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IT Outsourcing Auctions With Bilateral Efforts and Renegotiation

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ABSTRACT In information technology outsourcing (ITO), contracts are often awarded through reverse auctions, and renegotiations usually take place for contract amendment after the transaction parties exert joint efforts in project quality improvement. This paper studies an ITO contracting model with the above characteristics from a game-theoretical perspective. We examine the buyer's design of the initial project scope (which can be renegotiated afterward) and investigate the value of renegotiation to the buyer. The results show that a higher initial scope reduces both the information rent and the effort incentive of the winning provider, and the buyer's optimal initial project scope is expected to be adjusted upward in the renegotiation. The possibility of renegotiation has effects of both incentivizing the provider effort and generating information rent, but our analytical results show that the former effect is dominant, implying that both the buyer and the provider benefit from the possibility of renegotiation.

INDEX TERMS IT outsourcing, project scope, renegotiation, bilateral efforts, reverse auctions, incomplete contracts.

I. INTRODUCTION

In this digital era where information technology (IT) is widely applied in almost all organizations, IT outsourcing (ITO) becomes a great part of the world economy. Surveys report that 31% of IT services are outsourced in 2016 [1], and the global ITO market in 2015 is estimated to be $274.2 billion [2].

Unlike the procurement of standard goods like machines and parts, the outsourcing of IT services, which are commonly highly customized, faces significant uncertainties in the delivered quality. The quality uncertainty in ITO projects usually stems from the following facts. First, the development process of IT services is subject to various unforeseen contingencies [3]. For example, in software outsourcing projects, technical details are unlikely to be specified exhaustively in advance and project changes are unavoidable during the development process [4], which makes the final quality of the software highly unpredictable. Second, the quality of IT projects depends much on the efforts of both the buyer and the provider [5], but it is difficult to specify these efforts in contracts since they are typically non-verifiable [6], [7]. Therefore, both the buyer and the provider face moral hazard from the other side, which adds uncertainty to the final project quality. Third, the project quality itself is difficult to measure (e.g., it may involve subjective factors like satisfaction) [8], [9] and thus can not be explicitly stipulated in contracts, which makes it difficult to match the quality expected by the buyer and that delivered by the provider.

Since the efforts of the transaction parties, the performance of the final deliverables, and many unforeseen or non-verifiable contingencies cannot be effectively specified in contract terms, it is usually impractical for the transaction parties to write complete outcome-contingent contracts in ITO. Instead, firms tend to initiate ITO projects with relatively simple non-contingent contracts and resort to bilaterally beneficial renegotiation for contract amendment after contingencies unfold [11]. For example, Bharti Airtel (a leading telecom player in India) signed a $750 million ITO contract with IBM in 2004, and the contract was renegotiated to a value of more than $2.5 billion at the end of 2009 [12]. Although contract terms can hardly be complete, as a convention, it is necessary for any ITO contract to specify the project scope, which is defined as "the work performed to deliver a product, service, or result with the specified features and functions" [13]. For example, in an ITO contract between IBM and Korea Exchange, the project scope comprises comprehensive maintenance and contract management services covering system hardware, software, middleware, network, facilities and equipment [14]. All the required deliverables, according to industry norms, should be clearly defined in a specific, measurable, agreed upon, realistic, and time bound way [15], which indicates the verifiability and contractibility of the project scope.

With many potential providers available, organizations commonly use reverse auctions to award ITO contracts [16], [17]. It is estimated that nearly 75% of IT projects worthing over $5 million involve reverse auctioning between outsourcing providers [17]. For example, the U.S. General Services Administration announced in 2016 that it was opening bids on massive $50 billion in federal IT orders over the next decade [18].

The combination of reverse auction, bilateral efforts and renegotiation makes the buyer's outsourcing decision challenging. For example, it is unclear how the possibility of post renegotiation will distort the potential providers' willingness to bid and their incentive to improve the project quality. It is also unclear why some buyers prefer to start with a small pilot project before scaling it up [19], whereas others start big [20]. In this paper, we examine an ITO contracting model with above characteristics and address the following research questions:

- How does the buyer's design of the initial project scope affect the winning provider's effort level and information rent in ITO auctions with renegotiation?
- What is the value of renegotiation in ITO when both adverse selection and moral hazard coexist?

We find that a greater initial project scope reduces the winning provider's ability to extract information rent in the auction, but it also reduces the winning provider's incentive to exert effort in project quality improvement. Renegotiation is expected to increase the project scope, but this does not rule out cases where the realization of project quality is so bad that the two parties need to scale the project scope down through renegotiation. The possibility of renegotiation enables the winning provider to extract information through bidding (information effect), but it also provides incentive for the winning provider to exert project quality improvement effort (incentive effect). Results show that the incentive effect is always dominant, implying that reserving the possibility of renegotiation is beneficial to both the buyer and the provider.

The rest of the paper is organized as follows. Section II reviews the related literature and Section III presents the base model. In Section IV, the base model are analyzed by backward induction. In Section V, two new models are introduced as benchmarks of the base model, and the value of renegotiation are characterized through model comparison. Section VI concludes.

II. RELATED LITERATURE

This study contributes to the literature by providing game-theoretical analysis of ITO contract design when renegotiation, asymmetric information (adverse selection) and bilateral efforts (moral hazard) coexist. We identify three themes in the literature that our work is closely related to.

A. CONTRACT INCOMPLETENESS IN ITO

Among the large body of ITO research (see [21] for a comprehensive review), one important issue is to manage the contract incompleteness [5] caused by unforeseen contingencies [3], non-contractible behaviors [7] and immeasurable performance [9]. With incomplete contracts, the literature mainly examines issues such as ITO decisions [3], [8], ITO contract choice [22], ITO risks [10] and ITO success [4], as well as the roles of contractual provision [5], renegotiation design [7] and performance measurement [9] in mitigating rent seeking and improving project quality. However, these studies typically ignore the selection mechanism of winning provider under asymmetric information. Regarding the selection of winning provider, the previous studies have examined the evaluation of providers' characteristics [23], [24] and capabilities [25], the employment of two-stage selection approaches [26], [27], and the investigation of bidding processes (auctions) [28], [29]. These studies commonly involve no explicit modeling of bilateral efforts and renegotiation, which are important features related to the incompleteness of ITO contracting. Distinct from extant ITO research, this paper theoretically examines the auctioning of incomplete ITO contracts, considering non-verifiable bilateral efforts and *ex post* renegotiation.

B. CONTRACTING WITH NON-VERIFIABLE EFFORTS

This work is also related to the contracting literature involving joint efforts with uncontractible outcomes. Since outcome-based contracts are not enforceable, this literature usually examines simple non-contingent contracts in the initial stage combined with *ex post* renegotiation for transaction adjustment and surplus sharing [5], [7], [30]–[33]. The focus of this literature is alleviating the holdup problem which leads to underinvestment (see, e.g., [34] for a review). Our work differs from the extant studies in this literature as follows. First, we consider the selection of winning provider from multiple potential providers through auctions, which is not considered by above papers. Second, we focus on the value of renegotiation in terms of regulating information rent and incentivizing provider's improvement effort, rather than dealing with holdup problems.

C. AUCTIONS WITH (RE)NEGOTIATIONS

Our paper is also related to the literature which combines auctions and (re)negotiations. Reference [35] studies a procurement mechanism where the buyer can choose to accept the auction price or renegotiate it at a fixed cost. Reference [36] investigates a procurement model where the buyer audits the cost of the auction winner and then negotiates the final price with the winner. Reference [37] proposes a sequential "auction + bargaining" model which can increase the social welfare while maintaining desirable properties of auctions like transparency and allocation efficiency.

