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RESEARCH ARTICLE

On costless-renegotiation proofing in binary agency models

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Abstract

This paper analyzes the occurrence of renegotiation costs in dynamic, binary agency models with a risk-averse agent. I investigate technological interdependence arising from complementary tasks or substitutable tasks across periods. In addition, I analyze stochastic interdependence between periods. The analysis leads to two results. First, the timeliness of performance measures leads to zero costs from renegotiation. Surprisingly, timeliness may arise even in the case of stochastic interdependence. Second, neither technological nor stochastic interdependence is sufficient for renegotiation losses. The former finding is in line with results obtained in the LEN model, but the latter contrasts. In the binary agency model, renegotiation does not harm efficiency as long as raising incentives in the second period is ineffective for inducing higher effort in the first period.

JEL CLASSIFICATION

D86, M12, M41, M52

1 | INTRODUCTION

Employment contracts in business usually span several years, even though temporary employment is no exception. Long-term contractual relationships may be subject to renegotiation. Whenever contracting parties believe that mutual improvements are possible, there is no convincing reason to refrain from renegotiation. Unforeseeable contingencies represent one practical example in which parameters or events relevant to the contract cannot be reliably predicted or are unknown. Thus, they cannot become part of the initial contract but have to be dealt with during the contract term (if they eventuate). In contrast, foreseeable events could be accounted for in the initial contract, even if they are contingent on particular actions or factors.

However, a possible problem arises. The optimal way of including foreseeable events in the agreement may depend on the point in time during the contract term. For example, variable compensation may be tied to future performance to incentivize an employee to take actions

that foster the company's long-term performance. Yet high contingent incentives impose compensation risk on the employee. Therefore, as soon as long-term efforts are “sunk,” taking compensation risk off the (risk-averse) employee could be advantageous to both the employee and the company. In short, while high incentives are optimal ex ante before the employee takes long-term action, reduced incentives are optimal ex post.¹ This is problematic because the anticipation of renegotiation would dilute the effect of future incentives. Suppose the company was able to commit to the initial contract. In that case, the company could credibly announce not to renegotiate that contract and to stick to initially agreed-upon incentive rates. Consequently, the problem would disappear.

The announcement to refrain from renegotiation may not always be credible, and it is equivalent to stating the company's contractual commitment is limited. An obvious consequence is that some ex ante optimal contracts may be subject to renegotiation later. Thus, renegotiation effectively precludes the feasibility of those contracts. Less obvious is what causes renegotiation. The research question is what

characterizes settings that give rise to renegotiation, and what separates them from those where it is a nonissue? Which properties of tasks and performance measures lead to problems caused by renegotiation?

This paper aims to theoretically investigate causes for renegotiation and clarify when efficiency losses due to limited commitment occur. Efficiency losses arise because the possibility of renegotiation effectively restricts the set of contracts to those that are sequentially rational, i.e., renegotiation proof (Bolton, 1990; Fudenberg & Tirole, 1990). The literature analyzing limited commitment often uses the so-called LEN model (Christensen et al., 2002; Christensen et al., 2003; Indjejikian & Nanda, 1999; Schoendube, 2008). I deploy the binary agency model. In agency theory, the binary model is as popular as the LEN model is.² Given the (practical) importance of renegotiation, it is essential to identify and understand the drivers of its costs. Şabac (2015) comprehensively analyzes renegotiation effects in the LEN model and establishes conditions for costless-renegotiation proofing. A corresponding analysis for the binary agency model is lacking. My paper helps to fill this research gap. The investigation and its result are relevant to researchers and practitioners because the paper identifies task-related and situation-specific characteristics that give rise to an efficiency loss from (mutually beneficial) renegotiations. Therefore, the analysis in this paper can provide some guidance to the circumstances where accounting may help alleviate the problems caused by renegotiation, for example, by designing a performance measurement system with specific properties.

I consider a two-period agency model with binary action choice and outcome distribution in each period. The agent is risk-averse. No assumption is imposed concerning the specific functional form that displays risk aversion; therefore, results are general and not restricted to a particular utility function. I consider technological interdependence and stochastic interdependence between contracting periods. Both interaction effects are analyzed separately to carve out their individual “contribution” to renegotiation costs. Two findings stand out. First, stochastic interdependence never entails efficiency losses from renegotiation. Second, even with technological interdependence, renegotiation proofing can be costless. These are surprising results. They seem to stand in contrast to findings applicable to the LEN model. A closer look at the conditions of costly renegotiation proofing yields a commonality between the binary model and the LEN model. Renegotiation costs are unavoidable whenever future incentives can help to induce more effort in earlier periods.

My paper is closely related to Şabac (2015) as it supplements his analysis of renegotiation costs in the LEN model. Both papers complement each other and provide results on renegotiation costs for two widely deployed models in agency theory: the binary agency model and the LEN model. As Şabac (2015) shows, a necessary condition for renegotiation costs in the LEN model is that performance measures do not meet the “timeliness requirement.” Stated differently, the timeliness of performance measures leads to costless-renegotiation proofing in the LEN model (Şabac, 2015). The

timeliness condition corresponds to the sufficient statistic condition in Fudenberg et al. (1990). If the condition holds, outcomes in future periods do not provide information useful for inferring effort choices in earlier periods, that is, all information about effort in the current periods is included in the current period's performance measure(s). It ensures that asymmetric information at the time of renegotiation is not an issue, so renegotiation is costless. Timeliness possesses two dimensions: technological independence and stochastic independence of contract periods. Whenever the effect of the agent's effort is restricted to the current period and the noise terms across periods are uncorrelated—renegotiation proofing is costless. It is no surprise that timeliness is also sufficient for zero renegotiation costs in the binary agency model, as this paper shows. Therefore, the result is in line with Fudenberg et al. (1990) and Şabac (2015). However, the present paper demonstrates that the absence of timeliness need not imply costs from renegotiation. This result differs markedly from Şabac because, in the LEN model, the principal incurs costs from renegotiation along the equilibrium path with technological or stochastic interaction effects. Contrast this with the binary agency model. Here, stochastic interdependence is neither necessary nor sufficient for nonzero renegotiation costs. Technological interdependence is necessary but is not sufficient in that respect.

This paper is also related to the literature on commitment in long-term contracts. This literature has grown substantially in the recent past. Starting with the work by Hart and Tirole (1988), Bolton (1990), Fudenberg and Tirole (1990), and Fudenberg et al. (1990), many researchers analyzed the issue of limited commitment in a variety of settings. Analyses based on the LEN model include, for example, Indjejikian and Nanda (1999), Christensen et al. (2003), Schoendube (2008), Schoendube-Pirchegger and Schoendube (2017), and Christensen et al. (2020). The binary agency model provides the basis of analysis in Arya et al. (1997), Lukas (2010), and Ohlendorf and Schmitz (2012). A common feature of these contributions is that the model assumptions ensure commitment problems surface. The investigations center around finding substitutes for commitment, for example, intra-period aggregation of performance measures (Indjejikian & Nanda, 1999). In addition, they study differences between full-commitment contracts and limited-commitment contracts and consequences thereof, for example, inducing early or late effort if an agent's second-period productivity is not known *ex ante* (Schoendube, 2008). The models demonstrate that the principal's inability to commit to second-period incentive rates or bonuses causes renegotiation costs.³ This is common to both the LEN model and the binary agency model. However, as Şabac (2015) and this paper show, the circumstances differ under which that inability leads to an efficiency loss.

The paper's structure is as follows. Section 2 introduces the general model. The analysis of technological interdependence and stochastic interdependence between periods follows in Sections 3 and 4. I discuss results in Section 5. The final section summarizes and concludes.

