that maximizes the buyer's expected surplus.

A few other studies also examine auction-renegotiation procurement models but use auction and/or renegotiation differently. Wang (2000) studies a procurement auction model with renegotiation in which the buyer can, immediately after the auction, incur an expense to renegotiate with the winner to learn about the vendor's true cost. Huh and Park (2010) study a model in which the buyer audits the winner's cost immediately after the auction and negotiates with the winner to determine a final price. In both papers, negotiation occurs immediately after the auction as part of the cost discovery, whereas renegotiation in our paper occurs after the fulfillment of the initial contract and may lead to a scope expansion. Riordan and Sappington (1989) examine a two-stage defense procurement model, in which the buyer first uses an auction to choose a vendor to generate a design and then uses a direct mechanism to select a vendor (which could be the designer) for production. They focus on whether to invite additional vendors in the production stage.

Snir and Hitt (2004) propose a two-stage vendor-selection mechanism for IT outsourcing that tackles both vendor selection and hold-up problems. The buyer uses a screening contract to select a vendor in a pilot stage and awards a full-implementation contract only if the pilot project exceeds a minimum quality threshold. Their model differs from ours on the mechanisms used: we use an auction instead of a screening contract in the first phase and renegotiation instead of a predetermined threshold in the second stage. Moreover, the two phases in their model are exogenous, whereas our first phase has an endogenous scope.

3. Model

A buyer would like to outsource an IT project to one of n ($n \geq 2$) prequalified vendors through a reverse auction. Such an IT project can be application/software development, web development/hosting, database development/management, and so on (Bradford 2019). The procurement proceeds in two phases. Phase 1 is the *auction* phase in which the buyer conducts a reverse auction to select a vendor for carrying out the IT outsourcing project with a preannounced initial scope s_1. Then, the winner of the auction implements the initial scope s_1. Phase 2 is the *renegotiation* phase, in which the two parties can renegotiate the initial contract to expand the project's scope to $s = s_1 + s_2$. If the renegotiation succeeds, the vendor implements the additional scope s_2.

The value of the project to the buyer is a function of both scope and quality of deliverables. Specifically, denoting q_1 and q_2 as the quality of deliverables in phases 1 and 2, respectively, we assume

$$\text{Project value}_t = s_t \times q_t, \ t \in \{1, 2\}. \tag{1}$$

The project's scope s_t captures the number and substance of the required deliverables. For example, an enterprise resource planning (ERP) implementation project with more modules and requirements per module has a larger scope. The implementation quality q_t captures the degree to which the deliverables meet the buyer's demand (Sundqvist et al. 2014). A higher-quality implementation generates more value to the buyer for the same scope. For example, a higher-quality ERP implementation means that, on average, the modules and functionalities are better built (e.g., more efficient, easier to use, and producing higher quality reports). We assume that the quality levels q_1 and q_2 are observable but nonverifiable. Similiar assumptions have been made in several prior studies (e.g., Tunca and Zenios 2006). The nonverifiability of project quality arises because quality standards are often subjective and tacit.

We assume the quality of deliverables has both a stochastic and a deterministic component. Its deterministic component is a function of the two parties' up-front investments in quality. Specifically, we assume

$$q_t = q_0 + \gamma x + \theta z + \epsilon_t, \ t \in \{1, 2\}, \tag{2}$$

where q_0 ($q_0 > 0$) is the baseline quality, x is the buyer's up-front investment in quality with γ being the buyer's investment coefficient, z is the vendor's up-front investment in quality with θ being the vendor's investment coefficient, and ϵ_t is the stochastic component. The additive format of joint investments is commonly used in the literature (see, e.g., Xiao and Xu 2012, Li 2013, Agrawal and Oraiopoulos 2020).

In Equation (2), the baseline quality q_0 reflects the default quality of this type of IT project and is determined by the type of project and the current technology level. The buyer and the vendor can make up-front investments (x and z, respectively) at the beginning of the project to further improve its quality, and such investments can affect the entire project scope. Buyer up-front investments x may include developing detailed project requirements, securing more financial and managerial resources for the project, and committing resources to manage changes. For example, in its cloud-services procurement auction, the Federal Aviation Administration (2015) announced several investments it would make, such as the provision of telecommunications connectivity, computing infrastructure, directory services, and migration support tools. Such investments can benefit the entire project by enabling high-quality deliverables. The vendor's up-front investments could include, for instance, acquiring and training talents with relevant expertise, developing detailed implementation plans, and developing standards and interfaces for the buyer's specific needs.[3] Again, such vendor investments have a project-wide impact. For example, application-development vendors can appoint the most skillful developers that affect the quality of all modules.

We assume the vendor investment z is observable but nonverifiable (thus, noncontractible). It is observable because the buyer can closely examine the vendor's deliverables. It is nonverifiable because there is no verifiable measure of quality. The buyer investment x is publicly announced and observable by vendors.

We interpret coefficients γ and θ as the buyer's and vendor's *expertise*, respectively. Such expertise can be developed from domain knowledge, technical know-how, and past experiences from similar projects. Higher expertise allows a buyer or vendor to achieve a higher quality outcome with the same amount of time or effort. We assume that the buyer's expertise γ is public knowledge. In contrast, a vendor's expertise θ is the vendor's private information (or "type"). The vendors' expertise $\{\theta_i\}_{i=1}^n$ is independently and identically distributed (i.i.d.) on the support $[\underline{\theta}, \overline{\theta}]$ ($0 \leq \underline{\theta} < \overline{\theta}$) with a cumulative distribution function $F(\cdot)$ and a probability density function $f(\cdot)$. The distribution is common knowledge.

The stochastic component ϵ_t is a function of a project-specific latent state ϵ_0 and some random disturbances. The latent state ϵ_0 reflects the unknown state of the world that affects the quality of deliverables, such as the technological landscape, usage patterns, and end-user expectations. The latent state ϵ_0 is time persistent but initially unknown to the buyer or the vendors.

The phase-1 and phase-2 quality states ϵ_1 and ϵ_2 take values from $\{\epsilon_H, \epsilon_L\}$ ($\epsilon_H > \epsilon_L$). Their values are affected by environmental uncertainties such as uncertainties in the technological landscape, usage patterns, and end-user demands. To model the correlation between the two quality states, we assume that both are manifestations of a latent quality state ϵ_0, which also takes values from $\{\epsilon_H, \epsilon_L\}$. With probability $\rho_t \in [\frac{1}{2}, 1]$ ($t \in \{1, 2\}$), the phase-t quality state ϵ_t is the same as the latent quality state ϵ_0, and with probability $1 - \rho_t$, it takes the opposite value. The latent quality state ϵ_0 is drawn randomly from $\{\epsilon_H, \epsilon_L\}$ at the beginning of the project with probabilities λ and $1 - \lambda$, respectively, and a mean of zero. The buyer or vendors would not know the project's latent quality state ϵ_0, but they can observe the phase-1 quality state to update their belief about the latent quality state, which, in turn, affects their belief about phase-2 quality. We interpret ρ_t as the informativeness of the phase-t quality about the latent quality state ϵ_0: the higher ρ_t is, the more informative is the phase-t project quality. We assume that ρ_t and the distribution of ϵ_0 are common knowledge.

For notational convenience, we denote

$$P_j \equiv \Pr\{\epsilon_1 = \epsilon_j\}, j \in \{H, L\},$$
$$P_{j|i} \equiv \Pr\{\epsilon_2 = \epsilon_j \mid \epsilon_1 = \epsilon_i\}, i, j \in \{H, L\},$$

where P_j is the probability of ϵ_1 taking the value ϵ_j and $P_{j|i}$ is the probability of ϵ_2 taking the value ϵ_j conditional on ϵ_1 taking the value ϵ_i.[4] It can be verified that ϵ_1 and ϵ_2 are positively correlated in the sense that the phase-2 quality state is more likely to be high (low) if the phase-1 quality state is high (low). We further denote

$$\hat{\epsilon}_t \equiv \mathbb{E}[\epsilon_t], t \in \{1, 2\},$$
$$\hat{\epsilon}_{2|i} \equiv \mathbb{E}[\epsilon_2 \mid \epsilon_1 = \epsilon_i], i \in \{1, H, L\}$$

as the expected quality state of phase t and the conditional expected quality state of phase 2, respectively.

The buyer chooses a vendor via a sealed-bid, second-price reverse auction, in which every participating vendor submits a price and the one with the lowest price wins and receives the next lowest price as payment (Milgrom and Weber 1982, Krishna 2009).[5] The sealed-bid auction is commonly used in IT project procurement though, as we show in the online appendix (see Lemma A1), the revenue equivalence principle holds, and our results are not sensitive to the specific auction format used. We focus on a simple (i.e., no reserve price) reverse auction though we demonstrate in the extensions section that our main insights can still hold when there is an optimal reserve price.

The timeline of the game is as follows (see Figure 1). In phase 1, the auction takes place. During this phase, the buyer announces the initial scope s_1 and makes an up-front investment x for a cost of $\frac{1}{2}x^2$. Such a cost pattern is commonly used in literature (e.g., Bhattacharya et al. 2014, August et al. 2017).[6] After observing the initial scope s_1 and the buyer's up-front investment x, vendors place their bids in the reverse auction. The auction results in a winning bidder and a winning price p_1.

After the auction, the winning bidder makes an up-front investment z ($z \geq 0$) in quality improvements for a cost of $\frac{1}{2}z^2$. Similar cost functions are used in prior studies (e.g., Bhattacharya et al. 2014, August et al. 2017). The quadratic form captures the notion that improving project quality is increasingly harder. We note that, although the cost of quality investments is the same for all vendors, the impact of such investments on quality is different for vendors of different expertise (see Equation (2)).

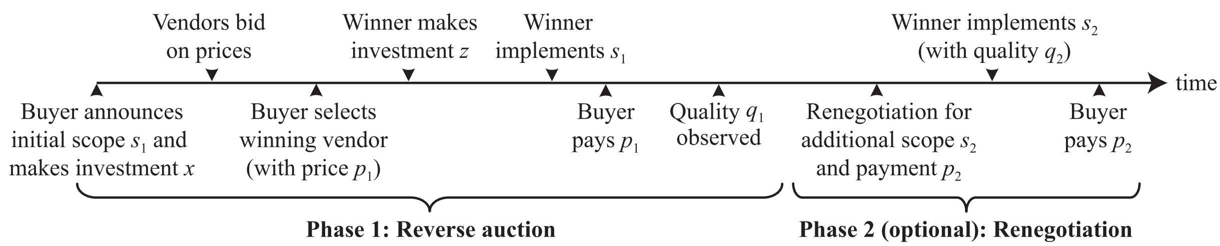
The winning bidder then implements the initial scope s_1 for a cost of $c_F(\theta) + \frac{1}{2}s_1^2$. The first component $c_F(\theta)$ is a one-time fixed cost and a decreasing function of the vendor's expertise θ (i.e., $c_F'(\theta) < 0$). The second component $\frac{1}{2}s_1^2$, the quadratic cost of the scope, captures the notion that, as the project gets larger, the marginal cost of scope is higher as a result of the increased complexity (Doğan et al. 2011). Overall, our assumption of the implementation cost suggests that vendors incur the same variable cost for increasing a project's scope but different fixed costs for initiating the project. For example, a higher expertise vendor has a lower fixed cost because the vendor has more experience or expertise in designing a system architecture or a technical solution.