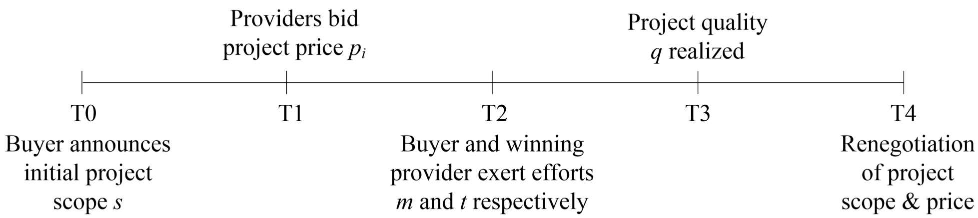

FIGURE 1. **Sequence of events.**

Reference [38] analyzes the problem of auctioning incomplete contracts with renegotiations; it compares the efficacy of auction and negotiation in terms of incentivizing potential providers to reveal their private information about possible design improvements early. The above studies do not consider the potential providers' incentive to exert efforts and thus do not involve moral hazard issues. In contrast, we examine the role of renegotiation and the buyer's initial contract design in terms of regulating the providers' information rents and inducing their incentive to improve the project quality.

III. MODEL SETUP

A buyer needs to award an ITO contract to one of n prequalified potential providers. The value of the project to the buyer is formalized as $q \times s$, where s is the project scope, representing the magnitude of functions the project covers, and q is the project quality, capturing the (average) effectiveness of the functions delivered. The multiplicative form of the project value reflects that the buyer can derive high value from the project only when the project is significant in both quality and quantity.

The realization of the project quality q depends on both the buyer (she) and the winning provider (he) selected by the buyer, and it is also subject to stochastic disturbances. Specifically, it is determined by the following factors:

(i) The winning provider's quality-improvement effort t and project expertise θ. Obviously, the winning provider can deliver higher project quality when he exerts more effort or when he is more expert. Thus, we assume the improvement of project quality contributed by the winning provider to be $\theta \times t$. Note that t is not verifiable and thus non-contractible. Moreover, we assume that provider i's ($i = 1, \cdots, n$) project expertise θ_i is provider i's private information. It is common knowledge that $\{\theta_i\}_{i=1}^{n}$ are independent and identically distributed over $[\underline{\theta}, \overline{\theta}]$, with a cumulative distribution function $F(\cdot)$ and a probability density function $f(\cdot)$.

(ii) The buyer's quality-improvement effort m and project expertise k. The buyer's input is also an important factor of project quality. Similarly, the improvement of project quality contributed by the buyer can be assumed to be $k \times m$, where m is also non-verifiable. Because buyers in practices have incentive to reveal information about their project experience to the providers in order to reduce the side effects of information asymmetry during project implementation, we assume k to be public information.

(iii) Stochastic disturbance ε. Even if the buyer and the winning provider exert deterministic efforts, there is still uncertainty in the realization of project quality. Such uncertainty is captured by ε, a random variable with mean μ and variance σ^2. The realization of ε is observable but non-verifiable. In line with practices, ε can also be interpreted as the initial project quality. For example, in many software development projects, providers usually customize the development for their clients based on some existing general modules, and the project quality of those general modules can be reflected by ε.

Under above assumptions, the project quality is formulated as $q = \varepsilon + km + \theta t$. Such additive form of effort outcome is a usual assumption in the literature [39], [40]. The quality-improvement efforts of the buyer and the winning provider incur costs $\frac{1}{2}m^2$ and $\frac{1}{2}t^2$ respectively, and the winning provider bears an additional cost $\frac{1}{2}s^2$ to deliver the functions covered in project scope s. Similar assumptions of quadratic costs for development or effort are also common in the literature related to research & development [41], [42].

The buyer uses the prevalent reverse English auction to select a winning provider. It is an open descending auction in which a publicly visible price decreases over time, and each provider chooses a price (time) at which he will permanently drop out of the auction. The auction terminates when $n-1$ providers quit, and the last (remaining) provider becomes the winner and will be paid the current price for delivering the IT project. The sequence of events is depicted in Fig. 1.

The buyer announces the project scope s to all potential providers at T0, and the potential providers then bid the project prices in the auction at T1. When the winning provider is determined via auction, the winning price (denoted as p) and the winner's expertise (denoted as θ) is revealed to the buyer. It is a common assumption in the auction literature that the auctioneer can know the winner's private type after bidding, by inferring from the bidding equilibrium for example [35] and [36]. At T2, both the buyer and the winning provider exerts non-verifiable efforts, m and t respectively, jointly to improve the project quality. As the bilateral efforts and uncertainty ε resolve, the project quality $q = \varepsilon + km + \theta t$ realizes at T3. Note that the project quality is perceived by both parties through a project demo rather than actual implementation, and the specified functions required in the

TABLE 1. Summary of notations.

Symbol	Definition
n	number of potential providers
s	project scope
q	project quality
ε	uncertainty in the project quality
μ	mean of ε
σ	standard deviation of ε
m	buyer's effort in improving project quality
k	buyer's expertise in improving project quality
t	winning provider's effort in improving project quality
θ	winning provider's expertise in improving project quality
θ_i	provider i's expertise in improving project quality
$[\underline{\theta}, \overline{\theta}]$	support of θ_i
$F(\cdot)$	cumulative distribution function of θ_i
$f(\cdot)$	probability density function of θ_i
p_i	provider i's bid on project price
p	winning bid
$\hat{p}$	renegotiated project price
$\hat{s}$	renegotiated project scope
α	winning provider's bargaining power

project scope have not been delivered yet. Because the project scope s is determined *ex ante* based on the buyer's estimation of the future project quality, it is highly possible that s is not *ex post* optimal when the actual project quality is realized. Therefore, at T4, the buyer and the winning provider may have incentives to renegotiate the project scope to a jointly more beneficial level $\hat{s}$, and then they can split the extra benefit resulted from the renegotiation (i.e., the renegotiation surplus) by adjusting the project price to $\hat{p}$. Assume that the shares of renegotiation surplus obtained by the winning provider and the buyer are α and $1-\alpha$ respectively, which are exogenously determined by their bargaining powers during renegotiation. For ease of exposition, we directly refer to α as the provider's bargaining power. Finally, the winning provider bears a cost $\frac{1}{2}\hat{s}^2$ to provide the functions required in scope $\hat{s}$, and the buyer derives a value $q \times \hat{s}$ from the project and transfer a payment $\hat{p}$ to the winning provider.

To avoid trivial results, we assume $k^2 + \overline{\theta}^2 \leq 1$. This assumption ensures the concavity of both sides' objective functions, and it rules out impractical situations where the project expertise of the buyer or/and the winning provider is so high that they would choose to input infinite efforts. Table 1 lists some important model notations.

IV. MODEL ANALYSIS

By backward induction, we first analyze the renegotiation process at T4.

A. RENEGOTIATION

At T4, observing the realized project quality $q = \varepsilon + km + \theta t$, the buyer and the winning provider seek to maximize the *ex post* joint profit by adjusting the project scope and price.

Lemma 1: The buyer and the winning provider will renegotiate the project scope to $\hat{s}(q) = q$.