2 | THE MODEL

I analyze a dynamic principal-agent relationship that lasts for two periods $t = 1, 2$. The long-term contract may be subject to renegotiation after the first period. On behalf of a principal (he), an agent (she) performs a task in each period. By assumption, the agent's unobservable effort is binary in each period, $e_t \in \{0, 1\}$, at costs $C(e_t) = ce_t, c > 0$. The verifiable economic outcome x_t in each period can be either high, H , or low, L . Effort influences the probability distribution of outcomes in the following way:

$$P(x_1 = H | e_1 = 1) > P(x_1 = H | e_1 = 0), \quad (1)$$

$$P(x_2 = H | e_1, x_1, e_2 = 1) > P(x_2 = H | e_1, x_1, e_2 = 0). \quad (2)$$

In the following sections, I specify the probabilities given by (1) and (2) so that they reflect the different interaction effects, which may be contingent on prior effort choices or outcomes. The specifications have two features in common: (i) In any given period, a higher effort increases the probability of a high outcome in that particular period; (ii) periods are interrelated. The interrelation is caused either by the first-period effort or the first-period outcome. An interrelation arising from effort is labeled technological interdependence. Stochastic interdependence refers to an interrelation that is due to the first-period outcome.

Due to the unobservability of the agent's effort, the principal offers outcome-contingent compensation to motivate the agent to expend high effort in each period. I assume a sufficiently valuable gross outcome in each period such that doing so is optimal for the principal; otherwise, the incentive problem becomes trivial. For each possible outcome sequence $(x_1 = i, x_2 = j), i, j \in \{L, H\}$, the principal specifies a payment s^{ij} for the agent. The corresponding probabilities $P(x_1 = i, x_2 = j | e_1, x_1, e_2) \equiv \pi_{e_1, e_2}^{ij}$ contingent on the agent's effort and the first-period outcome follow directly from (1) and (2).

To concentrate on costs of renegotiations (CRs), I assume zero discounting and no time preference, neither for the agent nor for the principal. The principal is risk-neutral, and the agent is risk-averse. Both strive for the maximization of their individual expected utility. Furthermore, the agent's utility from compensation and effort is separable.

To formalize the principal's program, let the agent's expected utility when selecting effort levels $e_1(e_2)$ in Period 1(2) be denoted:

$$E(U_{e_1, e_2(x_1)}) = \sum_{i,j} \pi_{e_1, e_2(x_1)}^{ij} \cdot u(s^{ij}) - c \cdot (e_1 + e_2(x_1)), i, j \in \{L, H\},$$

where $e_2(x_1)$ indicates that the agent selects effort in the second period being aware of the first-period outcome.

The principal demands that the agent expends high effort in each period. The principal's program obtains as follows:

$$\min_{s^{ij}} \sum_{i,j} \pi_{1,1}^{ij} s^{ij}, \quad i, j \in \{L, H\}, \quad (3)$$

subject to

$$E(U_{1,1(x_1)}) \geq \underline{u}, \quad (4)$$

$$E(U_{1,1(x_1)}) \geq E(U_{1,0(x_1)}), \quad (5)$$

$$E(U_{1,1(x_1)}) \geq E(U_{0,1(x_1)}), \quad (6)$$

$$E(U_{1,1(x_1)}) \geq E(U_{0,0(x_1)}). \quad (7)$$

To ensure the agent's participation given a reservation utility of \underline{u} , the individual rationality constraint (4) must be satisfied. Conditions (5)–(7) denote incentive compatibility constraints to make the agent prefer high effort in Periods 1 and 2 to all other effort combinations.

In the following sections, I analyze technological interdependence and stochastic interdependence between periods. Concerning technological interdependence, I distinguish between complementary tasks and substitutable tasks.⁴ The reason is the fundamentally different effect of the first-period effort on the likelihood of a high outcome in the second period. Given task complementarity (substitutability), more effort in Period 1 increases (decreases) that likelihood. For each setting, I compare the limited-commitment solution and the full-commitment solution.

The timeline in the agency is as follows:

- $t = 0$ Principal offers an initial two-period contract I to the agent, and the agent either accepts or rejects the contract. Rejecting the contract ends the agency.
- $t = 1$ Agent privately selects first-period effort e_1 .
- $t = 2$ Principal and agent observe first-period outcome x_1 , and the first-period payment is made according to contract I .
- $t = 3$ Limited commitment: Principal and agent renegotiate initial contract I and—if both agree—replace it by the renegotiated contract R . No renegotiation of I given full commitment.
- $t = 4$ Agent privately selects second-period effort e_2 .
- $t = 5$ Principal and agent observe second-period outcome x_2 , and the second-period payment is made according to contract I (full commitment) or R (limited commitment). Agency ends.

Given limited commitment, principal and agent sign a two-period contract I that may be subject to renegotiation after Period 1. Anticipating renegotiation leads to a renegotiation-proof contract R being signed at the beginning of the agency. Technically, the binding incentive compatibility constraint (5) characterizes the renegotiation-proof contract, that is, constraint (5) holds as equality in that contract.⁵ Given full commitment, principal and agent agree on a two-period contract that will not be subject to renegotiation after Period 1. Renegotiation is costless if the optimal contracts given full commitment and limited commitment show equal expected compensation costs.

3 | TECHNOLOGICAL INTERDEPENDENCE BETWEEN PERIODS

3.1 | Complementary tasks

To model complementary tasks, (1) and (2) are specified as follows:

$$P(x_1 = x^H | e_1) = p_{e_1}, \quad (8)$$

$$P(x_2 = x^H | e_1, e_2) = p_{e_1} \cdot q_{e_2}, \quad (9)$$

and the relations $p_{e_2=1} > p_{e_2=0}$ and $q_{e_2=1} > q_{e_2=0}$ hold. Effort in Period 1 has an impact on the second-period outcome. The high outcome in Period 2 becomes more likely with high effort than low effort in Period 1. As modeled in (9), effort choices in both periods are strategic complements (Bulow et al., 1985) because the marginal gain from first-period effort—measured as $P(x_2 = x^H | e_1 = 1, e_2) - P(x_2 = x^H | e_1 = 0, e_2)$ —is increasing in second-period effort e_2 and vice versa.⁶ Intuitively, one could consider the first-period effort as the initiation of an innovative project; if not properly executed, a high project outcome in Period 2 is less likely, and high effort in Period 2 will be less effective. Another example would be acquiring knowledge or new skills, which an employee will need in Period 2. If skills are not acquired, operating effort in Period 2 (again) will be less effective.