After the vendor implements initial scope s_1, the buyer pays the vendor p_1. By the end of this phase, the buyer learns the winning vendor's quality investment z, expertise θ, and the phase-1 quality q_1. By our assumption, the quality investment z and the phase-1 quality q_1 become observable after the project phase 1 is delivered (though they remain nonverifiable). The buyer can infer the vendor's expertise θ from the vendor's bid because, as we will show the sealed-bid, second-price reverse auction is truth telling.

At phase 2, the two parties may choose to renegotiate the project scope based on the expected phase-2 quality. If the renegotiation succeeds, the two parties determine an additional project scope s_2 and a payment p_2 for implementing it. Because the total cost of scope is $\frac{1}{2}(s_1 + s_2)^2$, the cost of implementing the additional scope is $\frac{1}{2}(s_1 + s_2)^2 - \frac{1}{2}s_1^2$ (there is no fixed cost in phase 2). Under this cost function, the greater the initial scope s_1, the higher the marginal cost of the additional scope, reflecting the added complexity of coordinating with a larger phase-1 project.

We denote u_1, u_2, and u as the winning vendor's phase-1, phase-2, and total expected surplus, respectively. Similarly, we denote v_1, v_2, and v as the buyer's

Figure 1. Sequence of Events



phase-1, phase-2, and total expected surplus, respectively. We adopt the generalized Nash bargaining solution (GNBS) for the renegotiation game.[7] Specifically, a GNBS prescribes that the two parties choose (s_2, p_2) to maximize the following Nash product (e.g., Binmore et al. 1986, Herweg and Schmidt 2020):

$$\max_{s_2, p_2} u_2^{\alpha} v_2^{1-\alpha} \quad \text{s.t.} \quad s_2 \geq 0, u_2 \geq 0, v_2 \geq 0. \tag{3}$$

The parameter $\alpha \in [0,1]$ captures the relative bargaining power of the winning vendor. One can easily verify that, in a GBNS, s_2 is chosen to maximize the renegotiation surplus $\mathcal{S}$ (e.g., Agrawal and Oraiopoulos 2020, Herweg and Schmidt 2020), defined as the sum of the two parties' phase-2 surpluses, that is,

$$\mathcal{S} = u_2 + v_2. \tag{4}$$

Meanwhile, p_2 is chosen to allocate the renegotiation surplus according to their bargaining powers (i.e., $u_2 = \alpha\mathcal{S}$ and $v_2 = (1-\alpha)\mathcal{S}$). Table 1 summarizes the notation used in our model.

4. Analysis

4.1. Renegotiation

Applying backward induction, we first analyze the renegotiation decision at phase 2 given the realization of phase-1 quality q_1. The winning vendor's phase-2 expected surplus u_2 is

$$u_2 = p_2 - \frac{1}{2}(s_1 + s_2)^2 + \frac{1}{2}s_1^2. \tag{5}$$

The buyer's phase-2 expected surplus v_2 is

$$v_2 = \mathbb{E}_{\epsilon_2}[q_2 s_2 \mid \epsilon_1] - p_2 = (q_0 + \gamma x + \theta z + \hat{\epsilon}_{2|1})s_2 - p_2. \tag{6}$$

We define the *ex post optimal scope* as the project scope that maximizes the expected renegotiation surplus conditional on the phase-1 quality state ϵ_1.

Lemma 1. *At phase 2, the ex post optimal scope is given by*

$$s^* = q_0 + \gamma x + \theta z + \hat{\epsilon}_{2|1}. \tag{7}$$

The two parties renegotiate if and only if $s^* > s_1$. If the renegotiation occurs, we have

$$s_2 = s^* - s_1, \tag{8}$$

$$p_2 = \frac{1}{2}s_2[(1+\alpha)s_2 + 2s_1], \tag{9}$$

$$\mathcal{S} = \frac{1}{2}s_2^2. \tag{10}$$

Because the renegotiation decision may depend on the phase-1 quality state, we define three possible renegotiation cases $\{N, O, A\}$ that a winning vendor may face. Here, "N" stands for the never-renegotiate case in which there is no renegotiation regardless of the phase-1 quality state; "A" stands for the always renegotiate case in which there is always renegotiation regardless of the phase-1 quality state; finally, "O" stands for the opportunistically renegotiate case in which there is renegotiation only if the phase-1 quality state is high (i.e. $\epsilon_1 = \epsilon_H$).

4.2. Vendor's Problem

4.2.1. Winning Vendor's Up-front Investment. The winning vendor makes an up-front investment after winning the auction but before the phase-1 quality is known. The vendor's up-front investment directly benefits the buyer but not the vendor. With renegotiation, however, the vendor can indirectly benefit from the up-front investment by capturing a share of the phase-2 renegotiation surplus which increases with the vendor's up-front investment. Noting that the winning vendor's phase-1 surplus is

$$u_1 = p_1 - c_F(\theta) - \frac{1}{2}s_1^2 - \frac{1}{2}z^2, \tag{11}$$

the winning vendor chooses up-front investment z to maximize the total expected surplus:

$$u(z;\theta,p_1) \equiv \mathbb{E}_{\epsilon_1}[u_1 + u_2] = \underbrace{p_1 - c_F(\theta) - \frac{1}{2}s_1^2 - \frac{1}{2}z^2}_{\text{(i)}} + \underbrace{\mathbb{E}_{\epsilon_1}\left\{\frac{\alpha}{2}\left[(q_0 + \gamma x - s_1 + \theta z + \hat{\epsilon}_{2|1})^+\right]^2\right\}}_{\text{(ii)}}. \tag{12}$$

In Equation (12), the term (i) is the vendor's phase-1 surplus and the term (ii) is the expected phase-2 surplus, which is computed as the vendor's expected

Table 1. Summary of Notation

n	Number of vendors
s_t	Project scope in phase $t \in \{1,2\}$
q_t	Realized quality in phase $t \in \{1,2\}$
q_0	Baseline quality
ϵ_t	Stochastic component in the phase-t quality, $t \in \{1,2\}$
ϵ_0	Latent state, $\epsilon_0 \in \{\epsilon_H, \epsilon_H\}$
λ	Probability of the high latent state $\epsilon_0 = \epsilon_H$
σ	Standard deviation of ϵ_0
ρ_t	Probability of $\epsilon_t = \epsilon_0$ in phase $t \in \{1,2\}$
$\hat{\epsilon}_t$	$= \mathbb{E}[\epsilon_t]$, $t \in \{1,2\}$, the expectation of ϵ_t
$\hat{\epsilon}_{2\|i}$	$= \mathbb{E}[\epsilon_2 \mid \epsilon_1 = \epsilon_i]$, $i \in \{1, H, L\}$, the expectation of ϵ_2 conditional on $\epsilon_1 = \epsilon_i$
$P_{j\|i}$	$= \Pr\{\epsilon_2 = \epsilon_j \mid \epsilon_1 = \epsilon_i\}, i, j \in \{H, L\}$, the distribution of ϵ_2 conditional on $\epsilon_1 = \epsilon_i$
P_j	$= \Pr\{\epsilon_1 = \epsilon_j\}$, $j \in \{H, L\}$, the distribution of ϵ_1
x	Buyer's up-front investment
γ	Buyer's expertise (i.e., investment coefficient)
z	Winning vendor's up-front investment
θ	Winning vendor's expertise or "type" (i.e., investment coefficient), $\theta_i \in [\underline{\theta}, \overline{\theta}]$
$c_F(\theta)$	Winning vendor's fixed cost
$F(\cdot), f(\cdot)$	Cumulative distribution function and probability density function of type θ_i
p_t	Payment in phase $t \in \{1,2\}$, where p_1 is the winning price of the auction
v_1,v_2, and v	Buyer's phase-1, phase-2, and total expected surplus
u_1,u_2, and u	Winning vendor's phase-1, phase-2, and total expected surplus
$\mathcal{S}$	Joint surplus generated by renegotiation
α	Winning vendor's bargaining power

share of the renegotiation surplus $\alpha\mathcal{S} = \alpha\frac{s_2^2}{2}$ (see Lemma 1).

Although the vendor incurs a convex investment cost of $\frac{1}{2}z^2$ in phase 1 (the term (i)), the vendor also enjoys a convex return from the investment z in phase 2 (the term (ii)), so the vendor's total expected surplus may not be concave in z. The following assumption ensures that the winning vendor's total expected surplus is always concave in the vendor's investment z to rule out infinite vendor investment.

Assumption 1. The highest vendor expertise and the vendor bargaining power satisfy $1 - \alpha\overline{\theta}^2 > 0$.

This assumption effectively sets an upper bound for the highest vendor expertise $\overline{\theta}$, and this upper bound is lower when the vendor has higher bargaining power α.

Lemma 2. *The winning vendor's optimal up-front investment is*

$$z^*(\theta) = \begin{cases} 0 & (N) \\ \alpha\theta P_H(q_0 + \gamma x - s_1 + \hat{\epsilon}_{2|H})y_O(\theta) & (O), \\ \alpha\theta(q_0 + \gamma x - s_1 + \hat{\epsilon}_2)y_A(\theta) & (A) \end{cases} \tag{13}$$

where $y_O(\theta) = \left(1 - \alpha\theta^2 P_H\right)^{-1}$ *and* $y_A(\theta) = \left(1 - \alpha\theta^2\right)^{-1}$ *($y_O < y_A$) are interpreted as the vendor's investment effectiveness under cases O and A, respectively, and conditions (N), (O), and (A) are given by*

$$(N): \quad q_0 + \gamma x - s_1 + \hat{\epsilon}_{2|H} \in (-\infty, 0)$$
$$(O): \quad q_0 + \gamma x - s_1 + \hat{\epsilon}_{2|H} \in \left[0, (\hat{\epsilon}_{2|H} - \hat{\epsilon}_{2|L})/y_O(\theta)\right)$$
$$(A): \quad q_0 + \gamma x - s_1 + \hat{\epsilon}_{2|H} \in \left[(\hat{\epsilon}_{2|H} - \hat{\epsilon}_{2|L})/y_O(\theta), \infty\right).$$

Lemma 2 also implies that the winning vendor's up-front investment depends on whether the renegotiation is expected to happen. Recall that the vendor's investment incentive comes solely from the vendor's share of renegotiation surplus. Therefore, in the case of "never renegotiate" (condition N), the vendor does not invest in quality improvements (i.e., $z^*(\theta) = 0$). In contrast, in the case of "opportunistically renegotiate" (condition O) or "always renegotiate" (condition A), the winning vendor makes a positive investment.