All proofs of lemmas, propositions and corollaries are provided in Appendix. Lemma 1 indicates that the *ex post* project scope $\hat{s}$ is a linearly increasing function of the project quality q. Since the project value is multiplicative in the project scope and quality, a higher project quality q means a higher marginal benefit if the parties increase the project scope, thus driving them to choose a higher *ex post* scope $\hat{s}$. Such renegotiation results in an additional profit to the buyer and the winning provider as a whole, which is referred to as the renegotiation surplus and is given by

$$\Delta_{\mathrm{R}}(s, q) \equiv \left[\hat{s}(q)q - \frac{1}{2}\hat{s}(q)^2\right] - \left(sq - \frac{1}{2}s^2\right). \tag{1}$$

By Lemma 1 and (1), we further obtain $\Delta_{\mathrm{R}}(s, q) = \frac{1}{2}[\hat{s}(q) - s]^2$. This implies that the magnitude of renegotiation surplus is determined by the extent of scope change (i.e., $|\hat{s}-s|$); the more significantly the project scope changes, the higher the renegotiation surplus will be.

The allocation of renegotiation surplus between the buyer and the winning provider is achieved by adjusting the project price. The provider's profit under the renegotiated contract (i.e., $\hat{p} - \frac{1}{2}\hat{s}^2 - \frac{1}{2}t^2$) should equal the provider's profit under the initial project scope and price (i.e., $p - \frac{1}{2}s^2 - \frac{1}{2}t^2$) plus the share of renegotiation surplus the provider obtains (i.e., $\alpha\Delta_{\mathrm{R}}(s, q)$). Thus, the renegotiated project price should be

$$\hat{p}(s, p, q) = p + \frac{1}{2}[\hat{s}(q)^2 - s^2] + \alpha\Delta_{\mathrm{R}}(s, q). \tag{2}$$

Equation (2) can be rewritten as $\hat{p} - p = \frac{1}{2}(\hat{s} - s)[2\alpha q + (1 - \alpha)(\hat{s} + s)]$, which shows that the signs of $(\hat{p} - p)$ and $(\hat{s} - s)$ are the same. Therefore, through renegotiation, the direction of project price adjustment is the same with that of project scope adjustment.

B. BILATERAL IMPROVEMENT EFFORTS

At T2, given the initial project scope s and the winning provider's price p and expertise θ, the buyer and the winning provider participate in a full-information static game of deciding their quality-improvement efforts. Applying regular analysis of full-information static games, we first examine the players' best response functions and then analyze the Nash equilibrium of bilateral efforts.

1) BEST RESPONSE FUNCTIONS

Given (s, p, θ) and the buyer's project quality improvement effort m, the expected profit of the winning provider when he chooses effort level t is given by

$$U_{\mathrm{S}}(s, p, \theta, m, t) = \mathbb{E}_{\varepsilon}[\hat{p}(s, p, q) - \frac{1}{2}\hat{s}(q)^2 - \frac{1}{2}t^2]. \tag{3}$$

Similarly, given (s, p, θ) and the winning provider's effort t, the buyer's expected profit when she chooses effort level m is given by

$$U_{\mathrm{B}}(s, p, \theta, m, t) = \mathbb{E}_{\varepsilon}[\hat{s}(q)q - \hat{p}(s, p, q) - \frac{1}{2}m^2]. \tag{4}$$

Maximizating one party's expected profit while regarding the other party's effort as given, we obtain the best response functions of the winning provider and the buyer respectively.

Lemma 2: Given (s, p, θ), the best response functions of the winning provider and the buyer are respectively given by

$$t(m) = \frac{\alpha\theta(\mu + km - s)^+}{1 - \alpha\theta^2}, \tag{5}$$

$$m(t) = \frac{[(1-\alpha)(\mu + \theta t) + \alpha s]k}{1 - (1-\alpha)k^2}. \tag{6}$$

Lemma 2 implies that, for any initial scope s and provider effort t, the buyer will always exert positive effort. However, whether the provider will exert positive effort depends on the relationship between the initial scope s and the buyer's effort m. Therefore, to induce appropriate provider effort, it is necessary to examine how one party's effort is affected by the initial scope and by the other party's effort.

Proposition 1: (i) The winning provider's effort t and the buyer's effort m are complementary strategies.

(ii) Given the other party's effort, the buyer's effort m increases in the initial scope s whereas the winning provider's effort t decreases in s.

Part (i) of Proposition 1 indicates that the two parties' efforts are mutually enhancing. The increase of one party's effort will increase the marginal contribution of the other party's effort to the renegotiation surplus ($\Delta_R(s, q) = \frac{1}{2}(\varepsilon + km + \theta t - s)^2$), thus incentivizing the other party to raise its effort to reap more renegotiation surplus. Part (ii) of Proposition 1 uncovers the direct effects of the initial scope on the two parties' efforts (note that the initial scope can also indirectly affect one party's effort via affecting the other party's effort). Specifically, a higher initial scope s directly suppresses the provider's effort t, which can be explained as follows. The incentive for the provider's effort comes solely from the renegotiation surplus. With a higher initial scope, the marginal contribution of provider effort to the renegotiation surplus is lower, thus leading the provider to reduce his effort. For the buyer, however, renegotiation surplus is only one minor source of return for her effort. The major source of return for her effort is the project value. With a higher initial scope, although the marginal contribution of buyer effort to the renegotiation surplus is lower (minor effect), the marginal contribution of buyer effort to the project value is increasing (major effect). As a result, the buyer tends to increase her effort when the initial scope is high.

2) NASH EQUILIBRIUM

Based on the analyses of the best response functions, the Nash equilibrium of the bilateral efforts can be characterized as follows.

Lemma 3: Given (s, p, θ), the Nash equilibrium efforts of the winning provider and the buyer are respectively given by

$$t^*(s, \theta) = \frac{\alpha\theta[\mu - (1-k^2)s]^+}{1 - \alpha\theta^2 - (1-\alpha)k^2}, \tag{7}$$

$$m^*(s, \theta) = \frac{[(1-\alpha)(\mu + \theta t^*(s, \theta)) + \alpha s]k}{1 - (1-\alpha)k^2}. \tag{8}$$

Lemma 3 shows that, in equilibrium, the buyer will always make positive effort, whereas the winning provider will exert positive effort only when the initial project scope is not too large (i.e., $s < \frac{\mu}{1-k^2}$). To better illustrate the underlying intuitions, we have the following proposition.

Proposition 2: (i) The buyer's (the winning provider's) equilibrium effort m^* (t^*) is increasing (decreasing) in the initial project scope s.

(ii) When $k > \theta$ ($k < \theta$), the expected project quality $\mathbb{E}_\varepsilon[q]$ increases (decreases) with the initial project scope s.

Part (i) of Proposition 2 extends the results of Proposition 1. Proposition 1 shows that the initial scope s has both direct and indirect effects on the provider's (the buyer's) effort: on the one hand, a higher initial scope s directly suppresses provider effort (incentivizes buyer effort); on the other hand, a higher s also indirectly increases provider effort (suppresses buyer effort) via increasing buyer effort (decreasing provider effort). Proposition 2 further indicates that the above indirect effects are dominated by the corresponding direct effects, making the equilibrium provider effort t^* decreasing with s and the equilibrium buyer effort m^* increasing with s. As regard Part (ii) of Proposition 2, the effect of s on the expected project quality $\mathbb{E}_\varepsilon[q]$ depends on the parties' project expertise, because $\mathbb{E}_\varepsilon[q]$ is additive in t^* and m^* (with the parties's project expertise being coefficients), and t^* and m^* are affected by s in opposite directions. When the buyer has higher expertise than the provider, the expected project scope is increasing with the initial scope (following the property of buyer effort); otherwise, the expected project scope is decreasing with the initial scope (following the property of provider effort).