Given the specification in (8) and (9), the second-period incentive compatibility constraint (5) conditional on the first-period outcome x_i can be expressed in the following way:

$$p_1 q_1 u^{iH} + (1 - p_1 q_1) u^{iL} - c \geq p_1 q_0 u^{iH} + (1 - p_1 q_0) u^{iL}, i \in \{L, H\}. \quad (10)$$

3.1.1 | Full commitment

The virtue of full commitment can be exemplified by rearranging (10) so that

$$(u^{iH} - u^{iL}) = \frac{c}{p_1(q_1 - q_0)} + \nu^{iH}, \nu^{iH} \geq 0, i \in \{L, H\}. \quad (11)$$

Equation (11) represents the incentive compatibility constraints relevant in Period 2 conditional on outcome $x_1 = i$ in Period 1.⁷ Under full commitment, these constraints need not be fulfilled with equality (as is required under limited commitment), but the principal can commit ex ante to any second-period bonus or payment difference. Note that $\nu^{iH} = 0$ leads to $(u^{iH} - u^{iL}) = \frac{c}{p_1(q_1 - q_0)}$. The latter term is the minimum incentive to warrant selection of high effort by the agent in Period 2 following outcome $x_1 = i$. By setting $\nu^{iH} > 0$, the principal can shift incentives for high effort from Period 1 into Period 2, this potentially relaxes incentive compatibility constraints (6) or (7). The solution to (3) given full commitment is contract I specified by the following payments⁸:

$$u^{LL} = \underline{u} + 2c - p_1(u^{HL} - u^{LL}) - (\pi_{1,1}^{HH} + \pi_{1,1}^{LH}) \frac{c}{p_1(q_1 - q_0)} - \pi_{1,1}^{HH} \nu^{HH} - \pi_{1,1}^{LH} \nu^{LH}, \quad (12)$$

$$u^{HL} = u^{LL} + (u^{HL} - u^{LL}), \quad (13)$$

$$u^{LH} = u^{LL} + \frac{c}{p_1(q_1 - q_0)} + \nu^{LH}, \quad (14)$$

$$u^{HH} = u^{HL} + \frac{c}{p_1(q_1 - q_0)} + \nu^{HH}, \quad (15)$$

where ν^{LH} and ν^{HH} are optimally chosen,⁹ and

$$\begin{aligned} & (u^{HL} - u^{LL}) \\ & \frac{2c - (p_1 q_1 - p_0 q_0) \frac{c}{p_1(q_1 - q_0)} - (\pi_{1,1}^{HH} - \pi_{0,0}^{HH}) \nu^{HH} - (\pi_{1,1}^{LH} - \pi_{0,0}^{LH}) \nu^{LH}}{(p_1 - p_0)}, \end{aligned} \quad (16)$$

or

$$\begin{aligned} & (u^{HL} - u^{LL}) \\ & \frac{c - (p_1 q_1 - p_0 q_1) \frac{c}{p_1(q_1 - q_0)} - (\pi_{1,1}^{HH} - \pi_{0,1}^{HH}) \nu^{HH} - (\pi_{1,1}^{LH} - \pi_{0,1}^{LH}) \nu^{LH}}{(p_1 - p_0)}, \end{aligned} \quad (17)$$

depending on whether incentive compatibility constraint (7), that is, $E(U_{1,1(x_1)}) \geq E(U_{0,0(x_1)})$, or (6), that is, $E(U_{1,1(x_1)}) \geq E(U_{0,1(x_1)})$, binds, respectively. One may be puzzled by the fact that constraint $E(U_{1,1(x_1)}) \geq E(U_{0,0(x_1)})$ could bind instead of $E(U_{1,1(x_1)}) \geq E(U_{0,1(x_1)})$ if the second-period incentive constraint (11) is binding. To gain intuition, note that the (strategic) complements setting describes the combination of unique tasks. That is, tasks are not interchangeable. If one task has not been executed well, it does not pay to execute the other task well either. For example, suppose an employee does not acquire knowledge or skills relevant to success in Period 1. In that case, high productive effort in Period 2 will not be viable because preconditions for success are not met. It follows $E(U_{1,1(x_1)}) = E(U_{0,0(x_1)}) > E(U_{0,1(x_1)})$. However, if the informativeness of first-period performance is low, high incentives are needed to induce high effort in the first period. Due to the complementarity of effort choices, the principal can shift incentives for first-period effort into the second period; bonuses in the second period also induce first-period effort. The principal has the option to set $\nu^{iH} > 0$, and thus, raising $(u^{iH} - u^{iL}), i = L, H$ above the renegotiation-proof level according to (11). If this incentive shift leads to $(u^{iH} - u^{iL}) = \frac{c}{p_1(q_1 - q_0)} + \nu^{iH} \geq \frac{c}{p_0(q_1 - q_0)}$, the principal need not be concerned about low second-period effort because high effort is viable even if low effort (p_0) was chosen in Period 1. (Note the term p_0 in the denominator of $\frac{c}{p_0(q_1 - q_0)}$.) But then, it must hold $E(U_{1,1(x_1)}) = E(U_{0,1(x_1)}) > E(U_{0,0(x_1)})$.

3.1.2 | Limited commitment

The solution follows from setting $\nu^{LH} = \nu^{HH} = 0$ in (12)–(15); it specifies the payments in contract R . The relevant $(u^{HL} - u^{LL})$ -term is given by (16) since (7) represents the relevant incentive constraint, constraint (6) is slack. Equation (7) may be slack, too, implying $(u^{HL} - u^{LL}) = 0$. If (7) binds, $(u^{HL} - u^{LL}) > 0$.

3.1.3 | CRs

Given the task characteristics in this section, renegotiation is not, in general, costless. CRs manifest in a difference between expected compensation given limited commitment and full commitment.

Proposition 3.1. Assume tasks in Periods 1 and 2 are complements.

- (i) $p_0 \leq \frac{(2q_0 - q_1)p_1}{q_0}$ is sufficient such that CRs are zero: $CR = 0$.
- (ii) For $p_0 \in \left(\frac{(2q_0 - q_1)p_1}{q_0}, \max \left\{ 1 - \frac{(1-p_1)q_1}{q_0}, \frac{1+(1-2p_1)(q_1-q_0)}{q_0} \right\} \right)$, there exists a threshold level \hat{p}_0 such that $CR = 0 \Leftrightarrow p_0 \leq \hat{p}_0$, else $CR > 0$.
- (iii) $p_0 \geq \max \left\{ 1 - \frac{(1-p_1)q_1}{q_0}, \frac{1+(1-2p_1)(q_1-q_0)}{q_0} \right\}$ is sufficient such that $CR > 0$.

Proof. All proofs are presented in Appendix A1. \square

Proposition 3.1 states that CRs are zero as long as the interaction effect arising from task complementarity is sufficiently strong.¹⁰ Thus, the key to Proposition 3.1 is the severeness of the incentive problem in the first period. Equivalently, the strength of the interaction effect between periods is essential. Assume the principal can fully commit to a two-period contract. If the first-period incentive problem is “minor,” that is, p_0 is sufficiently small, task complementarity creates a strong interaction effect. Providing high effort in Period 1 increases the chances of succeeding substantially, not only in Periods 2 and 1. In this case, the principal can use second-period bonuses to induce effort in Periods 2 and 1. The analysis shows that second-period bonuses set at their renegotiation-proof level, $(u^{LH} - u^{LL}) = (u^{HH} - u^{HL}) = \frac{c}{p_1(q_1 - q_0)}$ suffice to induce high effort in Periods 2 and 1. It gives rise to the pay structure $u^{LL} = u^{HL} < u^{LH} = u^{HH}$ implying $(u^{HL} - u^{LL}) = 0$. No bonus is needed in Period 1 as an incentive to provide high effort in that period. Moreover, there is no need to provide additional effort incentives for period 1 by raising second-period incentives above the renegotiation-proof level. Consequently, the optimal full-commitment contract I is identical to the renegotiation-proof contract R . Thus, CRs are zero (case (i) in Proposition 3.1).