Proposition 1. *Under cases O and A, the winning vendor's optimal up-front investment $z^*(\theta)$ increases in the buyer's up-front investment x and the vendor's bargaining power α, and decreases in the initial scope s_1.*

Proposition 1 shows how the buyer's up-front investment x and initial scope s_1 affect the vendor's investment z^*. Although both decisions work through the renegotiation surplus, their effects are different. A higher buyer investment x is associated with a higher vendor investment because, as suggested by Lemma 1, a higher x increases the additional scope s_2, which, in turn, increases the renegotiation surplus and the vendor's incentive to invest. In contrast, a higher initial scope s_1 reduces the vendor's investment because, for the same ex post optimal scope, a higher initial scope s_1 means a smaller additional scope and renegotiation surplus, thus a smaller incentive for the vendor to invest in quality improvements. When the vendor's bargaining power α increases, the vendor receives a larger share of the renegotiation surplus, which motivates the vendor to invest more. A higher α also leads to increased efficiency because it makes the vendor more of a residual claimant.

Substituting z^* into Equation (12), we obtain the winning vendor's total expected surplus under optimal investment, which is given by

$$u^*(\theta,p_1) \equiv u(z^*;\theta,p_1) = p_1 - c_F(\theta) - \frac{1}{2}s_1^2 + \begin{cases} 0 & (N) \\ \frac{1}{2}\alpha P_H(q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H})^2 y_O(\theta) & (O) \\ \frac{1}{2}\alpha\left[(q_0+\gamma x - s_1+\hat{\epsilon}_2)^2 y_A(\theta) + P_H P_L(\hat{\epsilon}_{2|H}-\hat{\epsilon}_{2|L})^2\right] & (A). \end{cases} \quad (14)$$

4.2.2. Vendors' Bidding Equilibrium. In the reverse auction, all prequalified vendors can submit a bid anticipating their costs. A winning bidder incurs a fixed cost and the cost of implementing the initial scope but also gains a share of renegotiation surplus at phase 2 as seen from Equation (14). We can rewrite Equation (14) as $u^*(\theta,p_1) = p_1 - c(\theta)$, where

$$c(\theta) \equiv c_F(\theta) + \frac{1}{2}s_1^2 - \begin{cases} 0 & (N) \\ \frac{1}{2}\alpha P_H(q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H})^2 y_O(\theta) & (O) \\ \frac{1}{2}\alpha\left[(q_0+\gamma x - s_1+\hat{\epsilon}_2)^2 y_A(\theta) + P_H P_L(\hat{\epsilon}_{2|H}-\hat{\epsilon}_{2|L})^2\right] & (A). \end{cases} \quad (15)$$

Noting that $c(\theta)$ decreases in the vendor's type θ and $\{c(\theta_i)\}_{i=1}^n$ are also i.i.d., we may view the reverse auction as a standard reverse auction among n risk-neutral bidders with $\{c(\theta_i)\}_{i=1}^n$ as their *true costs*. According to the auction theory (e.g., Krishna 2009), the revenue equivalence principle holds in our model (see Lemma A1 in Online Appendix EC.1). Thus, it is without loss of generality to restrict our attention to the second-price, sealed-bid auction, in which vendor i bids the vendor's true cost $c(\theta_i)$ in equilibrium.

Lemma 3. *In the reverse auction, vendors bid their true costs* $\{c(\theta_i)\}_{i=1}^n$. *The vendor with the highest expertise* $\theta_{(1)}$ *wins at price* $p_1 = c(\theta_{(2)})$ *with a total surplus of*

$$u^*(\theta_{(1)}, c(\theta_{(2)})) = c(\theta_{(2)}) - c(\theta_{(1)}). \quad (16)$$

We call the winning bidder's surplus *information rent*. Equation (16) shows that the winning bidder's information rent is the difference between the winning bidder's and the runner-up's true costs. In general, different vendors may face different renegotiation cases upon winning; with a general type distribution $F(\cdot)$, the buyer's problem becomes intractable. To make the problem tractable, we additionally assume a discrete distribution of the vendor expertise over $\{\theta_L,\theta_H\}$: for all $i \in \{1,\ldots,n\}$, $\theta_i = \theta_L$ with probability $\beta \in (0,1)$ and $\theta_i = \theta_H$ with probability $1-\beta$, where $\theta_L < \theta_H$. Then, given the likely vendor-specific renegotiation cases N, O, and A as described in Lemma 2, there could be four renegotiation scenarios $\mathcal{N}, \mathcal{O}, \mathcal{H}$, and $\mathcal{A}$ from the buyer's perspective, in which $\mathcal{N}$ $(\mathcal{O}, \mathcal{A})$ denotes the never-renegotiate (opportunistically-renegotiate, always-renegotiate) scenario in which both H- and L-type winning vendors face the case N (O, A), and $\mathcal{H}$ denotes the *hybrid* scenario in which the H-type winning vendor always renegotiates (A) and the L-type renegotiates opportunistically (O). The conditions for these renegotiation scenarios are summarized as follows:

$$(\mathcal{N}): \quad q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H} \in (-\infty, 0)$$

$$(\mathcal{O}): \quad q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H} \in [0, Q_H), \text{ where } Q_H \equiv (\hat{\epsilon}_{2|H} - \hat{\epsilon}_{2|L})/y_O(\theta_H)$$

$$(\mathcal{H}): \quad q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H} \in [Q_H, Q_L), \text{ where } Q_L \equiv (\hat{\epsilon}_{2|H} - \hat{\epsilon}_{2|L})/y_O(\theta_L)$$

$$(\mathcal{A}): \quad q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H} \in [Q_L, \infty).$$

By Equations (15) and (16), the *expected information rent* of the winner (at the beginning of phase 1) can be written as

$$\mathbb{E}_{\theta_{(1)},\theta_{(2)}}[u^*] = J_{HL}[c_F(\theta_L) - c_F(\theta_H)] + \begin{cases} 0 & (\mathcal{N}) \\ \frac{1}{2}\alpha P_H(q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H})^2 J_{HL}[y_O(\theta_H) - y_O(\theta_L)] & (\mathcal{O}) \\ J_{HL}\left\{\frac{1}{2}\alpha\left[(q_0+\gamma x - s_1+\hat{\epsilon}_2)^2 y_A(\theta_H) + P_H P_L(\hat{\epsilon}_{2|H}-\hat{\epsilon}_{2|L})^2\right] - \frac{1}{2}\alpha P_H(q_0+\gamma x - s_1 + \hat{\epsilon}_{2|H})^2 y_O(\theta_L)\right\} & (\mathcal{H}) \\ \frac{1}{2}\alpha(q_0+\gamma x - s_1+\hat{\epsilon}_2)^2 J_{HL}[y_A(\theta_H) - y_A(\theta_L)] & (\mathcal{A}), \end{cases}$$

where $J_{HL} = \Pr\{\theta_{(1)} = \theta_H, \theta_{(2)} = \theta_L\}$.

Proposition 2. *The expected information rent of the winner increases in the buyer's up-front investment* x *and the vendor's bargaining power* α *and decreases in the initial scope* s_1.

The results of Proposition 2 are intuitive: both increasing the buyer's up-front investment x and reducing initial scope s_1 have the effect of increasing marginal return from the vendor investment (as seen from Equation (12)). When the marginal return from vendor investment is higher, the high types enjoy a greater advantage, giving them greater information rent. The vendor's bargaining power α is a multiplier of the winning vendor's surplus (see Equation (14)). Thus, a higher α also results in more information rent for the winning vendor. These effects, combined with the earlier finding that vendor investment increases in x and α and decreases in s_1 (Proposition 1), highlight the buyer's trade-off: when the incentive for vendor investment is higher, the information rent accrued to the winning vendor also increases.

Our finding that a larger initial scope helps reduce vendor information rent stands in contrast to an earlier finding by Herweg and Schwarz (2018), which suggests a simpler design plus renegotiation can compress vendors' information rent. In Herweg and Schwarz (2018), the buyer is only concerned with the rent extraction problem with heterogeneous costs of implementing the scope; a smaller scope in their setting helps compress the winning vendor's information rent. By contrast, in our model, the buyer must balance rent extraction and incentivizing investment. In our setting, a larger initial scope leaves less room for renegotiation and, thus, undermines vendor investment, which limits the winning vendor's advantage over competitors and, hence, reduces the vendor's information rent.

4.3. Buyer's Problem

At phase 1, the buyer's problem is to choose initial scope s_1 and up-front investment x to maximize the buyer's total expected surplus:

$$\begin{aligned} v(s_1, x) &\equiv \mathbb{E}_{\theta_{(1)},\theta_{(2)},\epsilon_1}[v_1 + v_2] \\ &= \underbrace{\mathbb{E}_{\theta_{(1)},\theta_{(2)},\epsilon_1}\left[(q_0 + \gamma x + \theta_{(1)} z^*(\theta_{(1)}) + \epsilon_1)s_1 - \frac{1}{2}x^2 - c(\theta_{(2)})\right]}_{\text{(i) Buyer's expected phase-1 surplus}} \\ &+ \underbrace{\mathbb{E}_{\theta_{(1)},\epsilon_1}\left\{\frac{1-\alpha}{2}\left[(q_0 + \gamma x - s_1 + \theta_{(1)} z^*(\theta_{(1)}) + \hat{\epsilon}_{2|1})^+\right]^2\right\}}_{\text{(ii) Buyer's expected phase-2 surplus}}. \end{aligned} \tag{17}$$

In Equation (17), the term (i) is the buyer's expected surplus from the phase-1 contract, and the term (ii) is the buyer's share of the expected renegotiation surplus. The buyer's total expected surplus $v(s_1, x)$ depends on the renegotiation scenario (i.e., $\mathcal{N}$, $\mathcal{O}$, $\mathcal{H}$, or $\mathcal{A}$) induced by the buyer's decisions.

Similar to Assumption 1, we need to make a few technical assumptions to ensure that the buyer's problem has an interior solution and the buyer's optimal investment is finite.

Assumption 2. *We assume*

a. $0 \le \gamma < \min_{k\in\{\mathcal{N},\mathcal{O},\mathcal{H},\mathcal{A}\}} \overline{\gamma}_k$.
b. $Q_{\mathcal{H}1} \le Q_{\mathcal{O}2}$.
c. $Q_{\mathcal{A}} \le Q_{\mathcal{H}2}$.

The "Qs" are thresholds for the baseline quality q_0, and $\overline{\gamma}_k \in (0,1]$ is the upper bound for the buyer's expertise under renegotiation scenario $k \in \{\mathcal{N},\mathcal{O},\mathcal{H},\mathcal{A}\}$ (the formulas of all the terms are in Online Appendix EC.1, the proof of Lemma 4).

Assumption 2(a) sets an upper bound for the buyer's expertise γ. This assumption ensures that the buyer's expected surplus $v(s_1, x)$ is jointly concave in (s_1, x) under each renegotiation scenario ($\mathcal{N}$, $\mathcal{O}$, $\mathcal{H}$, and $\mathcal{A}$). By this assumption, we can obtain a local optimum for each scenario. Assumption 2, (b) and (c), further ensures that the buyer's global optimal decision is always an interior solution of a renegotiation scenario rather than a boundary solution between two adjacent scenarios; the latter is a trivial case and significantly complicates the analysis. Together, Assumption 2 implies that the buyer's global optimal solution can be obtained by comparing the interior solutions for different renegotiation scenarios. The following lemma outlines the condition for a renegotiation scenario to be optimal.