C. BIDDING EQUILIBRIUM AND INFORMATION RENT

Substituting (7)-(8) into (3), we obtain the winning provider's expected profit at T1, as given by

$$\begin{aligned} U_S^*(s, p, \theta) &\equiv U_S(s, p, \theta, m^*(s, \theta), t^*(s, \theta)) \\ &= p - \frac{1}{2}s^2 + \frac{1}{2}\alpha\sigma^2 \\ &\quad + \begin{cases} \dfrac{\alpha[\mu-(1-k^2)s]^2}{2[1-(1-\alpha)k^2]^2}, & \mu \le (1-k^2)s; \\ \dfrac{\alpha(1-\alpha\theta^2)[\mu-(1-k^2)s]^2}{2[1-\alpha\theta^2-(1-\alpha)k^2]^2}, & \mu > (1-k^2)s. \end{cases} \end{aligned} \tag{9}$$

At T1, if provider i wins the auction, then the expected cost provider i must bear to deliver the project is given by

$$c(s, \theta_i) \equiv p - U_S^*(s, p, \theta_i). \tag{10}$$

Check that $c(s, \theta_i)$ is decreasing in provider i's private type θ_i and is independent of other providers' types. Therefore, $\{\theta_i\}_{i=1}^n$ being independent and identically distributed (iid) implies that $\{c(s, \theta_i)\}_{i=1}^n$ are also iid, which means that $c(s, \theta_i)$ can be regarded as provider i's pseudo type. It is a standard result that under reverse English auction, in equilibrium each provider i will choose to drop out of the auction when the auction price reaches his expected cost $c(s, \theta_i)$ [43]. In equilibrium, the last (remaining) provider in the auction, whose expected cost is $c(s, \theta_{(1)})$, wins the auction at the dropping price of the second-last provider, i.e., $p = c(s, \theta_{(2)})$. Then the winning provider's expected profit in equilibrium will be

$$U_S^*(s, c(s, \theta_{(2)}), \theta_{(1)}) = c(s, \theta_{(2)}) - c(s, \theta_{(1)}), \quad (11)$$

which is also the information rent obtained by the winning provider. Equation (11) shows that the information rent equals the winning provider's relative advantage of expected cost compared to the best losing provider.

Proposition 3: The winning provider's information rent decreases with the initial scope s.

Propositions 2 and 3 reveal that the initial scope is a double-edged sword to the buyer: a high initial scope may suppress the winning provider's information rent (Proposition 3), but it also may reduce the winning provider's incentive to exert effort for project quality improvement (Proposition 2). Therefore, when deciding the initial scope, the buyer should trade off carefully between incentivizing provider effort and regulating information rent.

D. INITIAL PROJECT SCOPE

At T0, considering the subsequent processes of bidding, bilateral improvement efforts and renegotiation, the buyer maximizes her expected profit by setting the initial project scope. Substituting $p = c(s, \theta_{(2)})$, $m = m^*(s, \theta_{(1)})$ and $t = t^*(s, \theta_{(1)})$ into (4) and taking expectation over the order statistics of provider types, we obtain the buyer's expected profit at T0, which is given by

$$\begin{aligned} U_B(s) &\equiv \mathbb{E}_{\theta_{(1)},\theta_{(2)}}[U_B(s, c(s, \theta_{(2)}), \theta_{(1)}, m^*(s, \theta_{(1)}), t^*(s, \theta_{(1)}))] \\ &= \Phi(s) - \mathbb{E}_{\theta_{(1)},\theta_{(2)}}[U_S^*(s, c(s, \theta_{(2)}), \theta_{(1)})], \quad (12) \end{aligned}$$

where $\mathbb{E}_{\theta_{(1)},\theta_{(2)}}[U_S^*(s, c(s, \theta_{(2)}), \theta_{(1)})]$ is the information rent to the winning provider, and

$$\begin{aligned} \Phi(s) = \frac{1}{2}\mathbb{E}_{\theta_{(1)},\theta_{(2)},\varepsilon}\{&[\varepsilon + km^*(s, \theta_{(1)}) + \theta_{(1)}t^*(s, \theta_{(1)})]^2 \\ &- [t^*(s, \theta_{(1)})]^2 - [m^*(s, \theta_{(1)})]^2\} \end{aligned}$$

is the channel profit the project creates. Denote

$$\rho \equiv \frac{(\eta_2 - \eta_3)^+}{\eta_1 - \eta_3} < 1, \quad (13)$$

where

$$\eta_1 = \mathbb{E}_{\theta_{(1)}}\left[\frac{1 - \alpha\theta_{(1)}^4 - (1-\alpha)k^2}{[1 - \alpha\theta_{(1)}^2 - (1-\alpha)k^2]^2}\right],$$

$$\eta_2 = \mathbb{E}_{\theta_{(1)}}\left[\frac{(1 - \theta_{(1)}^2)[1 - (1-\alpha)k^2]}{[1 - \alpha\theta_{(1)}^2 - (1-\alpha)k^2]^2}\right],$$

$$\eta_3 = \mathbb{E}_{\theta_{(2)}}\left[\frac{(1 - \alpha\theta_{(2)}^2)(1 - k^2)}{[1 - \alpha\theta_{(2)}^2 - (1-\alpha)k^2]^2}\right].$$

Then we have the following proposition.

Proposition 4: The buyer's optimal initial project scope is

$$s^* = \frac{\mu\rho}{1 - k^2}.$$

We examine the property of s^* by numerical analysis. When $n = 5$, $\mu = 1$ and $\theta_i \sim U[0.1, 0.8]$, we illustrate in Fig. 2 how s^* changes with the provider's bargaining power α and the buyer's project expertise k. It can be observed that the buyer will set $s^* > 0$ only when the provider's bargaining power α exceeds some threshold. When α is low, the provider's share of renegotiation surplus is low, and thus he has little incentive to invest in the project quality. In this situation, incentivizing provider's effort in project quality is a dominant concern. Therefore, the buyer will set the initial scope as low as possible (i.e., $s^* = 0$), which provides the strongest incentive for the provider's effort. A zero initial scope means that the buyer does not require the winning provider to go beyond a prototype. When α is high, the winning provider captures a significant share the renegotiation surplus and extracts high information rent. In this situation, curbing the winning provider's information rent is no longer a trivial concern. Therefore, the buyer sets a relative high initial scope to strike a balance between inducing provider effort and curbing his information rent. We can also observe that the optimal initial scope s^* is increasing in the buyer's expertise k. With a higher k, the buyer's effort becomes more productive, and thus the buyer will increase the initial scope to induce more buyer effort and to exert more intense regulation on information rent.

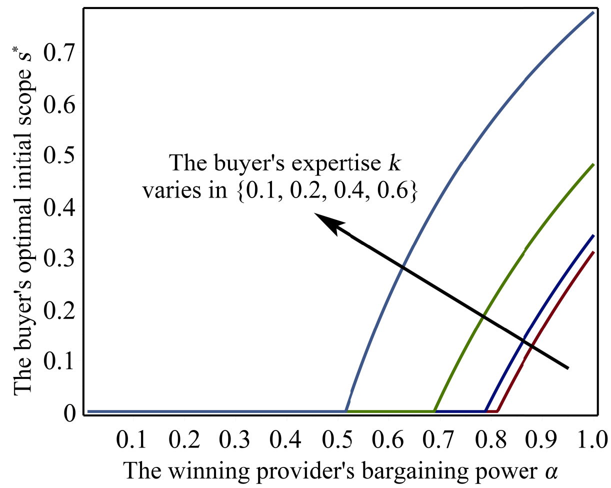

FIGURE 2. The buyer's optimal initial project scope s^* changes with the winning provider's bargaining power α and the buyer's project expertise k.