With p_0 increasing, the first-period incentive problem becomes more severe. At the same time, the interaction effect weakens. The principal reacts by offering $(u^{HL} - u^{LL}) > 0$ as an effort incentive in Period 1. Due to task complementarity, a second option exists given full commitment: The principal can raise second-period bonuses $(u^{LH} - u^{LL})$ and $(u^{HH} - u^{HL})$ above their renegotiation-proof level to

provide effort incentives for Period 1. By doing so, the allocation of incentives across periods could improve. As long as the first-period incentive problem is not severe, that is, $(p_1 - p_0)$ is sufficiently large, the option is not valuable, and CRs may continue to be zero (case (ii) in Proposition 3.1). For sufficiently severe incentive problems in Period 1, that is, when $(p_1 - p_0)$ is low or p_0 is large enough, the option is valuable. Exercising it reduces expected compensation costs for the principal. Lower compensation costs given full commitment in comparison to the limited-commitment contract imply strictly positive CRs (cases (ii) and (iii) of Proposition 3.1). These findings resemble the result in Fudenberg and Tirole (1990), where renegotiation takes place before all relevant information becomes available. In cases (ii) and (iii), the principal shifts incentives into the second period to provide incentives in the first period. Once the first-period effort is sunk, a mutually beneficial renegotiation is possible and can reduce the compensation risk the agent has to bear.

Table 1 exemplifies Proposition 3.1. Case 1 in Table 1 mirrors case (i) from Proposition 3.1. The interaction effect is strong. In addition, the performance measure available in Period 2 is less informative than the one in Period 1—measured based on the likelihood ratio $\frac{P(x_t=H|e_t=1) - P(x_t=H|e_t=0)}{P(x_t=H|e_t=1)}$, $t = 1, 2$. It necessitates comparably higher incentives in Period 2. Given the strong technological interdependence, second-period incentives spill back into the first period. Expected compensation costs do not differ between the full-commitment contract and the limited-commitment contract. Equality of compensation costs implies zero CRs. However, the interaction effect becomes weaker when moving from Cases 1 to 4. Consequently, first-period incentives—measured by $(u^{HL} - u^{LL})$ —must rise above zero. Yet, as evident in Case 2, renegotiation proofing can remain costless. Renegotiation entails additional costs only if $(p_1 - p_0)$ becomes sufficiently small (and the interaction effect sufficiently weak). Cases 3 and 4 in Table 1 show this for cases (ii) and (iii) of Proposition 3.1.

3.2 | Substitutable tasks

To model substitutable tasks based on (1) and (2), let effort influence the probability distribution of outcomes in the following way:

$$P(x_1 = x^H) = p_{e_1}, \quad (18)$$

$$P(x_2 = x^H) = (1 - p_{e_1}) \cdot q_{e_2}. \quad (19)$$

As before, higher effort increases the probability of the high outcome in any given period. However, the higher the effort in Period 1, the lower the probability of a high outcome in Period 2. This impact of first-period effort represents the substitution effect, and its extent depends on the probability of the high outcome in Period 1, p_{e_1} . To provide intuition for substitutable tasks, think of a performance evaluation setting. Meeting a performance target in one period (quarter or half-year etc.) may make it harder to achieve it in the next period because demand is limited or there exists only a specific performance potential for the whole time under consideration. For example, one can

| Commitment | Payments | Case 1 $p_0 = 0.1$ | Case 2 $p_0 = 0.5$ | Case 3 $p_0 = 0.7$ | Case 4 $p_0 = 0.8$ |
|------------|----------|-----------------------|-----------------------|-----------------------|-----------------------|
| Full | u^{LL} | 38.67 | 37.50 | 32.24 | 23.33 |
| | u^{HL} | 38.67 | 38.80 | 39.10 | 40.00 |
| | u^{LH} | 46.07 | 44.91 | 43.10 | 35.37 |
| | u^{HH} | 46.07 | 46.20 | 46.51 | 47.41 |
| | EC | 1947.06 | 1947.21 | 1950.06 | 1964.88 |
| Limited | u^{LL} | 38.67 | 37.50 | 33.00 | 24.00 |
| | u^{HL} | 38.67 | 38.80 | 39.30 | 40.30 |
| | u^{LH} | 46.07 | 44.91 | 40.41 | 31.41 |
| | u^{HH} | 46.07 | 46.20 | 46.70 | 47.70 |
| | EC | 1947.06 | 1947.21 | 1950.63 | 1970.96 |

Note: Parameters: $p_1 = 0.9, q_0 = 0.5, q_1 = 0.8, c = 2, \underline{u} = 40; u(s) = \sqrt{s}$.

TABLE 1 Complementary tasks: Optimal payments and expected compensation costs (EC)

think of a cost-reduction effort. Suppose the manager spends much effort cutting costs by trying several different cost-reducing measures in the year's first half. In that case, it becomes more difficult to reduce further costs in the year's second half (for given production levels).

Given the specification in (18) and (19), the second-period incentive compatibility constraint (5) conditional on outcome $x_1 = i$ in Period 1 obtains as

$$(1 - p_1)q_1 u^{iH} + [1 - (1 - p_1)q_1] u^{iL} - c \geq (1 - p_1)q_0 u^{iH} + [1 - (1 - p_1)q_0] u^{iL}, i \in \{L, H\}. \quad (20)$$

3.2.1 | Full commitment

The (possible) benefit of full commitment shows up in the rearranged version of (20):

$$(u^{iH} - u^{iL}) = \frac{c}{(1 - p_1)(q_1 - q_0)} + \nu^{iH}, \nu^{iH} \geq 0, i \in \{L, H\}. \quad (21)$$

Full commitment allows the principal to select $\nu^{iH} > 0$ so that constraint (20) will not be fulfilled with equality. Yet the optimal full-commitment contract shows $\nu^{iH} = 0, i = L, H$, implying (20) holds with equality. Therefore, the following payments characterize the optimal contract I :

$$u^{LL} = \underline{u} + 2c - \frac{p_1 c}{p_1 - p_0} - \frac{q_1 c}{(1 - p_1)(q_1 - q_0)}, \quad (22)$$

$$u^{HL} = u^{LL} + \frac{c}{p_1 - p_0} + q_1 \frac{c}{(1 - p_1)(q_1 - q_0)}, \quad (23)$$

$$u^{LH} = u^{LL} + \frac{c}{(1 - p_1)(q_1 - q_0)}, \quad (24)$$

$$u^{HH} = u^{HL} + \frac{c}{(1 - p_1)(q_1 - q_0)}. \quad (25)$$

3.2.2 | Limited commitment

Since incentive constraint (20)—relevant for effort selection in Period 2—holds with equality, the full-commitment contract represented by (22)–(25) is renegotiation proof. Hence, the optimal limited-commitment contract R is identical to the full-commitment contract I given by (22)–(25).

3.2.3 | CR

Since the full-commitment contract and the limited-commitment contract are identical, it immediately follows that renegotiation proofing is costless. The result is formally stated in Proposition 3.2.

Proposition 3.2. Assume tasks in Periods 1 and 2 are substitutes. Then, CRs are always zero.

To provide intuition for Proposition 3.2, note that higher effort in Period 1 decreases the chances of success in Period 2. Stated differently, lower effort in Period 1 increases the chances of success in Period 2. Therefore, any increase of either $(u^{HH} - u^{HL})$ or $(u^{LH} - u^{LL})$ above the sequentially rational, renegotiation-proof level requires even higher incentives $(u^{HL} - u^{LL})$ in Period 1. A cyclist competing for a stage victory illustrates the mechanism well.¹¹ Assume race organizers offer a small reward for the cyclist who leads the race at half-time and a substantially larger reward for the leader at the finish. The prospect of winning a high prize for stage victory leads the cyclist to reduce effort early on, for example, staying in the slipstream for as long as possible. If the prize for the stage winner rises, the incentive

to minimize effort early on becomes stronger. Hence, if race organizers want cyclists to compete for the reward at halftime, they also have to increase that reward.