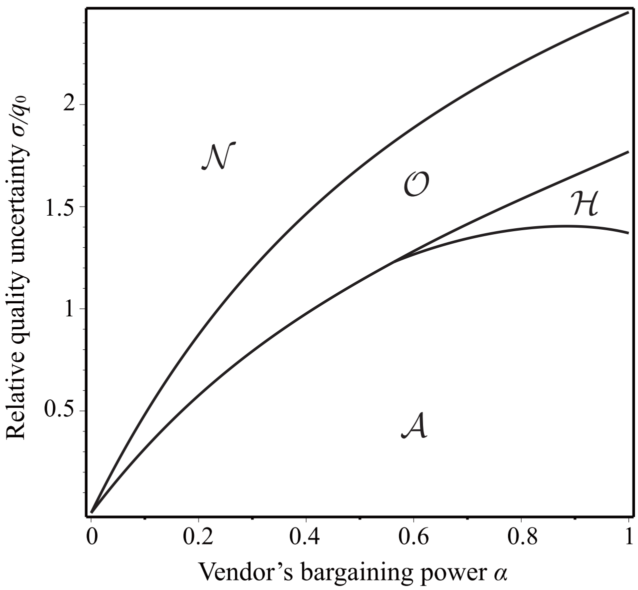
Lemma 4. *The buyer's optimal initial scope s_1^*, up-front investment x^*, and the corresponding expected surplus $v^* \equiv v(s_1^*, x^*)$ are as follows:*

$$(s_1^*, x^*, v^*) = \begin{cases} (s_{1\mathcal{N}}^*, x_{\mathcal{N}}^*, v_{\mathcal{N}}^*) & \text{if } q_0 \in (0, Q_1] \\ (s_{1\mathcal{O}}^*, x_{\mathcal{O}}^*, v_{\mathcal{O}}^*) & \text{if } q_0 \in (Q_1, Q_2] \\ (s_{1\mathcal{H}}^*, x_{\mathcal{H}}^*, v_{\mathcal{H}}^*) & \text{if } q_0 \in (Q_2, Q_3] \\ (s_{1\mathcal{A}}^*, x_{\mathcal{A}}^*, v_{\mathcal{A}}^*) & \text{if } q_0 \in (Q_3, \infty) \end{cases}, \tag{18}$$

where the "Qs" are thresholds for the baseline quality q_0 ($Q_1 \le Q_2 \le Q_3$), and s_{1k}^* and x_k^* denote the interior optimal solution for the renegotiation scenario $k \in \{\mathcal{N},\mathcal{O},\mathcal{H},\mathcal{A}\}$ with the corresponding expected surplus v_k^* (the formulas of all terms are in Online Appendix EC.1).

Noting that the scenarios $\mathcal{N}, \mathcal{O}, \mathcal{H}$, and $\mathcal{A}$ are in ascending order of the likelihood of renegotiation, Lemma 4 shows that the buyer optimally induces a higher likelihood of renegotiation when the baseline quality q_0 is relatively high. This is because a higher baseline quality q_0 reduces the impact of uncertainty on the quality of deliverables in phase 1 so that the ex post optimal scope is more likely to be larger than the initial scope (Lemma 1). To measure quality uncertainty relative to the baseline quality q_0, we define σ/q_0 as the *relative quality uncertainty*, where σ is the standard deviation of the latent quality state ϵ_0.[8] We visualize the results of Lemma 4 by mapping out the optimal renegotiation scenarios as a function of the relative quality uncertainty σ/q_0 and the vendor's bargaining power α (Figure 2). As seen from this figure, the optimal scenario can be $\mathcal{N}$, $\mathcal{O}$, $\mathcal{H}$, or $\mathcal{A}$. As predicted by Lemma 4, as the relative quality uncertainty σ/q_0 decreases and the vendor's bargaining power α increases, the optimal scenario moves from $\mathcal{N}, \mathcal{O}, \mathcal{H}$ to $\mathcal{A}$ with an increasing likelihood of renegotiation. Intuitively, this is because, when α is high and σ is low, the vendor's marginal return from the vendor's investment is high, making it less costly to motivate the

Figure 2. The Buyer's Optimal Renegotiation Scenario as a Function of the Relative Quality Uncertainty (σ/q_0) and the Vendor's Bargaining Power α



Note. Parameters: $n = 2$, $\theta_H = 0.9$, $\theta_L = 0.45$, $\beta = 0.5$, $\gamma = 0.4$, $\lambda = 0.8$, $\rho_1 = 0.85$, and $\rho_2 = 0.7$.

vendor investment. It may seem counterintuitive for the buyer to induce renegotiation when the vendor's bargaining power is high, but when this is the case, the vendor is well positioned to make an efficient investment decision. Renegotiation capitalizes on this situation by making the high-bargaining-power vendor a residual claimant (Che and Hausch 1999). This can indirectly benefit the buyer because a vendor expecting a high renegotiation surplus bids lower in the reverse auction phase.

Having examined the buyer's preferred renegotiation scenarios, we now explore the buyer's decisions, namely the initial scope s_1 and the up-front investment x, focusing on their strategic relationship. Following Bulow et al. (1985), we say that they are strategic substitutes (*substitutes* for short) if $\frac{\partial^2 v}{\partial s_1 \partial x} < 0$ and strategic complements (*complements* for short) if $\frac{\partial^2 v}{\partial s_1 \partial x} > 0$. We pay particular attention to the strategic relationship because the buyer should coordinate between the two decisions.

Proposition 3.

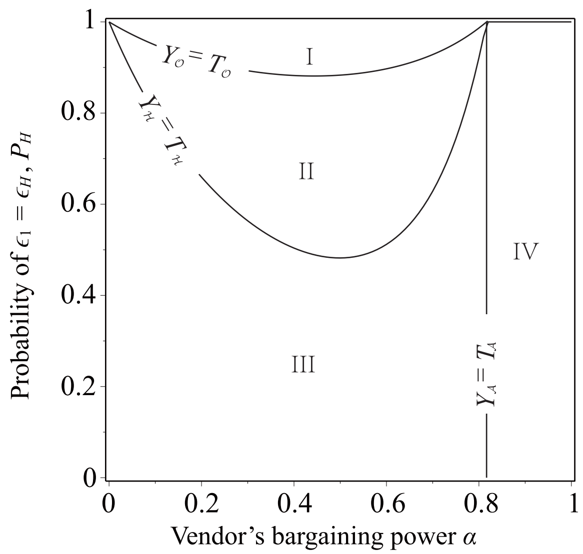
i. *Under the never-renegotiate scenario $\mathcal{N}$, the initial scope s_1 and the up-front investment x are always complements for the buyer.*

ii. *Under the renegotiation scenario $k \in \{\mathcal{O}, \mathcal{H}, \mathcal{A}\}$, s_1 and x are complements (substitutes) for the buyer if $Y_k > T_k$ ($Y_k < T_k$), where Y_k (T_k) corresponds to the strength of the complementarity (substitutability) between s_1 and x in phase 1 (phase 2). The formulas of Y_k and T_k are in Equations (EC.3) and (EC.4) of the online appendix, respectively.*

We illustrate the prediction of Proposition 3 in Figure 3, in which we plot the strategic relationship between s_1 and x as a function of the vendor's bargaining power α and the probability of the high-quality state in phase 1, P_H. We observe that, under the opportunistically-renegotiate scenario $\mathcal{O}$, s_1 and x are complements in most cases except when phase 1 is very likely to realize the high-quality state (P_H is high) and the vendor's bargaining power is not high. Further, s_1 and x are more likely substitutes under the hybrid scenario $\mathcal{H}$ than under scenario $\mathcal{O}$. Under the always-renegotiate scenario $\mathcal{A}$, s_1 and x are complements if and only if the vendor's bargaining power α exceeds a threshold regardless of the probability of the high-quality state in phase 1.

The intuition of Proposition 3 is as follows. Recall that the buyer's expected surplus is composed of two parts: phase-1 initial contract surplus and phase-2 renegotiation surplus (see Equation (17)). For the former, the buyer's initial scope s_1 and up-front investment x are always complements: a higher initial scope s_1 justifies more buyer investment x because the investment would have a broader impact; conversely, a higher buyer investment translates into a higher project quality, thus incentivizing the buyer to set a higher initial scope. For the phase-2 buyer surplus, s_1 and x are substitutes: a higher initial scope s_1 implies less room for additional scope s_2 in phase 2; thus, the optimal buyer investment that maximizes the phase-2 surplus is lower. Conversely, a higher buyer investment x implies a higher implementation quality; thus, to maximize the phase-2 surplus, the buyer should set a lower initial scope s_1 to leave more space for additional scope in phase 2. The overall relationship between s_1 and x depends on the relative weight of the two phases. In the never-renegotiate scenario ($\mathcal{N}$), the buyer's expected surplus solely comes from phase 1, implying s_1 and x are complements. In the opportunistically-renegotiate scenario ($\mathcal{O}$), because renegotiation occurs only with probability P_H, the proportion of buyer surplus from renegotiation is small. Consequently, the buyer mainly cares about the phase-1 surplus, implying that s_1 and x are mostly complements except when the buyer's phase-2 surplus is sufficiently large. The latter occurs when P_H is very high and the vendor's bargaining power is not too high. In the always-renegotiate scenario ($\mathcal{A}$), expected surplus from renegotiation is no longer a function of P_H. The relative weight of phase-2 surplus from renegotiation is a function of vendor bargaining power α. When α is small, the phase-2 surplus dominates, causing s_1 and x to be substitutes; conversely, s_1 and x become complements. In the hybrid-renegotiation scenario ($\mathcal{H}$), the probability of renegotiation is higher than that in scenario $\mathcal{O}$ but lower than that in scenario $\mathcal{A}$; thus, s_1 and x are more likely to

Figure 3. Strategic Relationship Between s_1 and x as a Function of α and P_H



Scenario	Zones where s_1 and x are	
	substitutes	complements
$\mathcal{N}$	-	I, II, III, IV
$\mathcal{O}$	I	II, III, IV
$\mathcal{H}$	I, II	III, IV
$\mathcal{A}$	I, II, III	IV

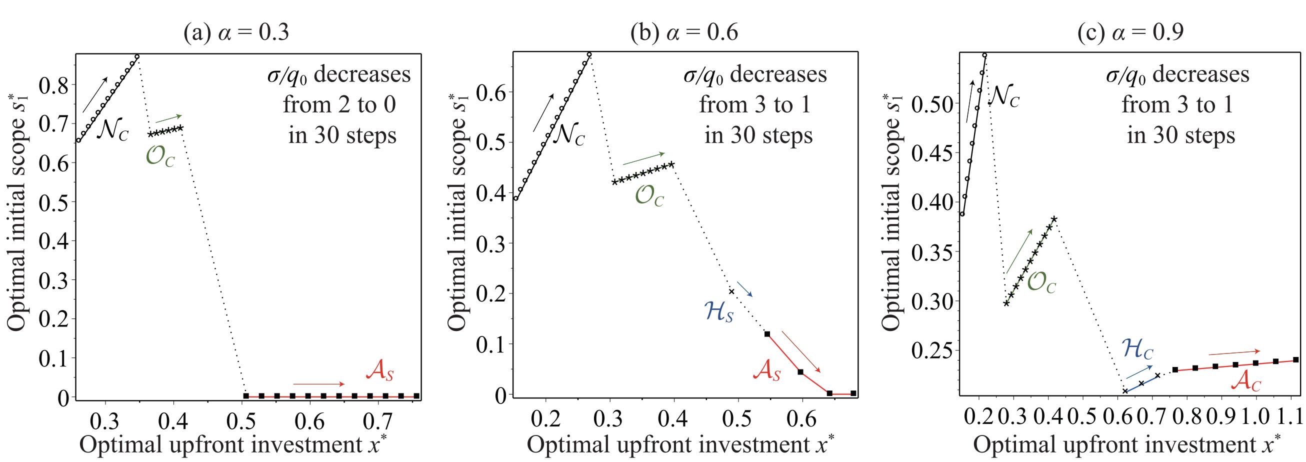
Note. Parameters: $n = 2$, $\theta_H = 0.9$, $\theta_L = 0.1$, and $\beta = 0.5$.

be substitutes in scenario $\mathcal{H}$ than in scenario $\mathcal{O}$ but less likely than in scenario $\mathcal{A}$.