The buyer's optimal initial project scope provides additional implications which are organized as corollaries.

Corollary 1: Under the buyer's optimal initial scope s^*, the equilibrium efforts of the winning provider and the buyer are respectively given by

$$t^*(s^*, \theta) = \frac{\alpha\mu\theta(1-\rho)}{1 - \alpha\theta^2 - (1-\alpha)k^2} > 0, \quad (14)$$

$$m^*(s^*, \theta) = \frac{\mu k[(1-\alpha)(1-k^2) + \alpha\rho(1-\theta^2)]}{(1-k^2)[1 - \alpha\theta^2 - (1-\alpha)k^2]} > 0. \quad (15)$$

By Corollary 1, the buyer's optimal initial scope always ensures that both parties will exert positive efforts in project quality improvement. Although it is possible for the buyer to choose some initial scope which eliminates provider effort and thus information rent, it is optimal for her to tolerate some information rent in exchange for project quality improvement.

Corollary 2: The expected renegotiated project scope is greater than the initial scope, i.e., $\mathbb{E}_{\theta_{(1)},\varepsilon}[\hat{s}] > s^*$

Corollary 2 implies that, in expectation, the buyer would like to start with a relatively small scope and scale it up after the project quality realizes. This is consistent with many practical IT projects [19], but is not trivial because a conservative initial scope has both a positive effect of encouraging provider effort and a negative effect of increasing the winning provider's information rent. We note that this finding does not depend on any model parameter (including the provider's bargaining power), suggesting that the buyer is always willing to forgo some information rent in exchange for provider effort. We also want to note that this finding does not rule out the case where the realization of the project quality is so bad that the two parties need to scale the project scope down through renegotiation.

With s^*, the buyer's optimal expected profit will be

$$\begin{aligned} U_{\mathrm{B}}^* &\equiv U_{\mathrm{B}}(s^*) \\ &= \frac{\mu^2\alpha(1-\rho)[(\eta_2-\eta_3)^+ + \eta_1 - 2\eta_2 + \eta_3]}{2(1-k^2)} \\ &\quad + \frac{\sigma^2}{2} + \frac{\mu^2}{2(1-k^2)}. \end{aligned} \tag{16}$$

V. VALUE OF RENEGOTIATION

The previous section has revealed that, as long as renegotiation exists, information rent is always concurrent with the provider's project quality improvement effort. As will be shown later, if renegotiation is prohibited, the winning provider will exert no effort and obtains no information rent. Therefore, the use of renegotiation generates two effects simultaneously: the incentive effect, referring to the buyer's ability to incentivize the winning provider to exert effort, and the information effect, referring to the buyer's capability to regulate information rent. The combination of the two effects determines the overall value of renegotiation to the buyer. To capture the above two effects and evaluate the value of renegotiation, we introduce two benchmark models: the no-renegotiation model (I) and the full-information model (II).

A. BENCHMARK I: NO-RENEGOTIATION MODEL

When renegotiation is prohibited, given the initial project scope s, project price p and the buyer's effort m, the winning provider's expected profit at T2 when he chooses effort t is

$$U_{\mathrm{S}}^{\mathrm{I}}(s,p,t) = p - \frac{1}{2}t^2 - \frac{1}{2}s^2, \tag{17}$$

which implies that the winning provider has no incentive to make any effort, i.e., $t_{\mathrm{I}}^* = 0$. Intuitively, any provider effort directly benefits the buyer through the improvement of project quality. Without a surplus sharing mechanism (e.g., through renegotiation), the provider will not benefit from his own effort, thus has no interest in making such an effort. From the buyer's perspective, given s, p, and the winning provider's expertise θ and effort t, the buyer's expected profit when she chooses effort m is given by

$$U_{\mathrm{B}}^{\mathrm{I}}(s,p,\theta,m,t) = \mathbb{E}_{\varepsilon}[(\varepsilon + km + \theta t)s - p - \frac{1}{2}m^2]. \tag{18}$$

Check that the optimal solution of buyer effort is $m_{\mathrm{I}}^* = sk$. The above results show that the two parties' effort decisions are independent of each other, which is distinct from the complementary relationship they have when there is renegotiation (Proposition 1).

At T1, anticipating that it is not beneficial to make any effort, all potential providers' expected costs of delivering the project are the same, i.e., $\frac{1}{2}s^2$. According to the standard analysis of auction theory [43], all potential providers will choose to drop at the same price $p_{\mathrm{I}} = \frac{1}{2}s^2$. The buyer can randomly choose one provider as the winner. Substituting $p_{\mathrm{I}} = \frac{1}{2}s^2$ and $t_{\mathrm{I}}^* = 0$ into (17), we obtain that the winning provider's expected profit in equilibrium (which is also the information rent) is $U_{\mathrm{S}}^{\mathrm{I}*} = 0$.

At T0, the buyer's expected profit when she chooses initial scope s is

$$U_{\mathrm{B}}^{\mathrm{I}}(s) \equiv U_{\mathrm{B}}^{\mathrm{I}}(s,p_{\mathrm{I}},\theta,m_{\mathrm{I}}^*,t_{\mathrm{I}}^*) = \mu s - \frac{1}{2}(1-k^2)s^2. \tag{19}$$

It is easy to obtain that the optimal initial project scope for the buyer is

$$s_{\mathrm{I}}^* = \frac{\mu}{1-k^2}, \tag{20}$$

and the buyer's maximized expected profit becomes

$$U_{\mathrm{B}}^{\mathrm{I}*} \equiv U_{\mathrm{B}}^{\mathrm{I}}(s_{\mathrm{I}}^*) = \frac{\mu^2}{2(1-k^2)}. \tag{21}$$

B. BENCHMARK II: FULL-INFORMATION MODEL

When renegotiation is possible but there is no information asymmetry, the processes of renegotiation and bilateral efforts are identical to the base model. Therefore, the renegotiated project scope is $\hat{s}_{\mathrm{II}}(q) = q$ (as characterized in Lemma 1), and the Nash equilibrium of bilateral efforts is

$$t_{\mathrm{II}}^*(s,\theta) = \frac{\alpha\theta[\mu-(1-k^2)s]^+}{1-\alpha\theta^2-(1-\alpha)k^2}, \tag{22}$$

$$m_{\mathrm{II}}^*(s,\theta) = \frac{[(1-\alpha)(\mu+\theta t_{\mathrm{II}}^*(s,\theta))+\alpha s]k}{1-(1-\alpha)k^2} \tag{23}$$

(as characterized in Lemma 3). However, the buyer's selection of winning provider is distinct from the base model. Under full information, it is unnecessary for the buyer to use auctions to select the winning provider, because she can directly identify the provider with the lowest expected cost. Since each provider i's expected cost of delivering the project $c_{\mathrm{II}}(s,\theta_i)$ (as characterized by (10)) is decreasing in the provider's expertise θ_i, obviously the buyer will choose the provider with expertise $\theta_{(1)}$ as the winner and offers him a price that equals to his expected cost $c_{\mathrm{II}}(s,\theta_{(1)})$. As a result, the winning provider's expected profit (information rent) is $U_{\mathrm{S}}^{\mathrm{II}*}=0$, whereas the buyer reaps the entire surplus created by the project, i.e.,

$$U_{\mathrm{B}}^{\mathrm{II}}(s)=\mathbb{E}_{\theta_{(1)},\varepsilon}[(\varepsilon+km_{\mathrm{II}}^{*}(s,\theta_{(1)})+\theta_{(1)}t_{\mathrm{II}}^{*}(s,\theta_{(1)}))\hat{s}_{\mathrm{II}} - \frac{1}{2}\hat{s}_{\mathrm{II}}^{2}-\frac{1}{2}(m_{\mathrm{II}}^{*}(s,\theta_{(1)}))^{2}-\frac{1}{2}(t_{\mathrm{II}}^{*}(s,\theta_{(1)}))^{2}]. \quad (24)$$