Another practical example would be a sales manager. Meeting the sales target in the first quarter comes at the cost of lower chances to meet the target in the second quarter. If the reward for the second quarter increases, *missing* the performance target in Period 1 by withholding effort becomes more attractive as it translates into higher chances of receiving the increased reward in Period 2.¹² Hence, raising incentives in Period 2 requires an increase in incentives in Period 1.

4 | STOCHASTIC INTERDEPENDENCE

Let effort influence the probability distribution of outcomes in the following way:

$$P(x_1 = H) = p_{e_1}, \quad (26)$$

$$P(x_2 = H | x_1 = H) = g_{e_2}, \quad (27)$$

$$P(x_2 = H | x_1 = L) = b_{e_2}. \quad (28)$$

As evident from (27) and (28), the first-period outcome causes the interaction.¹³ The distributional assumption in (26)–(28) is very general. Consequently, quite different scenarios and interpretations of the setting are possible. For example, there could be a positive interaction between periods: $b_{e_2=1} \leq p_{e_1=1} < g_{e_2=1}$, so that second-period success becomes more likely with a success in Period 1. One can think of a bandwagon effect; a high realized demand in the first period indicates a high probability of attaining similar sales in the next period. In contrast, the model can also capture a negative interaction effect: $b_{e_2=1} \geq p_{e_1=1} > g_{e_2=1}$, and second-period success becomes less likely with a success in Period 1. If $p_{e_1=1} < b_{e_2=1} < g_{e_2=1}$, there is a positive trend, and success in Period 2 is generally more likely than in Period 1 (in a growing market).¹⁴

Based on the specification in (26)–(28), the second-period incentive constraint (5) can be reformulated as two separate constraints, each being contingent on a specific first-period outcome:

$$g_1 \cdot (u^{HH} - u^{HL}) + u^{HL} - c \geq g_0 \cdot (u^{HH} - u^{HL}) + u^{HL}, \quad (29)$$

$$b_1 \cdot (u^{LH} - u^{LL}) + u^{LL} - c \geq b_0 \cdot (u^{LH} - u^{LL}) + u^{LL}. \quad (30)$$

Equation (29) represents the relevant second-period incentive constraint following the high outcome in Period 1, and (30) the corresponding constraint following the low outcome in Period 1.

4.1 | Full commitment

If the principal can fully commit to a two-period contract, he can set:

$$(u^{HH} - u^{HL}) = \frac{c}{(g_1 - g_0)} \cdot \nu^{HH}, \nu^{HH} \geq 1, \quad (31)$$

$$(u^{LH} - u^{LL}) = \frac{c}{(b_1 - b_0)} \cdot \nu^{LH}, \nu^{LH} \geq 1, \quad (32)$$

so that second-period incentives may exceed the renegotiation-proof level if either $\nu^{HH} > 1$ or $\nu^{LH} > 1$.¹⁵ The optimal full-commitment contract I , however, shows $\nu^{HH} = \nu^{LH} = 1$. This leads to the following optimal payments if incentive constraints (5)–(7) jointly bind:

$$u^{LL} = \underline{u} + 2c - p_1 \frac{c}{p_1 - p_0} - \frac{b_1 c}{b_1 - b_0}, \quad (33)$$

$$u^{HL} = u^{LL} + \left[\frac{c}{p_1 - p_0} - \frac{g_1 c}{g_1 - g_0} + \frac{b_1 c}{b_1 - b_0} \right], \quad (34)$$

$$u^{LH} = u^{LL} + \frac{c}{b_1 - b_0}, \quad (35)$$

$$u^{HH} = u^{HL} + \frac{c}{g_1 - g_0}. \quad (36)$$

If (5) singly binds, these payments are optimal:

$$u^{LL} = \underline{u} + 2c - p_1 g_1 \frac{c}{g_1 - g_0} - (1 - p_1) b_1 \frac{c}{b_1 - b_0}, \quad (37)$$

$$u^{HL} = u^{LL}, \quad (38)$$

$$u^{LH} = u^{LL} + \frac{c}{b_1 - b_0}, \quad (39)$$

$$u^{HH} = u^{LL} + \frac{c}{g_1 - g_0}. \quad (40)$$

4.2 | Limited commitment

If the principal cannot commit to a two-period contract, $\nu^{HH} = \nu^{LH} = 1$ must hold in (31) and (32), respectively. Since the optimal full-commitment contract I features this property, the limited-commitment contract R and the full-commitment contract are identical.

4.3 | CRs

From the preceding analysis, it is clear that there are no CRs. I state this formally in the following proposition.

Proposition 4.1. Assume stochastic interdependence between Periods 1 and 2. Then, CRs are always zero.

The intuition for costless-renegotiation proofing is as follows: Raising $(u^{LH} - u^{LL})$ above the renegotiation-proof level increases the payoff for the outcome sequence $\{x_1 = L, x_2 = H\}$, other things equal. It makes low effort in period 1 more attractive because it is associated with a higher probability of achieving the low outcome $x_1 = L$ than high effort is. Consequently, raising $(u^{LH} - u^{LL})$ would require raising $(u^{HL} - u^{LL})$ to maintain incentive compatibility; therefore, it cannot be optimal.

Why does it not help either to raise $(u^{HH} - u^{HL})$ above the renegotiation-proof level? Raising $(u^{HH} - u^{HL})$ increases the expected return from selecting high effort instead of low effort in Period 1. To maintain expected utility at the reservation utility level, the principal could (i) reduce $(u^{LH} - u^{LL})$ or (ii) reduce $(u^{HL} - u^{LL})$. Option (i) requires that $(u^{LH} - u^{LL})$ is above the renegotiation-proof level (otherwise, one cannot reduce it without losing incentive compatibility). However, $(u^{LH} - u^{LL})$ being above its renegotiation-proof level has been argued to be non-optimal. Therefore, only option (ii) remains. Seizing that option leads to a reduction of u^{HL} accompanied by an increase in u^{HH} . It implies more variation in payments, which is costly given the agent's risk aversion. Hence, $(u^{HH} - u^{HL})$ is set at the renegotiation-proof level just as $(u^{LH} - u^{LL})$ —and the full-commitment contract is renegotiation proof.

An alternative way to explain the result builds on the fact that there exists “pure” stochastic interaction between periods—outcome probabilities in period 2 do not condition on first-period effort. (This contrasts with technological interdependence, where outcome probabilities in Period 2 are conditional on first-period effort.) One can interpret this as the timeliness of performance measures. Intuitively, one could be tempted to think that the outcome in the second period provides information about first-period effort because, from an ex ante perspective at the beginning of the agency, second-period outcomes are contingent on first-period effort (see footnote 13). Yet, as evident in (27) and (28), all information helpful in inferring the first-period effort is included in the performance measure available in the first period. In such a situation, raising second-period incentives above the renegotiation-proof level cannot lead to a better contract. Therefore, the result is similar to the one for the LEN model, where the timeliness of performance measures leads to zero renegotiation costs (Şabac, 2015).

5 | DISCUSSION OF RESULTS

The preceding analysis demonstrates that CRs do not regularly surface in binary (dynamic) agency models. First, stochastic interdependence between periods is neither necessary nor sufficient for CRs to occur. Second, technological interdependence between periods is necessary but not sufficient for CRs to occur; and third, a sufficient condition for zero CRs is stochastic and technological independence between periods.