To see the implications of Proposition 3 for the buyer's optimal decisions, we plot the buyer's optimal initial scope s_1 and up-front investment x as a function of the relative quality uncertainty σ/q_0 in Figure 4. We observe that, when the relative quality uncertainty decreases, the buyer increases the up-front investment to improve the implementation quality but may either increase or decrease the initial scope, depending on the likelihood of renegotiation. In scenario $\mathcal{N}$, because the buyer's initial scope and up-front investment are always complements, the initial scope also increases. A similar phenomenon is observed in scenario $\mathcal{O}$ because of the mostly complementary relationship between the two decisions. In scenario $\mathcal{A}$, however, the vendor's bargaining power determines the relationship according to Proposition 3. When the vendor's bargaining power α is not high (Figure 4, (a) and (b)), as the quality uncertainty decreases, the initial scope weakly decreases and the up-front investment increases; when the vendor's bargaining power is high (Figure 4(c)), both the initial scope and the up-front investment increase.

We note that, in some extreme cases, the initial scope s_1 can be zero (e.g., when $\alpha = 0.3$ and σ is very low). We interpret such cases as the buyer being interested in the smallest possible initial project. The

Figure 4. (Color online) Buyer's Optimal s_1 and x as a Function of the Relative Quality Uncertainty



Notes. k_C (k_S) denotes the renegotiation scenario $k \in \{\mathcal{N}, \mathcal{O}, \mathcal{H}, \mathcal{A}\}$ with s_1 and x being complements (substitutes). Parameters: $n = 2$, $\theta_H = 0.9$, $\theta_L = 0.45$, $\beta = 0.5$, $\gamma = 0.4$, $\lambda = 0.8$, $\rho_1 = 0.85$, $\rho_2 = 0.7$, and $q_0 = 1$.

intuition is as follows. When the initial scope is very small, vendors are willing to compete aggressively in phase 1, anticipating that, in phase 2, they have a high chance of renegotiating the project's scope and earning a large surplus. Such small-scope initial contracts seem common in practice: buyers often design the initial contract to be a pilot or discovery project with the intent of expanding the project's scope when the initial project turns out to be successful (Snir and Hitt 2004, Hertzum et al. 2012, Fenton 2016). Moreover, there is also anecdotal evidence that some vendors anticipate a project to be renegotiated in their favor and, therefore, bid very aggressively to win the initial contract (Bajari et al. 2014, Herweg and Schwarz 2018).

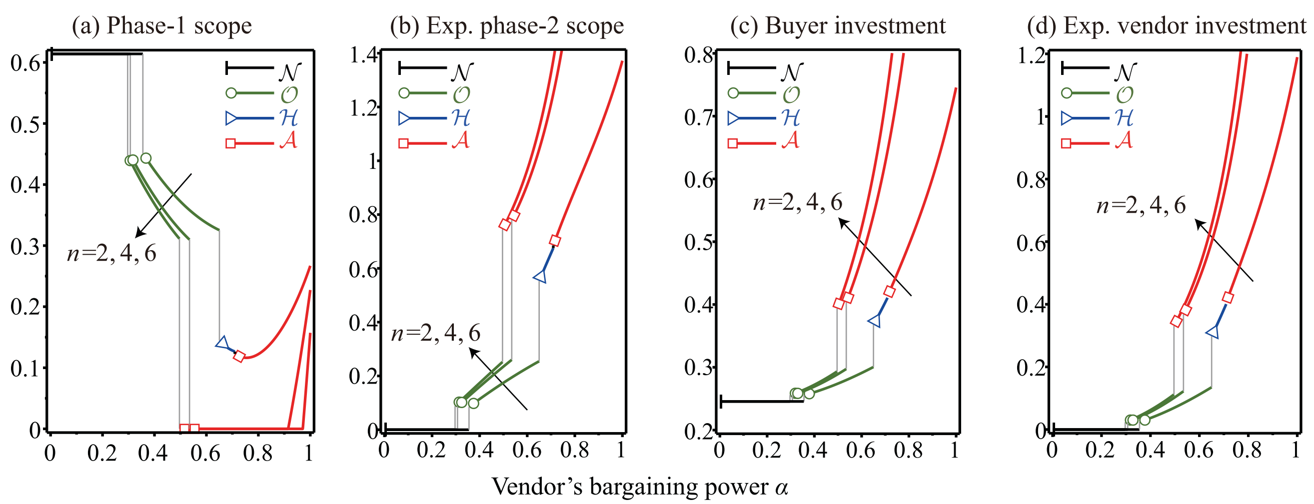
4.4. Comparative Statics

Having solved the model, we now turn our attention to how the initial scope and buyer up-front investment change with underlying model primitives. We focus on two key factors, namely, the degree of vendor competition and the degree of information asymmetry. Because it is not possible to compare equilibrium results analytically, we resort to numerical analyses.

4.4.1. Number of Competing Vendors. To examine how competition affects the buyer's relative reliance on the phase-1 auction and the phase-2 renegotiation, we vary the number of vendors n from two to six with a step size of two, for which a larger n represents more competition. As depicted in Figure 5, the buyer's optimal decisions inducing scenario $\mathcal{N}$ are unaffected by competition because no vendor would make any investment. In optimal scenarios $\mathcal{O}$, $\mathcal{H}$, and $\mathcal{A}$, however, the buyer responds to a larger n by reducing the initial scope s_1 (Figure 5(a)) and increasing the up-front investment x (Figure 5(c)). This result is interesting because, although increased competition makes the reverse auction more efficient, the buyer relies on the auction less, in contrast with earlier research (e.g., Bajari et al. 2008). The intuition is as follows: with a larger n, the expected expertise of the winner is higher, making it more attractive to increase x and reduce s_1 to induce more vendor investment (Figure 5(d)). We also observe that a larger n leads to a higher phase-2 scope (Figure 5(b)). Intuitively, as a larger n leads to higher investments from both sides, the optimal ex post scope tends to increase because of the improved implementation quality. In sum, with a larger pool of qualified vendors, the buyer prefers a smaller initial scope for the auction phase and a larger scope for the renegotiation phase.

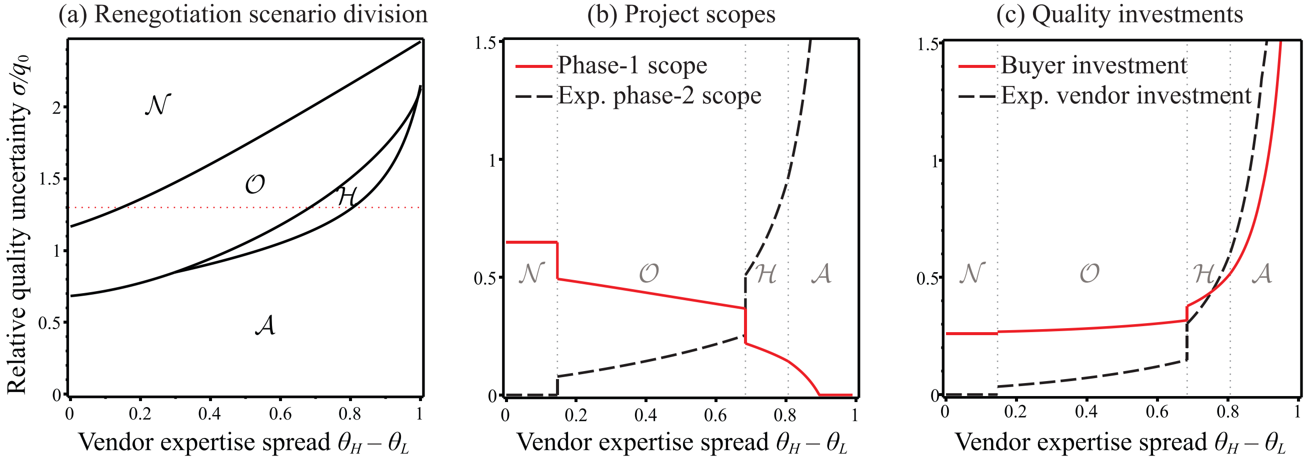
4.4.2. Effect of Information Asymmetry. It is interesting to examine whether the buyer relies more or less on auctions when the degree of information asymmetry increases. We capture the degree of information asymmetry by varying the dispersion of vendor expertise while fixing its mean. In particular, we fix the mean expertise to 0.5 while varying the spread $\theta_H - \theta_L$ from zero to one. With a greater expertise spread, we can expect greater information asymmetry. Figure 6 illustrates the results of numerical analysis with $n = 2$, $\alpha = 0.8$, $\gamma = 0.4$, $\lambda = 0.8$, $\rho_1 = 0.85$, $\rho_2 = 0.7$, and $\beta = 0.5$. Figure 6(a) illustrates the optimal renegotiation scenario as a function of the vendor expertise spread and the relative quality uncertainty. We observe that the buyer is more likely to induce a higher likelihood of

Figure 5. (Color online) Effect of the Number of Competing Vendors on the Buyer's Decisions



Note. Parameters: $\theta_H = 0.9$, $\theta_L = 0.45$, $\beta = 0.5$, $\gamma = 0.4$, $\lambda = 0.8$, $\rho_1 = 0.85$, $\rho_2 = 0.7$, $q_0 = 0.741$, and $\sigma = 1$.