Maximizing the above equation with respect to s yields the optimal initial project scope

$$s_{\mathrm{II}}^{*}=\frac{\mu\rho_{\mathrm{II}}}{1-k^{2}}, \quad (25)$$

where $\rho_{\mathrm{II}}=\frac{(\eta_2-x_3)^{+}}{\eta_1-x_3}<1$, $x_3=\mathbb{E}_{\theta_{(1)}}\left[\frac{(1-\alpha\theta_{(1)}^{2})(1-k^{2})}{[1-\alpha\theta_{(1)}-(1-\alpha)k^{2}]^{2}}\right]$.

With s_{II}^{*}, the buyer's maximized expected project is

$$U_{\mathrm{B}}^{\mathrm{II}*}\equiv U_{\mathrm{B}}^{\mathrm{II}}(s_{\mathrm{II}}^{*})=\frac{\sigma^{2}}{2}+\frac{\mu^{2}}{2(1-k^{2})} + \frac{\mu^{2}\alpha(1-\rho_{\mathrm{II}})[(\eta_2-x_3)^{+}+\eta_1-2\eta_2+x_3]}{2(1-k^{2})}. \quad (26)$$

C. COMPARISON OF MODEL RESULTS

Comparing the results of the base model, benchmark I and benchmark II, we obtain the following proposition.

Proposition 5: For $\alpha\in(0,1]$, the following inequalities hold:

$$0\le s_{II}^{*}\le s^{*}<s_{I}^{*},$$
$$0<m_{II}^{*}<m^{*}<m_{I}^{*},$$
$$0=t_{I}^{*}<t^{*}<t_{II}^{*}.$$

Based on previous analyses, Proposition 5 further highlights the implication of the buyer's strategic use of the initial project scope in terms of incentivizing provider effort and regulating information rent. When there is no renegotiation (benchmark I), due to the lack of appropriate instrument to incentivize provider effort, the buyer has to undertake all the responsibility of project quality improvement herself. Thus, the buyer should set a high project scope to make it profitable for herself to make an effort. When there is renegotiation but no asymmetric information (benchmark II), the buyer's decision on the initial scope can affect the winning provider's effort but does not cause information rent. Therefore, the buyer sets a relatively low initial scope to induce as much provider effort as possible, thus relieving the pressure of project quality improvement on herself (note that by $q=km+\theta t+\varepsilon$, the buyer's and the winning provider's efforts are substitutes in terms of improving the project quality.) In the base model, renegotiation and asymmetric information coexist, and the buyer's decision on initial scope has effects on both the information rent and the winning provider's effort. As a result, the buyer sets a moderate initial scope to achieve the balance between regulating information rent and inducing provider effort.

D. VALUE OF RENEGOTIATION

In benchmark I, due to the lack of revenue-sharing mechanism, the winning provider has no incentive to improve the project scope and extracts no information rent as well. In benchmark II, with renegotiation being a revenue-sharing mechanism, the buyer is able to incentivize the winning provider to exert effort without causing information rent. Therefore, the gross benefit of renegotiation without information rent can be captured by the difference of the buyer's expected profits between benchmark II and I, i.e.,

$$U_{\mathrm{B}}^{\mathrm{II}*}-U_{\mathrm{B}}^{\mathrm{I}*}=\frac{\sigma^{2}}{2}+\Delta_1, \quad (27)$$

where

$$\Delta_1=\frac{\mu^{2}\alpha(1-\rho_{\mathrm{II}})[(\eta_2-x_3)^{+}+\eta_1-2\eta_2+x_3]}{2(1-k^{2})}. \quad (28)$$

In (27), the first term $\frac{1}{2}\sigma^{2}$ represents the responsive benefit of renegotiation, because it stems from the parties' ability to react to project uncertainties through renegotiation. The second term Δ_1 captures the incentive effect of renegotiation, because it is generated due to the fact that the renegotiation in benchmark II can incentivize provider effort.

Both the base model and benchmark II involve renegotiation which provides incentive for provider effort. The only difference is that the renegotiation in the base model also causes information rent simultaneously. Therefore, we can capture the information effect of renegotiation (denoted as Δ_2) by the gap of buyer profits between benchmark II and the base model:

$$\Delta_2=U_{\mathrm{B}}^{\mathrm{II}*}-U_{\mathrm{B}}^{*} =\frac{\mu^{2}\alpha(1-\rho_{\mathrm{II}})[(\eta_2-x_3)^{+}+\eta_1-2\eta_2+x_3]}{2(1-k^{2})} -\frac{\mu^{2}\alpha(1-\rho)[(\eta_2-\eta_3)^{+}+\eta_1-2\eta_2+x_3]}{2(1-k^{2})}. \quad (29)$$

Based on the above formulation, we can quantify the value of renegotiation under asymmetric information by

$$V_{\mathrm{R}}\equiv U_{\mathrm{B}}^{*}-U_{\mathrm{B}}^{\mathrm{I}*}=\frac{1}{2}\sigma^{2}+\Delta_1-\Delta_2. \quad (30)$$

Proposition 6: The renegotiation's incentive effect always dominates its information effect, i.e., $\Delta_1>\Delta_2$.

Proposition 6 implies that the buyer is better off to reserve the renegotiation option than prohibiting it *ex ante*. Providers also embrace the possibility of renegotiation because it enables them to earn information rent conditional on winning the contract.

VI. CONCLUSION

In ITO projects, joint efforts from both the buyer and the service provider are essential for the improvement of project quality, and renegotiations are commonly adopted for contract amendment and surplus redistribution. This paper studies a game-theoretical ITO contracting model, where multiple potential providers compete in project price in a reverse auction, and renegotiation of project scope may take place after the buyer and the winning provider exert project quality improvement efforts. We contribute to the ITO contracting literature by providing a novel theoretical framework that connects several important aspects of ITO contracts, by offering new insights on how to manage such complex service auctions, and by uncovering the value of renegotiation when contract incompleteness, adverse selection and moral hazard coexist.

Our main findings are as follows. We find that the two parties' efforts are complementary strategies, i.e., they are mutually enhancing. The increase of one party's effort will increase the marginal contribution of the other party's effort to the renegotiation surplus, thus incentivizing the other party to raise its effort to reap more renegotiation surplus. We also find that a higher initial scope suppresses the winning provider's information rent but also reduces the winning provider's incentive to exert effort. The buyer's optimal initial scope always ensures positive efforts from both sides, and in the renegotiation the project scope is expected to be adjusted upwards. The possibility of renegotiation provides incentives for the winning provider to exert effort (incentive effect), but it also enables the winning provider to extract information rent (information effect). These conflicting effects determines the value of the renegotiation to the buyer. Our analytical result shows that the incentive effect of renegotiation always dominates the information effect, implying that both the buyer and the providers benefit from the possibility of renegotiation. This explains why firms usually do not commit not to renegotiate ITO contracts and why renegotiation is so prevalent in ITO projects.