Intuition for individual results is provided in the sections above and does not need to be repeated. Instead, a unifying intuitive explanation for costless-renegotiation proofing follows. One can think of a

firm's two-period project, and compensation for the person in charge depends on initial performance and performance in the final project period. In addition, assume a compensation consultant advises the firm based on this paper concerning a refinement of the compensation scheme. When would the recommendation be *not* to increase the bonus for the final period of the project? The consultant would recommend no increase if the “final bonus” already provides the employee with enough incentives to work hard in the initial period or if raising the “final bonus” does harm rather than good in terms of effort incentives in the initial period. And these two instances correspond to those settings where renegotiation proofing of an initial incentive-compatible contract is costless.

Starting with the result concerning stochastic interaction in Proposition 4.1, the fact that timely performance measurement does not lead to renegotiation costs is already known from work by Fudenberg et al. (1990). The result in the present paper is still surprising to some extent because the agent's performance in Period 1 depends on her effort choice, and first-period performance determines the chances to succeed in Period 2.¹⁶ Stated differently, while a setting with timely performance measurement cannot give rise to costs from renegotiation (Fudenberg et al., 1990; Şabac, 2015), timeliness itself may not always be evident. In the LEN model, the timeliness of performance measures requires technological and stochastic independence. In the binary agency model, the latter is not necessary. So even if there is stochastic interdependence, the sufficient statistic condition is met so that long-term contracts do not have value.

Technological interdependence can lead to efficiency losses from renegotiation in the binary agency model. Losses occur only in settings with complementary tasks but never if tasks are substitutes. Thus, whenever higher first-period effort positively (negatively) affects the chances of success in the second period, renegotiation can be costly (is costless). It points to another difference between the binary and LEN model regarding renegotiation costs, which deserves attention. Consider the LEN model as in Christensen et al. (2003) with independent effort but a positive correlation of error terms across periods. It seems to generate an effect similar to this paper's setting of substitutable tasks. A high positive correlation between the performance measure noise terms generates a high negative impact of first-period effort on second-period performance.¹⁷ While this leads to renegotiation costs in the LEN model, it does not lead to such costs in the binary model. The different results follow from the specific source of the interaction effect. In the LEN model, the effect is due to the correlation of error terms; in this paper's model, the effect follows from higher effort directly.

A notable difference between the setups in the binary model and the LEN model exists, which one should not overlook. The optimal sequence of actions is ex ante fixed in the binary model, but it is subject to optimization in the LEN model. One could say that the binary agency model comes with (an implicit) commitment to actions. Still, bonuses in the second period may or may not be committed to by the principal. The former means the principal can commit to actions along the equilibrium path. In the LEN model, given the multitude of possible effort choices in the second period, there is a difference between

(i) commitment to actions and (ii) actions induced along the equilibrium path. According to Şabac (2015, p. 3), “[r]enegotiation changes both how information is used efficiently ex post and the optimal actions to be induced.” Therefore, he distinguishes between (i) and (ii). In (i), the focus is on efficient contracts; in (ii), optimal contracts take center stage. Introducing the renegotiation option in (i) and (ii) may lead to different effects. As Şabac (2015) demonstrates, there could be no loss from renegotiation in (i) but a loss in (ii) given an otherwise identical setting. For example, a long-term effect of first-period effort is innocuous in (i) but not in (ii), given an equal number of performance measures and tasks in the second period. Nevertheless, settings (i) and (ii) and the binary model share the same sufficient condition for costless renegotiation. It is the timeliness of performance measures, that is, the absence of technological and stochastic interdependence.

A comparison of the LEN model in setting (i) with the binary model appears necessary, given that both feature a commitment to actions. Assume the principal can commit to exogenously given actions in the LEN model. A sufficient condition for zero renegotiation costs is that there are as many tasks as performance measures in the second period (Şabac, 2015, Proposition 3).¹⁸ It points to another notable difference between the binary and LEN model. With a commitment to actions and equal numbers of actions and performance measures in the second period, renegotiation costs are always zero in the LEN model. However, they can be larger than zero in the binary model (if tasks are complements). In the LEN model, the commitment to actions requires a unique set of weights attached to performance measures in the second period, which becomes a part of the initial contract. Thus, whatever the realizations of first-period performance measures are, there is no scope to negotiate a better (more efficient) contract after the first period. In contrast, in the binary model, the initial contract may include slack in second-period incentive constraints, offering an opportunity for a mutually beneficial renegotiation after the first period.

Finally, one could conjecture whether and when an endogenous action choice entails a loss from renegotiation in the binary model. If there are n action levels, $e_{i0} < e_{i1} < \dots < e_{i(n-1)}$, in each period, the principal optimizes over actions to be implemented by the contract. In the binary agency model, implementing high effort is assumed to be optimal because otherwise, the incentive problem would vanish. Now, one can assume that $\{e_{1i}, e_{2j}(e_{1i}, x_1 = H), e_{2k}(e_{1i}, x_1 = L)\}$, $i, k, j \in \{0, 1, 2, \dots, n-1\}$ represent the optimal effort levels in Periods 1 and 2 contingent on the first-period effort. As in the binary model, the principal has the option to set bonuses in Period 2 that include slack in the corresponding incentive constraints, that is, bonuses that are higher than incentive compatibility requires to induce $\{e_{2j}(e_{1i}, x_1 = H), e_{2k}(e_{1i}, x_1 = L)\}$. Based on results derived in the previous section for substitutable tasks and stochastic interdependence, including slack in the initial contract does not appear useful in this more general model setup. The reason is that the same interaction effects between periods are present. Consider the following example with substitutable tasks. Assume e_{14} is to be induced in the first period and e_{23} in the second period, irrespective of the first-period outcome. Setting bonuses in Period 2 above sequentially rational

levels would force the principal to raise the first-period bonus to preserve incentive compatibility in that period. This intuitive reasoning applies to any combination of effort levels to be induced in Periods 1 and 2. Thus, the results from above will likely stand. It implies zero CRs in these two settings. If tasks are complements, the principal likely benefits from raising bonuses above sequentially rational levels, contingent on low informativeness of the first-period outcome, just as the principal does in the binary model. Hence, the principal may be unable to avoid an efficiency loss as soon as renegotiation becomes possible in a setting with complementary tasks.

6 | SUMMARY AND CONCLUSION

This paper investigates renegotiation proofness in the binary agency model. Both technological interdependence and stochastic interdependence between periods are analyzed. I impose no particular assumption concerning the functional form that displays the agent's risk aversion. Thus, results hold for any possible utility function provided it captures risk aversion.

Renegotiation proofness does not affect efficiency as long as raising second-period incentives is ineffective for inducing higher effort in the first period. This ineffectiveness arises if (i) tasks across periods are substitutes so that higher effort in the first period reduces the probability of success in the second period, if (ii) the interaction between periods is restricted to stochastic effects, or if (iii) neither technological nor stochastic interaction is present. The latter condition matches the sufficient condition to avoid renegotiation costs in the LEN model. The timeliness of performance measures ensures zero renegotiation costs. Surprisingly, timeliness may result in the binary agency model even with stochastic interaction effects.

Besides the expected commonality that timeliness of performance measures precludes costs from renegotiation, the comparison between the binary model and the LEN model yields another commonality. Technological or stochastic interdependence is necessary but not sufficient for losses from renegotiation to occur. This finding crucially depends on the (rarely made) assumption that the principal can commit to actions in the LEN model; the assumption is usually implicit in the binary model. Given that technological or stochastic interaction effects are present in the LEN model and the binary model, one can state that renegotiation costs are unavoidable whenever properly setting second-period incentives can help to induce more effort in the first period. Despite the differences in the models and their assumptions, they are comparable regarding the cause of renegotiation costs.