Figure 6. (Color online) Effect of Information Asymmetry on the Buyer's Decisions



Note. Parameters: $n = 2$, $\alpha = 0.8$, $\gamma = 0.4$, $\lambda = 0.8$, $\rho_1 = 0.85$, $\rho_2 = 0.7$, $\beta = 0.5$, $\beta\theta_L + (1-\beta)\theta_H = 0.5$ and $\theta_H - \theta_L$ varies from zero to one; for (a), the relative quality uncertainty σ/q_0 varies from zero to ∞; for (b) and (c), $\sigma/q_0 = 1.3$ and $\sigma = 1$.

renegotiation as the expertise spread increases. Figure 6, (b) and (c), visualizes how the project scopes in two phases and the investments from the buyer and the vendor change with the expertise spread given the relative quality uncertainty. We observe that, as the expertise spread increases, the buyer should decrease the initial scope s_1 (Figure 6(b)) and increase the up-front investment x (Figure 6(c)), suggesting increased reliance on renegotiation. The reason is as follows. As we increase the expertise spread, the winner tends to have higher expertise, which motivates the buyer to induce more vendor investment (Figure 6(c)) by increasing the investment x and reducing the initial scope (Proposition 1). When the vendors' expertise is more dispersed, the relative advantage of the winning vendor over competitors increases, which leads to higher information rent to the winner. Figure 6 reveals that the buyer responds to the increased expertise spread by incentivizing vendor investment rather than regulating information rent. Finally, the expected phase-2 scope increases in the expertise spread. The intuition is similar to Figure 5(b) and, thus, omitted.

5. Extensions

5.1. Auction Design with a Reserve Price

In the main model, we assume a simple reverse auction with no reserve price, which may not maximize the buyer's surplus. Here, we introduce a reserve price and examine whether or how it may affect our results. With a reserve price r, if all vendors bid higher than r, there is no trade. Otherwise, the winner is paid the next lowest bid or the reserve price, whichever is lower. It is a standard result that in a second-price auction, bidders bid truthfully regardless of the reserve price (Krishna 2009). Therefore, a bidder with type θ bids $c(\theta; s_1, x)$ (Equation (15)).[9] The buyer maximizes the expected total surplus, $v(s_1, x, r)$, by choosing s_1, x, and r jointly.

Recall that the equilibrium bid $c(\theta; s_1, x)$ decreases in vendor expertise θ; thus, the highest equilibrium bid is $c(\theta_L; s_1, x)$. When $r \geq c(\theta_L; s_1, x)$, the reserve price does not bind, and the buyer's total expected surplus stays the same as before. When $r < c(\theta_H; s_1, x)$, all vendors are excluded, and the auction ends with no trade. This is never optimal because the buyer can obtain a positive surplus without using a reserve price. Without loss of generality, we can focus on cases $c(\theta_H; s_1, x) \leq r \leq c(\theta_L; s_1, x)$.

We call the reserve price $r = c(\theta_L; s_1, x)$ "degenerate" because it is equivalent to no reserve price as in our main model. The reserve prices $c(\theta_H; s_1, x) \leq r < c(\theta_L; s_1, x)$ are "nondegenerate" in the sense that they exclude L-type vendors but not H-type. Among the nondegenerate reserve prices, the buyer prefers $r = c(\theta_H; s_1, x)$ because the buyer can pay the least when there is a single H-type vendor. In this case, the buyer's optimal initial scope $\hat{s}_1^*$ and up-front investment $\hat{x}^*$ are given by

$$(\hat{s}_1^*, \hat{x}^*) = \arg\max_{s_1, x} v(s_1, x, c(\theta_H; s_1, x)). \tag{19}$$

Denoting the buyer surplus $\hat{v}^* \equiv v(\hat{s}_1^*, \hat{x}^*, c(\theta_H; \hat{s}_1^*, \hat{x}^*))$, we have the following lemma on the optimal reserve price.

Lemma 5. *The optimal reserve price is nondegenerate (i.e., $r^* = c(\theta_H; \hat{s}_1^*, \hat{x}^*)$) if $\hat{v}^* > v^*$ and degenerate (i.e., $r^* = c(\theta_L; s_1^*, x^*)$, which is equivalent to no reserve price) otherwise. When the optimal reserve price is nondegenerate,* *the optimal initial scope* $\hat{s}_1^*$, *up-front investment* $\hat{x}^*$, *and buyer surplus* $\hat{v}^*$ *are given by*

$$(\hat{s}_1^*, \hat{x}^*, \hat{v}^*) = \begin{cases} \left(s^*_{1\hat{\mathcal{N}}}, x^*_{\hat{\mathcal{N}}}, v^*_{\hat{\mathcal{N}}}\right) & \text{if } q_0 \in (0, \hat{Q}_1] \\ \left(s^*_{1\hat{\mathcal{O}}}, x^*_{\hat{\mathcal{O}}}, v^*_{\hat{\mathcal{O}}}\right) & \text{if } q_0 \in (\hat{Q}_1, \hat{Q}_2], \\ \left(s^*_{1\hat{\mathcal{A}}}, x^*_{\hat{\mathcal{A}}}, v^*_{\hat{\mathcal{A}}}\right) & \text{if } q_0 \in (\hat{Q}_2, \infty) \end{cases} \quad (20)$$

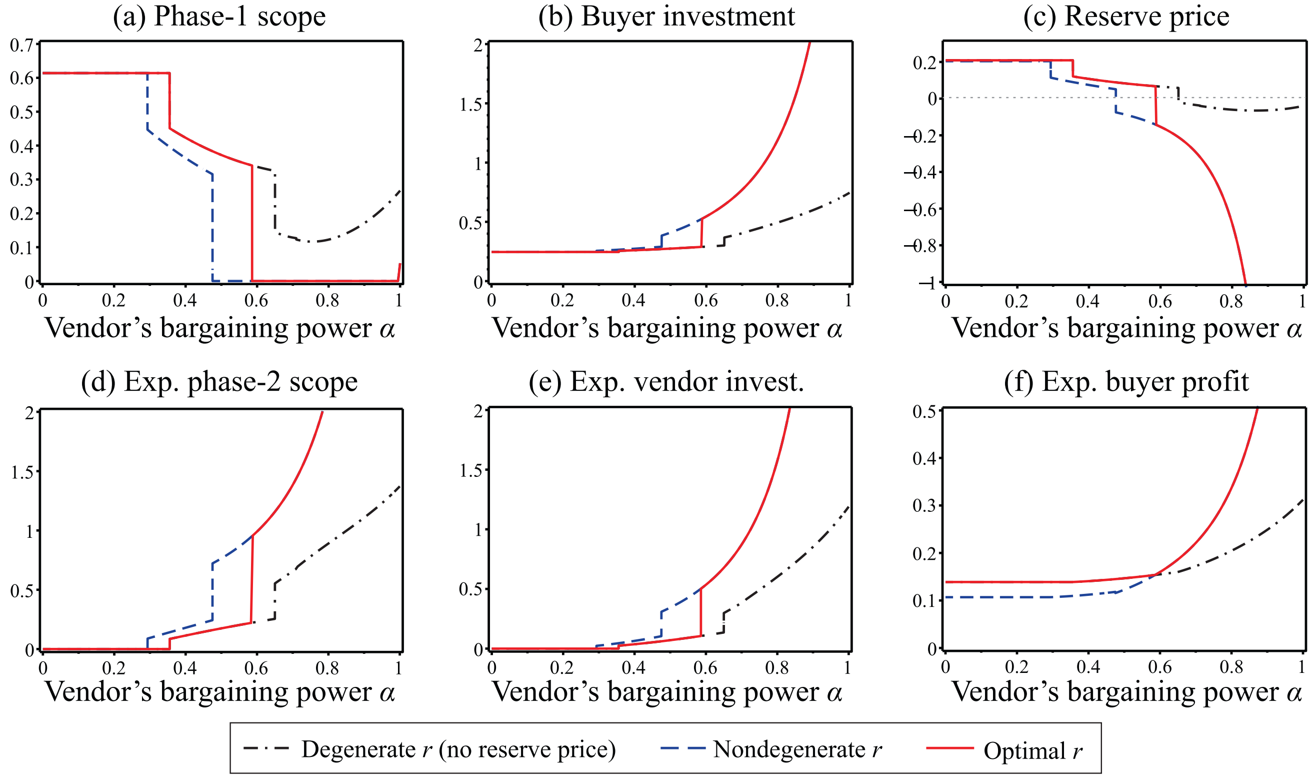
where the formulas of all terms are in the online appendix.

The three conditions in Equation (20) correspond to the never- ($\hat{\mathcal{N}}$), opportunistically-($\hat{\mathcal{O}}$), and always-renegotiate ($\hat{\mathcal{A}}$) scenarios with a nondegenerate reserve price, respectively.[10] Figure 7 illustrates the results of Lemma 5. Figure 7, (a) and (b), shows that introducing a reserve price reduces s_1 and increases x. This is because the reserve price can help regulate information rent so that the buyer can further reduce the initial scope s_1 and increase the up-front investment x to incentivize vendor investment. Figure 7(c) shows that the optimal reserve price decreases in the vendor's bargaining power α. This is because, when vendors have higher bargaining power, a more aggressive reserve price is needed to exclude low-expertise vendors. The reserve price may also be negative when the initial scope s_1 and one-time fixed cost $c_F(\theta)$ are small (Figure 7(c)). A negative reserve price $r < 0$ indicates that the vendors should pay to be selected for the first phase of the project. Furthermore, with a nondegenerate reserve price $r = c(\theta_H; s_1, x)$, the buyer can achieve a larger phase-2 scope (Figure 7(d)) and induce greater vendor investment (Figure 7(e)) than no reserve price. The numerical simulation also reveals that the buyer is better off with an optimal reserve price (Figure 7(f)).

Proposition 4. *When a nondegenerate reserve price r is adopted, the buyer's phase-1 scope* s_1 *and up-front investment x are complements under scenario* $\hat{\mathcal{N}}$, *substitutes under scenario* $\hat{\mathcal{A}}$, *and complements (substitutes) under scenarios* $\hat{\mathcal{O}}$ *if* $P_H < \tilde{P}$ ($P_H > \tilde{P}$), *where the expression of* $\tilde{P} \in (0,1)$ *is provided in Equation (EC.24) in the online appendix.*

The intuition of Proposition 4 is as follows. The reserve price increases the buyer's surplus from both the phase-1 auction (in which s_1 and x are complements) and, if any, the phase-2 renegotiation (in which s_1 and x are substitutes) by excluding low-expertise vendors. Moreover, the increase from the phase-2 renegotiation is more significant because, with the reserve price regulating information rent, the buyer can further lower the initial scope s_1 and increase the investment x to motivate more vendor investment and obtain more renegotiation surplus. This makes s_1 and

Figure 7. (Color online) The Buyer's Optimal Decision Results with a Degenerate, Nondegenerate, and Optimal Reserve Price r



Note. Parameters: $n = 2$, $\theta_H = 0.9$, $\theta_L = 0.45$, $\beta = 0.5$, $\gamma = 0.4$, $\lambda = 0.8$, $\rho_1 = 0.85$, $\rho_2 = 0.7$, $\sigma = 1$, $\sigma/q_0 = 1.35$, and $c_F(\theta) = 0.03/(1+\theta)$.

x always substitutes in the always-renegotiate scenario ($\hat{\mathcal{A}}$). However, the effect of the reserve price on phase-2 surplus is discounted in scenario $\hat{\mathcal{O}}$ because the renegotiation occurs only with probability P_H. As a result, if the probability P_H is higher than a threshold $\tilde{P}$, the substitutability between s_1 and x can be preserved as in the scenario $\hat{\mathcal{A}}$; otherwise ($P_H < \tilde{P}$), the reserve price would increase the weight of the phase-1 surplus more than the phase-2 surplus for the buyer, making s_1 and x complements. In scenario $\hat{\mathcal{N}}$, s_1 and x are always complements because the renegotiation never occurs, which is similar to the situation without a reserve price.