The present study can be extended from several directions. First, it is interesting to examine the effect of other contracting instruments other than the initial project scope. As different instruments may have qualitatively different effects on the provider's effort and information rent, it is of particular interest to explore the strategic relationship between different contracting instruments when they are employed together. Second, the reverse English auction is only one of the most commonly adopted provider selection mechanisms, and one may consider other mechanisms such as the multi-attribute auctions. Asking the providers to bid on price and other dimensions (e.g., quality, lead time, warranty) may introduce new tradeoffs and make the buyer's contracting problem more intriguing.

APPENDIX

Proof of Lemma 1: In renegotiation, the buyer and the winning provider choose a new project scope $\hat{s}$ to maximize the *ex post* joint profit $\hat{s}q - \frac{1}{2}\hat{s}^2 - \frac{1}{2}m^2 - \frac{1}{2}t^2$. It is easy to verify that the optimal solution is given by $\hat{s}(q) = q$. □

Proof of Lemma 2: Under assumption $k^2+\overline{\theta}^2 \leq 1$, $\frac{\partial^2 U_S}{\partial t^2} = \alpha\theta^2 - 1 \leq 0$ and $\frac{\partial^2 U_B}{\partial m^2} = (1-\alpha)k^2 - 1 \leq 0$ hold, implying that both parties' expected profits are concave in their own efforts. Thus, the best response functions can be uniquely determined by the following first-order conditions:

$$\frac{\partial U_S}{\partial t} = (\alpha\theta^2 - 1)t + \alpha\theta(\mu + km - s) = 0, t \geq 0;$$

$$\frac{\partial U_B}{\partial m} = (1-\alpha)(\mu + \theta t)k + \alpha sk - [1-(1-\alpha)k^2]m = 0, \ m \geq 0.$$

Solving above equations yields the results of Lemma 2. □

Proof of Proposition 1: Part (i) can be proved by $\frac{\partial^2 U_S}{\partial t \partial m} = \alpha\theta k > 0$ and $\frac{\partial^2 U_B}{\partial m \partial t} = (1-\alpha)k\theta > 0$, and part (ii) can be proved by $\frac{\partial t(m)}{\partial s} = -\frac{\alpha\theta}{1-\alpha\theta^2}1_{\mu+km-s>0} \leq 0$ and $\frac{\partial m(t)}{\partial s} = \frac{\alpha s}{1-(1-\alpha)k^2} \geq 0$. □

Proof of Lemma 3: We analyze the Nash equilibrium by two situations.

(i) When $\mu + km - s \leq 0$, solving (5)-(6) yields $m^* = \frac{[(1-\alpha)\mu+\alpha s]k}{1-(1-\alpha)k^2}$ and $t^* = 0$. Substituting the solution back into $\mu + km - s \leq 0$ yields $\mu - (1-k^2)s \geq 0$.

(ii) When $\mu + km - s > 0$, solving (5)-(6) yields

$$t^* = \frac{\alpha\theta[\mu - (1-k^2)s]}{1-\alpha\theta^2-(1-\alpha)k^2},$$
$$m^* = \frac{[(1-\alpha)\mu + \alpha(1-\theta^2)s]k}{1-\alpha\theta^2-(1-\alpha)k^2}.$$

Substituting the solution back into $\mu + km - s > 0$ yields $\frac{\mu-(1-k^2)s}{1-\alpha\theta^2-(1-\alpha)k^2} > 0$. The assumption $k^2 + \overline{\theta}^2 \leq 1$ indicates $1-\alpha\theta^2-(1-\alpha)k^2 > 0$, which implies that $\mu + km - s > 0$ is equivalent to $\mu - (1-k^2)s > 0$.

Combining the above results, we obtain the equilibrium efforts of the winning provider and the buyer, as characterized in Lemma 3. □

Proof of Proposition 2: Taking the first-order partial derivatives of t^* and m^* with respect to s yields

$$\frac{\partial t^*}{\partial s} = -\frac{(1-k^2)\alpha\theta 1_{\mu>(1-k^2)}}{1-\alpha\theta^2-(1-\alpha)k^2} \leq 0,$$
$$\frac{\partial m^*}{\partial s} = \frac{\alpha k(1-\alpha)\theta^2(1-k^2)(1-1_{\mu>(1-k^2)s})}{[1-(1-\alpha)k^2][1-\alpha\theta^2-(1-\alpha)k^2]} + \frac{\alpha k(1-\theta^2)}{1-\alpha\theta^2-(1-\alpha)k^2} > 0.$$

which proves Part (i) of Proposition 2. Substituting $t^*(s,\theta)$ and $m^*(s,\theta)$ into $q = \varepsilon + km + \theta t$ and taking expectation over ε, one obtains

$$\mathbb{E}_\varepsilon[q] = \frac{\mu + \alpha(k^2-\theta^2)s}{1-\alpha\theta^2-(1-\alpha)k^2}.$$

It is easy to verify that $\frac{\partial \mathbb{E}_\varepsilon[q]}{\partial s} > 0$ when $k > \theta$ and $\frac{\partial \mathbb{E}_\varepsilon[q]}{\partial s} < 0$ when $k < \theta$, which proves Part (ii) of Proposition 2. □

Proof of Proposition 3: The mixed partial derivative of $c(s,\theta)$ with respect to s and θ is

$$\frac{\partial^2 c(s,\theta)}{\partial s \partial \theta} = \frac{2\alpha^2\theta(1-k^2)[1-\alpha\theta^2+(1-\alpha)k^2]\beta}{[1-\alpha\theta^2-(1-\alpha)k^2]^3} \geq 0$$

where $\beta = [\mu - (1-k^2)s]^+ \geq 0$. This implies that $\frac{\partial c(s,\theta)}{\partial s}$ is increasing in θ. Thus, $\frac{\partial[c(s,\theta_{(2)})-c(s,\theta_{(1)})]}{\partial s} = \frac{\partial c(s,\theta_{(2)})}{\partial s} - \frac{\partial c(s,\theta_{(1)})}{\partial s} \leq 0$, which concludes the proof. □

Proof of Proposition 4: Since the equilibrium of bilateral efforts are piecewise, we analyze the buyer's optimal initial scope by two situations.

(i) When $\mu \le (1-k^2)s$, the buyer's expected profit (12) can be rewritten as

$$U_{\rm B}(s) = \frac{\sigma^2}{2} + \frac{\alpha^2 k^2[k^2 s^2 - (\mu - s)^2] + \mu^2[(2\alpha-1)k^2+1]}{2[1-(1-\alpha)k^2]^2},$$

and the second-order derivative is

$$\frac{\partial^2 U_{\rm B}}{\partial s^2} = \frac{\alpha^2 k^2(k^2-1)}{[1-(1-\alpha)k^2]^2} < 0.$$

This implies that $U_{\rm B}(s)$ is concave in s and thus the optimal solution can be uniquely determined by the following Karush-Kuhn-Tucker conditions:

$$\frac{\partial U_{\rm B}}{\partial s} + \lambda = 0,\ s \ge \frac{\mu}{1-k^2},\ \lambda\Big(s - \frac{\mu}{1-k^2}\Big) = 0,\ \lambda \ge 0.$$

If $\lambda > 0$, then $s = \frac{\mu}{1-k^2}$ and $\lambda = -\frac{\partial U_{\rm B}}{\partial s} = 0$, which contradicts $\lambda > 0$. If $\lambda = 0$, then $\frac{\partial U_{\rm B}}{\partial s} = 0$, which yields $s = \frac{\mu}{1-k^2}$. Therefore, the local optimal solution of the initial project scope under condition $\mu \le (1-k^2)s$ is $s = \frac{\mu}{1-k^2}$.