In sum, the paper demonstrates that technological or stochastic interactions between contract periods do not always imply an efficiency loss from renegotiation in the binary agency model. The nature of the agent's tasks and their corresponding effects on the outcome distributions determine whether or not a possible renegotiation constrains the set of feasible contracts. If it does so, it signals that substitutes for commitment, for example, the aggregation of performance measures or a modification of task assignments may be needed.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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ENDNOTES

- ¹ As Bolton (1990, p. 304) puts it: "In order to achieve ex ante efficiency, one generally needs to specify ex post outcomes that are Pareto inefficient."
- ² For example, the well-established textbooks by Christensen and Demski (2002) and Demski (2010) use the binary agency model.
- ³ Şabac (2015, Fn. 5) suggests a different cause. According to Şabac (2015), the source of renegotiation costs is the limited commitment to actions instead of what is usually concluded to be the source-limited commitment to future incentive rates. One could argue that a commitment to actions requires a commitment to incentive rates because actions are not contractible. It follows that a commitment to actions is inextricably tied to a commitment to incentives rates. If one is lacking, it implies the other is lacking as well, and costs of renegotiation (CRs) may arise.
- ⁴ Work by Nikias et al. (2005) and Lukas (2010) deploy these task scenarios in their binary agency models.
- ⁵ In order to find the equilibrium contract, it is without loss of generality to focus on renegotiation-proof contracts (Fudenberg & Tirole, 1990).
- ⁶ Results do not change qualitatively, if tasks are strategic substitutes. For example, if $P(x_2 = x^H) = [p_{e_1} + (1 - p_{e_1}) \cdot q_{e_2}]$, the marginal gain of first-period effort decreases in second-period effort, and vice versa. Yet complementarity of effort choices remains in effect because higher effort in Periods 1 and 2 increases the probability of the high outcome in Period 2.
- ⁷ It is also called sequential rationality constraint (Baron & Besanko, 1987).
- ⁸ See Appendix A1 for the derivation of all payment schemes.
- ⁹ To explicitly determine these parameters would require an optimization stage with much more exposition and case discriminations between parameters. Since the proofs rely on different rankings of payments given full commitment and limited commitment, their precise levels need not be determined.
- ¹⁰ Instead of (2), a more general way to model task complementarity would be to assume $P(x_2 = x^H) = p_{e_1}^\alpha q_{e_2}$, where $\alpha \in [0, 1]$ indicates the degree of complementarity. (Parameter α is equal to one in 2.) Setting $P(x_2 = x^H) = (1/\kappa) \cdot p_{e_1} q_{e_2}$, $\kappa \in [p_{e_1}, 1]$, would be a linear version of that general way, and κ measures the degree of complementarity. Using it in the model leads to a qualitatively similar result. With an increasing degree of complementarity, that is, κ increasing, the threshold level \hat{p}_0 in Proposition 3.1 is decreasing. Conversely, with κ reaching its minimum value p_{e_1} , complementarity vanishes, periods are independent, and the threshold equals $\hat{p}_0 = p_1$, so that renegotiation is costless for all p_0 .
- ¹¹ The example is adapted from Nikias et al. (2005, pp. 54–55).

- ¹² Work by Bouwens and Kroos (2011) provides empirical evidence for this employee conduct.
- ¹³ It should be noted that the ex ante probability (before Period 1) of a high outcome in Period 2 depends on first-period effort, that is, $P(x_2 = H|e_1, e_2) = p_{e_1} g_{e_2} + (1 - p_{e_1}) b_{e_2}$. This dependency is an inevitable consequence of the incentive problem in Period 1. However, after Period 1, the probability of a high outcome in Period 2 is independent from prior effort choices so that only second-period effort is relevant, as (27) and (28) show.
- ¹⁴ One could easily extend the list. Setting $g_{e_2} = b_{e_2}$ creates the boundary case of stochastic independence, and it would be on a par with the special case of no complementarity mentioned in footnote 10.
- ¹⁵ For purposes of exposition, the benefit of full commitment is slightly differently modeled than in sections before.
- ¹⁶ Work by Lukas (2023), who uses a similar model setup, also suggests that the effect of stochastic interaction may not be obvious. He investigates whether frequent evaluation (performance evaluation in each period) or infrequent evaluation (performance evaluation once at the end of Period 2) is optimal. He finds that frequent evaluation can be optimal even if one assumes risk neutrality for principal and agent, and the agent is protected by limited liability.
- ¹⁷ The author thanks Florin Şabac for suggesting this way to clarify the different costs for renegotiation proofing.
- ¹⁸ If the number of performance measures exceeds the number of tasks in the second period, CRs can arise even with a commitment to actions because contingent on realized performance measures in the first period, different combinations and weights of performance measures in the second period could be optimal. Efficiency losses from renegotiation cannot occur if performance information concerning first-period effort is timely.
- ¹⁹ See, for example, Rothschild and Stiglitz (1970) or Shaked-and-Shantikumar (1994, Ch. 2).
- ²⁰ Setting $(u^{LH} - u^{LL}) = (u^{HH} - u^{HL}) = \frac{c}{p_1(q_1 - q_0)}$, that is, at the renegotiation-proof level, and setting $(u^{HL} - u^{LL}) = 0$ leads to the following conditions such that constraints (6) and (7) are slack:

$$\begin{aligned} \frac{q_1}{q_1 - q_0} &\geq \frac{p_1}{p_1 - p_0} \\ \frac{q_0}{q_1 - q_0} &\geq \frac{p_1}{p_1 - p_0} \Leftrightarrow p_0 \leq \frac{(2q_0 - q_1)p_1}{q_0}. \end{aligned}$$

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APPENDIX A

A.1 | Derivation of payments: Complementary tasks

For convenience, the principal's program is restated:

$$\min_{s^i} \sum_{i,j} \pi_{1,1}^{ij} s^{ij}, \quad (\text{A1})$$

subject to

$$E(U_{1,1}(x_1)) \geq 0, \quad (\text{A2})$$

$$E(U_{1,1}(x_1)) \geq E(U_{0,0}(x_1)), \quad (\text{A3})$$

$$E(U_{1,1}(x_1)) \geq E(U_{0,1}(x_1)), \quad (\text{A4})$$

$$p_1 q_1 u^{HH} + (1 - p_1 q_1) u^{HL} - c \geq p_1 q_0 u^{HH} + (1 - p_1 q_0) u^{HL}, \quad (\text{A5})$$

$$p_1 q_1 u^{LH} + (1 - p_1 q_1) u^{LL} - c \geq p_1 q_0 u^{LH} + (1 - p_1 q_0) u^{LL}. \quad (\text{A6})$$

Conditions (A5) and (A6) represent a reformulation of incentive compatibility constraint (5) conditioned on the specific first-period outcome, $x_1 = L, H$.

To examine whether incentive constraint (A3) or incentive constraint (A4) is slack (given optimal payments), relation

$$[E(U_{0,1}(x_1)) - E(U_{0,0}(x_1))] \geq 0. \quad (\text{A7})$$

can be used.