5.2. Costly Learning of Project Quality

In the main model, we assume that the learning of the project quality is costless in the sense that no matter how small the phase-1 scope is, one learns the same amount about the phase-2 quality. This may lead to the buyer adopting a zero scope for phase 1. A more natural assumption is that learning improves with the phase-1 scope. Specifically, we let the informativeness of the phase-t project be $\rho_t = \frac{1}{2}(ds_t + 1)$, $t \in \{1, 2\}$, where $0 < d < \frac{1}{\bar{s}}$ and $\bar{s}$ is the maximum scope. By this formulation, if the buyer chooses a zero scope for phase 1 ($s_1 = 0$), then $\rho_1 = \frac{1}{2}$, implying that phase 1 is completely uninformative. As s_1 increases, the informativeness level ρ_1 increases but never reaches one, the perfect information case. We refer to d as the learning coefficient; a higher d means that one learns more from the same phase-1 scope.

It can be verified that the expectation of phase-2 quality state ϵ_2 conditional on phase-1 quality state ϵ_1 is now dependent on both s_1 and s_2:

$$\hat{\epsilon}_{2|1} = \frac{1}{2}(\epsilon_H + \epsilon_L) + \frac{1}{2}(\epsilon_H - \epsilon_L)a_i(s_1)s_2,$$
$$i = H \text{ if } \epsilon_1 = \epsilon_H, i = L \text{ if } \epsilon_1 = \epsilon_L,$$

where the formulas of $a_H(s_1)$ and $a_L(s_1)$ are provided in Equations (EC.29) and (EC.30) of the online appendix, respectively. The phase-2 scope s_2 and the winning vendor's optimal up-front investment $z^*(\theta)$ are as follows:

$$s_2 = \frac{(\mu + \gamma x - s_1 + \theta z)^+}{1 - (\epsilon_H - \epsilon_L)a_i(s_1)},$$
$$z^*(\theta) = \frac{\alpha\theta\phi(s_1)(\mu + \gamma x - s_1)^+}{1 - \alpha\theta^2\phi(s_1)},$$

where $\mu = q_0 + (\epsilon_H + \epsilon_L)/2$, and $\phi(s_1) = \mathbb{E}_{\epsilon_1}\{[1 - (\epsilon_H - \epsilon_L)a_i(s_1)]^{-1}\}$.

We prove that the results of Propositions 1 and 2 and Lemma 3 all hold qualitatively (see Online Appendix EC.3). However, the buyer's problem becomes analytically intractable because of the complications in solving s_1. We resort to numerical analyses to obtain insights on the effect of costly learning. In Figure 8, we plot the buyer's optimal decisions as a function of the vendor's bargaining power α and the learning coefficient d. It shows that when the learning coefficient d increases, the buyer tends to set a greater initial scope s_1^* (Figure 8(a)) because a higher d increases the learning benefits of implementing the initial scope. Moreover, a higher d amplifies the strength of complementarity between s_1 and x in phase-1 but reduces the strength of substitutability between s_1 and x in phase-2. Therefore, as the learning coefficient d increases, the initial scope s_1 and buyer investment x are more likely to be complements (Figure 8(c)), and hence, the buyer's optimal investment x^* also increases (Figure 8(b)).

5.3. Buyer Investment in Cost Reduction

In the main model, we only consider the buyer's investment in quality improvement. One may wonder whether our findings extend to buyer investment in cost reduction, another popular form of investment. We next study an alternative specification by redefining x as buyer investment in cost reduction instead of quality improvement. Specifically, we assume that the phase-t quality $q_t = q_0 + \theta z + \epsilon_t$, $t \in \{1, 2\}$. Further, we assume the winning vendor's implementation cost is $\frac{s_t^2}{2(1+\gamma x)}$, where x is the buyer's investment in cost reduction and $\gamma \geq 0$ is the associated investment coefficient. As before, we assume γ is common knowledge.

It can be verified that the phase-2 scope s_2 and the winning vendor's optimal investment $z^*(\theta)$ are as follows, in which the superscript "c" (cost reduction) is used to distinguish notation from those of the main model:

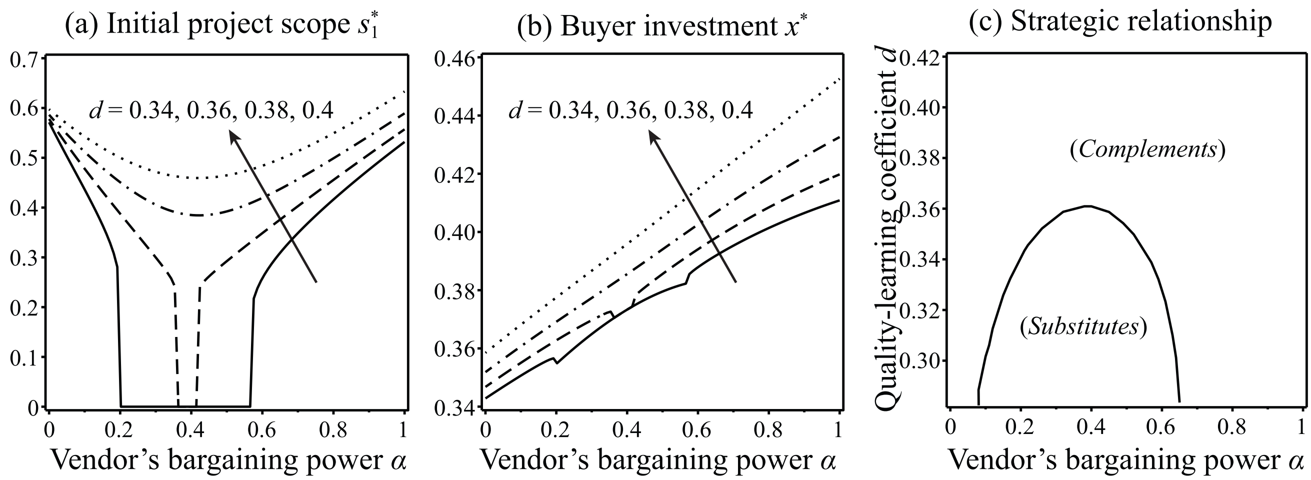
$$s_2 = \left[(1 + \gamma x)(q_0 + \theta z + \hat{\epsilon}_{2|1}) - s_1\right]^+,$$
$$z^*(\theta) = \begin{cases} 0 & (N^c) \\ \alpha\theta P_H\left[(1 + \gamma x)(q_0 + \hat{\epsilon}_{2|H}) - s_1\right]y_O^c(\theta) & (O^c) \\ \alpha\theta\left[(1 + \gamma x)(q_0 + \hat{\epsilon}_2) - s_1\right]y_A^c(\theta) & (A^c) \end{cases},$$

where $y_O^c(\theta) = \left[1 - \alpha\theta^2 P_H(1 + \gamma x)\right]^{-1}$, $y_A^c(\theta) = \left[1 - \alpha\theta^2 (1 + \gamma x)\right]^{-1}$, and the conditions for the never- (N^c), opportunistically-(O^c), and always-renegotiate (A^c) cases are given by

$$\begin{aligned} (N^c):&\quad q_0 + \hat{\epsilon}_{2|H} - s_1/(1 + \gamma x) \in (-\infty, 0) \\ (O^c):&\quad q_0 + \hat{\epsilon}_{2|H} - s_1/(1 + \gamma x) \in \left[0, (\hat{\epsilon}_{2|H} - \hat{\epsilon}_{2|L})/y_O^c(\theta)\right) \\ (A^c):&\quad q_0 + \hat{\epsilon}_{2|H} - s_1/(1 + \gamma x) \in \left[(\hat{\epsilon}_{2|H} - \hat{\epsilon}_{2|L})/y_O^c(\theta), \infty\right) \end{aligned}.$$

We prove that Propositions 1 and 2 and Lemma 3 all hold qualitatively (see Online Appendix EC.4). However, the buyer's problem becomes analytically intractable because of increased complexity in solving x. We resort to numerical analyses for insights on the effect of buyer investments in cost reduction. The buyer's optimal decisions as a function of the vendor's bargaining power α and the buyer's investment

Figure 8. Buyer's Optimal Decision with Costly Learning



Note. Parameters: $n = 2$, $\lambda = 0.5$, $\epsilon_H = 2$, $\epsilon_L = -2$, $\beta = 0.5$, $\theta_H = 0.5$, $\theta_L = 0.1$ $\gamma = 0.3$, and $q_0 = 1$.

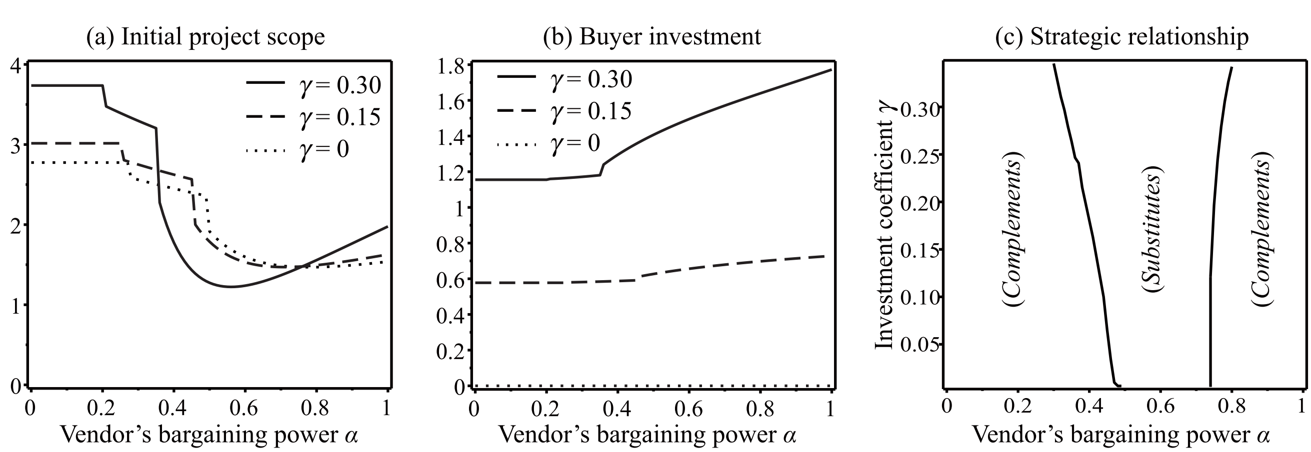
coefficient γ are illustrated in Figure 9. Figure 9(b) shows that, with a higher γ, the buyer makes a higher up-front investment x to capitalize on increased investment effectiveness. However, the initial scope s_1 may increase or decrease (Figure 9(a)), depending on the strategic relationship between s_1 and x. As observed in Figure 9(c), s_1 and x are substitutes only when α is neither too low nor too high; otherwise, they are complements. As we demonstrate (Figure 2), when the vendor's bargaining power α is low, the buyer prefers scenarios with a low probability of renegotiation (i.e., the never- and opportunistically-renegotiate scenarios). Under these scenarios, the buyer puts more weight on the phase-1 surplus than phase-2; therefore, s_1 and x are complements. When α is high, the buyer prefers the scenario with a high probability of renegotiation (the always-renegotiate scenario). Because the buyer obtains a small share $(1 - \alpha)$ of renegotiation surplus, the phase-1 surplus still dominates, and hence, s_1 and x are also complements. When α is moderate, the buyer emphasizes the phase-2 renegotiation surplus, and s_1 and x become substitutes. In line with these arguments, we observe from Figure 9(a) that, when the buyer's investment coefficient γ increases from 0 to 0.3, the initial scope s_1 decreases for low or high α but increases for moderate α.