(ii) When $\mu \ge (1-k^2)s$, the buyer's objective function (12) can be rewritten as

$$\begin{aligned} U_{\rm B}(s) = \mathbb{E}_{\theta_{(1)},\theta_{(2)}}\Bigg[&\frac{\sigma^2}{2} + \frac{\alpha(1-\alpha\theta_{(2)}^2)[\mu-(1-k^2)s]^2}{2[1-\alpha\theta_{(2)}^2-(1-\alpha)k^2]^2} \\ &+ \frac{\alpha\theta_{(1)}^2(1-\alpha)[\mu-(1-k^2)s]^2}{2[1-\alpha\theta_{(1)}^2-(1-\alpha)k^2]^2} \\ &+ \frac{\mu^2 + \alpha s^2[k^2-(1-k^2)\theta_{(1)}^2] - \alpha(\mu-s)^2}{2[1-\alpha\theta_{(1)}^2-(1-\alpha)k^2]}\Bigg], \end{aligned}$$

and the second-order derivative is

$$\begin{aligned} \frac{\partial^2 U_{\rm B}}{\partial s^2} &= -\alpha(1-k^2)(\eta_1 - \eta_2) \\ &\le -\mathbb{E}_{\theta_{(1)}}\left[\frac{\alpha^2(1-k^2)(1-\theta_{(1)}^2)(k^2+\theta_{(1)}^2)}{[1-\alpha\theta_{(1)}^2-(1-\alpha)k^2]^2}\right] < 0. \end{aligned}$$

This implies that $U_{\rm B}(s)$ is concave in s, and thus the optimal solution can be uniquely determined by the following Karush-Kuhn-Tucker conditions:

$$\begin{aligned} \frac{-\partial U_{\rm B}}{\partial s} - \lambda_1 + \lambda_2 = 0, \quad & s \ge 0,\ s \le \frac{\mu}{1-k^2}, \\ \lambda_1 s = 0, \quad & \lambda_2\Big(\frac{\mu}{1-k^2} - s\Big) = 0,\ \lambda_1 \ge 0,\ \lambda_2 \ge 0. \end{aligned}$$

Below we analyze the optimal solution by situations.

a) If $\lambda_1 > 0$ and $\lambda_2 > 0$, then $s = 0$ and $s = \frac{\mu}{1-k^2}$, which is a contradiction.

b) If $\lambda_1 > 0$ and $\lambda_2 = 0$, then $s = 0$ and $\lambda_1 = \alpha\mu(\eta_3 - \eta_2)$. The condition $\lambda_1 > 0$ requires that $\eta_3 > \eta_2$.

c) If $\lambda_1 = 0$ and $\lambda_2 > 0$, then $\lambda_2 = -\mathbb{E}_{\theta_{(1)}}\Big[\frac{\alpha\mu\theta_{(1)}^2}{1-\alpha\theta_{(1)}^2-(1-\alpha)k^2}\Big] < 0$, which contradicts $\lambda_2 > 0$.

d) If $\lambda_1 = 0$ and $\lambda_2 = 0$, then $\frac{\partial U_{\rm B}}{\partial s} = -\alpha(1-k^2)(\eta_1 - \eta_3)s + \alpha\mu(\eta_2 - \eta_3) = 0$, with the solution being $s = \frac{\mu(\eta_2 - \eta_3)}{(1-k^2)(\eta_1 - \eta_3)}$. The condition $s \ge 0$ requires $\eta_2 \ge \eta_3$.

Combining the results of a)-d), the local optimal solution for $\mu \ge (1-k^2)s$ can be written as $s = \frac{\mu\rho}{1-k^2}$, where ρ is given by (13). Since $\mu \ge (1-k^2)s$ contains $\mu = (1-k^2)s$, the local optimal solution for $\mu \le (1-k^2)s$, i.e., $s = \frac{\mu}{1-k^2}$, is a feasible but non-optimal solution for $\mu \ge (1-k^2)s$. Therefore, the local optimal solution for $\mu \ge (1-k^2)s$ is also the global optimal solution. □

Proof of Corollary 1: The result is immediately obtained by substituting s^* into (7)-(8). □

Proof of Corollary 2: By Lemma 1 and (7)-(8),

$$\hat{s} - s^* = (\varepsilon - \mu) + \frac{\mu - (1-k^2)s^*}{1-\alpha\theta_{(1)}^2 - (1-\alpha)k^2}.$$

It follows that renegotiation leads to higher project scope (i.e., $\hat{s} > s^*$) when the uncontrollable factors affecting project quality turn out to be favorable than expected (i.e., $\varepsilon > \mu$) or not seriously unfavorable (i.e., $\mu - \frac{\mu-(1-k^2)s^*}{1-\alpha\theta_{(1)}^2-(1-\alpha)k^2} < \varepsilon < \mu$), and the scope will be adjusted downwards (i.e., $\hat{s} < s^*$) only when the project quality is badly harmed by uncontrollable incidents (i.e., $\varepsilon < \mu - \frac{\mu-(1-k^2)s^*}{1-\alpha\theta_{(1)}^2-(1-\alpha)k^2}$). However, in expectation, we have

$$\mathbb{E}_{\theta_{(1)},\varepsilon}[\hat{s}] - s^* = \mathbb{E}_{\theta_{(1)}}\left[\frac{\mu - (1-k^2)s^*}{1-\alpha\theta_{(1)}^2 - (1-\alpha)k^2}\right] > 0,$$

which concludes the proof. □

Proof of Proposition 5: First compare the base model and benchmark I. By $0 \le \rho < 1$, we have $s^* = \frac{\mu\rho}{1-k^2} < \frac{\mu}{1-k^2} = s_{\rm I}^*$ and $t_{\rm I}^* = 0 < \frac{(1-\rho)\alpha\mu\theta_{(1)}}{1-\alpha\theta_{(1)}^2-(1-\alpha)k^2} = t^*(s^*, \theta_{(1)})$. Check that $m^*(s^*, \theta_{(1)})$ (given by (15)) is increasing in ρ, which indicates $m^*(s^*, \theta_{(1)}) < m^*(s^*, \theta_{(1)})|_{\rho=1} = \frac{\mu k}{1-k^2} = m_{\rm I}^*$.

Next compare the base model and benchmark II. Check that s^*, $m^*(s^*, \theta_{(1)})$ and $t^*(s^*, \theta_{(1)})$ are increasing, increasing and decreasing in ρ, respectively, and that the above decisions are identical with those of benchmark II if $\rho = \rho_{\rm II}$. Therefore, the comparison of the base model and benchmark II depends on the relationship between ρ and $\rho_{\rm II}$. Since ρ is decreasing in η_3 and $\eta_3 < x_3$, it follows that $\rho > \rho|_{\eta_3 = x_3} = \rho_{\rm II}$, indicating that $s^* > s_{\rm II}^*$, $m^* > m_{\rm II}^*$ and $t^* < t_{\rm II}^*$. □

Proof of Proposition 6: By (28)-(29), we obtain

$$\Delta_1 - \Delta_2 = \frac{\mu^2\alpha(1-\rho)[(\eta_2-\eta_3)^+ + \eta_1 - 2\eta_2 + x_3]}{2(1-k^2)} > 0,$$

which concludes the proof. □

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