In sum, when the buyer investment has the effect of reducing implementation cost instead of improving quality, buyer decisions and the strategic relationship between the initial scope and the buyer investment are qualitatively similar to our main findings in Proposition 3.

6. Conclusion

Motivated by several challenges facing IT outsourcing, we investigate a hybrid procurement model in

Figure 9. Buyer's Optimal Decision with Investment in Cost Reduction



Note. Parameters: $n = 2$, $\beta = 0.5$, $\theta_H = 0.5$, $\theta_L = 0.1$, $\lambda = 0.8$, $\rho_1 = 0.85$, $\rho_2 = 0.7$, $\sigma = 1$, and $q_0 = 3$.

which the initial phase of a project is determined by a reverse auction, but the two parties can renegotiate a second phase to add additional scope. In this model, the buyer needs to both incentivize noncontractible vendor investments that solely benefit the buyer and curb the information rent of the winning vendor with two up-front decisions: initial project scope and buyer up-front investment in implementation quality. Using this model, we generate several insights about the roles of renegotiation and the initial project scope and the coordination between the two buyer decisions.

This research contributes several novel insights to the literature. First, we show that it may be sometimes beneficial for a buyer organization to induce ex post renegotiation as a way of alleviating the hold-up problem. When a renegotiation occurs, the vendor can claim a share of surplus generated by the renegotiation, which can motivate noncontractible vendor investment that is absent in a pure fixed-price reverse auction. Although ex post renegotiation happens for many reasons, such as flaws in the initial contract (e.g., Herweg and Schmidt 2020), we highlight a new reason: that renegotiation may alleviate the hold-up problem.

Our second major insight is about the pivotal role of the initial project scope in IT outsourcing. We show that the initial scope affects both information rent and vendor investment: a high initial scope leaves little room for ex post renegotiation, thus undermining vendor investment. When renegotiation seldom occurs, the expected information rent of the winning vendor is low because the vendor does not have strong incentives to invest and, therefore, cannot turn the advantage in investment efficiency into information rent. Understanding this, a buyer may strategically set a low initial project scope to incentivize renegotiation and noncontractible vendor investment. This finding offers a rational explanation for the observation that many IT outsourcing projects start small and allow scope expansion (e.g., Barry et al. 2002). Although scope expansion happens for many other reasons (e.g., a lack of clarity and foresight), this is the first study to show that buyers can strategically use anticipated scope expansions to motivate noncontractible vendor investments.

Another novel insight from this research is about how initial scope and buyer investment should be jointly used. Like initial scope, buyer investment also affects both information rent and vendor investment, only in the opposite direction: a smaller buyer investment decreases vendor investment and curbs information rent. Because the buyer investment is more beneficial when the project scope is larger, one may intuitively think that initial scope and buyer investment are strategic complements; high initial scope should go hand in hand with higher buyer investment. We show, however, that the opposite may also be optimal. Although the buyer should use high initial scope and high up-front investment (i.e., treat the two measures as complements) to maximize phase-1 buyer surplus, the buyer should use low initial scope and high buyer investment (substitutes) to maximize phase-2 surplus from renegotiation. Whether the two decisions are complements or substitutes depends critically on the renegotiation scenario and the vendor's bargaining power. When a buyer prefers little or no renegotiation, the buyer should focus on phase-1 surplus and, thus, treat the two decisions as strategic complements. When the buyer prefers renegotiation but the vendor's bargaining power is low, the buyer needs both low initial scope and high buyer investment to induce renegotiation; thus, the two decisions are substitutes. When the vendor's bargaining power is high, the vendor has strong incentives to invest, and the buyer can once again treat two decisions as complements; high initial scope and high buyer investment can maximize the combined surplus from the two phases.

Our model produces a few counterintuitive results. For example, we show that the buyer prefers renegotiation to occur when the vendor's bargaining power is high. This is because a vendor with higher bargaining power is well positioned to make an efficient up-front investment that increases the value of the project to the buyer. As a result, the buyer should induce renegotiation in such a case. This may explain why Korea Exchange extended its IT service contract with IBM, an industry-leading vendor with high bargaining power, and why Google, NASA, and USRA extended their contracts with D-WAVE, the only supplier of quantum computers (IBM 2009, Alto 2017).

We also show that, as the number of competing vendors increases, the investment efficiency of the top bidder is higher, and the buyer prefers a smaller initial scope for the reverse auction so that the buyer can capitalize on the increased efficiency. This contrasts with the conventional wisdom that one should rely more on auctions when there are many bidders (e.g., Bajari et al. 2008). Herweg and Schmidt (2017) also show that intensified competition leads to increased renegotiation, but their argument is a supplier-side one: suppliers leverage their private information more through renegotiation when competition is intense. By contrast, we offer a buyer-side explanation: the buyer proactively induces more renegotiation to capitalize on the winner's increased investment efficiency.

We show that our main results are robust under several alternative specifications, including permitting a reserve price in the reverse auction, making the informativeness of the phase-1 project a function of its scope, and making the buyer investment cost-reducing instead of quality-enhancing.

Our findings generate several predictions for empirical research on IT outsourcing. First, our results suggest that buyers who suffer from the hold-up problem are more likely to use a smaller initial scope and renegotiate a larger scope after the initial contract. Second, auctions of contracts that have a smaller scope but permit scope expansion are more profitable to buyers than auctions of contracts that have a large but inflexible scope. Third, buyers who have relatively low bargaining power are more likely to start with low initial project scope and to renegotiate with the vendor. Some of our comparative static results are also readily testable. For example, our results show that a higher expertise vendor is more likely to renegotiate; when there is a large pool of qualified vendors, we expect buyer investment to be higher and the initial project scope to be lower.

Our research can be extended in several ways. For example, our current model captures vendor differences in investment efficiency and fixed costs; future research can extend our model to allow other types of vendor differences, such as heterogeneous implementation costs. Another way of extending the model is to consider transaction costs associated with renegotiation though we expect our main insights to hold even with added transaction costs. Although our research focuses on IT outsourcing, our findings may also hold implications for other outsourcing contexts in which the hold-up and information asymmetry problems are prominent. It will also be interesting to compare our hybrid procurement model with other procurement mechanisms in IT outsourcing and other related contexts.

Acknowledgments

The authors thank department editor Kartik Hosanagar, the anonymous associate editor, and the three anonymous reviewers for constructive suggestions. The authors' names are in alphabetical order. All errors and omissions are the sole responsibility of the authors.

Endnotes

[1] These are sometimes called "auction-determined" reverse auctions. Some reverse auctions are "buyer determined" in the sense that, after collecting the bids, the buyer makes the award decision based on price and other factors (e.g., vendor reputation and prior collaboration) (Engelbrecht-Wiggans et al. 2007, Brosig-Koch and Heinrich 2014, Fugger et al. 2015). We focus on the auction-determined format in this paper and refer readers to Wyld (2011) for more discussion on the buyer-determined format.

[2] Project scope refers to the work that needs to be accomplished to deliver a product, service, or result with the specified features and functions (PMI 2017, pp. 131).

[3] In practice, the two parties can invest in implementation quality improvement as well as cost reduction. We focus on quality-improvement investments for the following main reason. In the case of a fixed-price contract (which is the setting we study), vendors have incentives to invest in cost reduction but not quality improvement. Our goal is to investigate how the buyer can motivate the latter kind of investment using a combination of auction and renegotiation. In some sense, we can assume that the vendor would make cost-reducing investments anyway; thus, we do not need to explicitly model such investments.

[4] By Bayesian rule, we have $P_H = \lambda\rho_1 + (1-\lambda)(1-\rho_1)$, $P_{H|H} = \frac{\rho_1\rho_2\lambda+(1-\rho_1)(1-\rho_2)(1-\lambda)}{\rho_1\lambda+(1-\rho_1)(1-\lambda)}$, and $P_{L|L} = \frac{\rho_1\rho_2(1-\lambda)+(1-\rho_1)(1-\rho_2)\lambda}{\rho_1(1-\lambda)+(1-\rho_1)\lambda}$.

[5] We note that the price-only reverse auction can also be generalized to a "scoring auction" in which price and nonprice elements (e.g., quality, time to delivery), provided they are observable, can be factored into a score that is used to determine the auction winner. Prior research shows that such scoring auctions can sometimes be mapped into a price-only auction (Che 1993, Branco 1997). For simplicity, we only consider the price-only format in this paper.

[6] Some of the buyer's up-front investments, for example, project planning and requirement specification, occur at the beginning of the project. Others may occur during (e.g., process reengineering) or after (e.g., training) the project, but these investments need to be budgeted and pledged in advance. The exact timing of the buyer's investment is not crucial to our model results; what is important is that the buyer can make a credible commitment to the investment. For simplicity, we simply say that the buyer makes the investment before the project begins.

[7] A renegotiation setting is commonly modeled as Nash bargaining (e.g., Herweg and Schwarz 2018, Agrawal and Oraiopoulos 2020, Herweg and Schmidt 2020). For example, Herweg and Schmidt (2015, p. 9) employ the GNBS equilibrium concept to characterize the renegotiation outcome, noting that "the GNBS is the only bargaining solution that is Pareto efficient, invariant to equivalent utility representations and independent of irrelevant alternatives. Furthermore, it reflects the relative bargaining power of the two parties."

[8] Recalling that ϵ_0 is a Bernoulli variable with $\Pr\{\epsilon_0 = \epsilon_H\} = \lambda$ and mean zero, we can derive that $\sigma = \epsilon_H\sqrt{\frac{\lambda}{1-\lambda}}$.

[9] To better present the results with a reserve price, we rewrite the vendors' true costs (Equation (15)) as $c(\theta; s_1, x)$, a function of the initial scope s_1 and the buyer's up-front investment x.

[10] Because a nondegenerate reserve price excludes L-type vendors, the hybrid scenario $\hat{\mathcal{H}}$ in which L- and H-type vendors face different renegotiate scenarios no longer exists.

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