A.1.0.1 | Limited commitment

Given limited commitment, (A5) and (A6) must hold with equality implying $(u^{HH} - u^{HL}) = (u^{LH} - u^{LL}) = \frac{c}{p_1(q_1 - q_0)}$. Equation (A7) simplifies to

$$p_0 [p_0 (q_1 - q_0) (u^{HH} - u^{HL})] + (1 - p_0) [p_0 (q_1 - q_0) (u^{LH} - u^{LL})] - c \geq 0, \quad (\text{A8})$$

and then to

$$\left(\frac{p_0}{p_1}\right) \cdot c - c < 0. \quad (\text{A9})$$

Given (A9), it follows that the term in brackets in (A7) is negative. This implies $E(U_{0,0}(x_1)) \geq E(U_{0,1}(x_1))$ so that (A3) potentially binds but (A4) is always slack. If (A3) is slack, it implies $(u^{HL} - u^{LL}) = 0$ and (5) singly binds or the corresponding constraints (A5) and (A6) bind, respectively. If (A3) binds, using $(u^{HH} - u^{HL}) = (u^{LH} - u^{LL}) = \frac{c}{p_1(q_1 - q_0)}$ allows for determining $(u^{HL} - u^{LL})$. Finally, substituting the optimal bonuses into participation constraint (A2) is necessary to determine optimal payments.

A.1.0.2 | Full commitment

The principal may set

$$(u^{iH} - u^{iL}) = \frac{c}{p_1(q_1 - q_0)} + \nu^{iH}, \nu^{iH} > 0, i = L, H; \quad (\text{A10})$$

that is, (A5) and (A6) will hold as strict inequality. Substituting (A10) into (A7) leads to

$$p_0 \left[p_0(q_1 - q_0) \left(\frac{c}{p_1(q_1 - q_0)} + \nu^{HH} \right) \right] + (1 - p_0) \left[p_0(q_1 - q_0) \left(\frac{c}{p_1(q_1 - q_0)} + \nu^{LH} \right) \right] - c \geq 0. \quad (\text{A11})$$

As long as the left-hand side of (A11) is negative, (A3) continues to bind, and (A4) is slack. Then, optimal state-contingent payments obtain by plugging in (A10) into (A3), that is, $E(U_{1,1}) = E(U_{0,0})$, and the binding participation constraint (A2). If the left-hand side of (A11) is positive, (A4) binds and (A3) is slack. Then, substitute correspondingly to obtain optimal state-contingent payments.

A.1.1 | Proof of Proposition 3.1

A.1.1.1 | Mean-preserving spread criterion

I (mostly) rely on the mean-preserving spread criterion for convex functions to prove costless-renegotiation proofing—if this exists. In this case, it will be shown that any *feasible* full-commitment compensation contract that is *not* renegotiation proof represents a mean-preserving spread of the renegotiation-proof contract under limited commitment. Hence, the *optimal* full-commitment contract must be renegotiation proof, implying zero renegotiation costs.

It is useful to expound the substance of this criterion briefly.¹⁹ Let

$$\mathcal{P} \equiv \{u^{LL}, u^{HL}, u^{LH}, u^{HH}\}$$

be an incentive scheme characterized by state-contingent payments $\{u^{LL}, u^{HL}, u^{LH}, u^{HH}\}$, where $u^{ij} \equiv u(s^{ij})$, and corresponding probabilities $\pi_{e_1, e_2}^{ij}, i, j \in \{L, H\}$, such that the agent, in expectation, receives the reservation utility, $E[U(\mathcal{P})] = \sum_{ij} \pi_{e_1, e_2}^{ij} u^{ij} = \underline{u}, i, j = \{L, H\}$ conditional on selecting $e_1 = e_2 = 1$. Expected compensation costs K amount to:

$$K(\mathcal{P}) \equiv E[H(U(\mathcal{P}))] = \sum_{ij} \pi_{e_1, e_2}^{ij} h(u^{ij}),$$

where $h(u^{ij})$ is the inverse of the utility function $u(s^{ij})$ and, thus, is a convex function. Accordingly, let $\hat{\mathcal{P}} = \{\hat{u}^{LL}, \hat{u}^{HL}, \hat{u}^{LH}, \hat{u}^{HH}\}$ be an alternative incentive scheme such that $E[U(\hat{\mathcal{P}})] = \underline{u}$ and $K_{\hat{\mathcal{P}}} \equiv E[H(\hat{\mathcal{P}})] = \sum_{ij} \pi_{e_1, e_2}^{ij} h(\hat{u}^{ij})$. If $\hat{\mathcal{P}}$ is a mean-preserving spread of \mathcal{P} , $K(\mathcal{P}) \leq K(\hat{\mathcal{P}})$ holds. The more variation in payments, the higher are expected compensation costs for offering the agent a contract that provides her with the reservation utility.

A.1.1.2 | Proof of proposition

Case (i). If $p_0 \leq \frac{(2q_0 - q_1)p_1}{q_0}$, incentive constraint (5) singly binds and both (6) and (7) are slack (see 16 and the derivation in Appendix A.1).²⁰

In this case, raising $(u^{LH} - u^{LL}) = (u^{HH} - u^{HL})$ above their renegotiation-proof level can—at best—further relax constraints (6) or (7). However, it cannot be beneficial, that is, lead to lower expected compensation costs, since the two constraints are already slack (and it is impossible to reduce further $(u^{LH} - u^{LL})$, which is zero given the assumed pay structure). Therefore, full commitment cannot lead to lower expected compensation costs than limited commitment.

Case (iii). $u^{LL} < u^{LH} < u^{HL} < u^{HH}$ holds in the renegotiation-proof contract \mathcal{P}_{LC} if $p_0 > \frac{1 + (1 - 2p_1)(q_1 - q_0)}{q_0}$. Now, raise $(u^{LH} - u^{LL}) = \frac{c}{p_1(q_1 - q_0)}$ above its renegotiation-proof level and set

$$(u^{LH'} - u^{LL'}) = \frac{c}{p_1(q_1 - q_0)} + \nu^{LH}, \nu^{LH} > 0, \quad (\text{A12})$$

in a feasible full-commitment contract $\mathcal{P}_{FC} \equiv \{u^{LL'}, u^{LH'}, u^{HL'}, u^{HH'}\}$. Sustaining the same level of expected utility, effects of (A12) on state-contingent utility levels are as follows:

$$u^{LL'} = u^{LL} + \delta^{LL}, \quad (\text{A13})$$

$$u^{LH'} = u^{LH} + \delta^{LH} = u^{LH} + \delta^{LL} + \nu^{LH}, \quad (\text{A14})$$

$$u^{HL'} = u^{HH} + \delta^{HL} = u^{HL} + \delta^{LL} - \frac{\pi_{11}^{LH} - \pi_{00}^{LH}}{p_1 - p_0} \nu^{LH}, \quad (\text{A15})$$

$$u^{HH'} = u^{HH} + \delta^{HH}, \quad (\text{A16})$$

where $\delta^{LL} = \left[\frac{p_1}{p_1 - p_0} (\pi_{11}^{LH} - \pi_{00}^{LH}) - \pi_{11}^{LH} \right] \cdot \nu^{LH}$ and $\delta^{HH} = \delta^{HL}$. Simplifying the δ -terms gives

$$\delta^{LL} = \left[\frac{p_0 p_1 [(1 - p_1)q_1 - (1 - p_0)q_0]}{p_1 - p_0} \right] \cdot \nu^{LH} \geq 0 \Leftrightarrow p_0 \geq 1 - (1 - p_1) \frac{q_1}{q_0}, \quad (\text{A17})$$

$$\delta^{LH} = \delta^{LL} + \nu^{LH} = \left[\frac{p_0 p_1 [(1 - p_1)q_1 - (1 - p_0)q_0 + p_1 - p_0]}{p_1 - p_0} \right] \cdot \nu^{LH} > 0, \quad (\text{A18})$$

$$\delta^{HL} = \frac{(1 - p_0)(1 - p_1)(p_1 q_1 - p_0 q_0)}{p_1 - p_0} \nu^{LH} < 0, \quad (\text{A19})$$

$$\delta^{HH} = \delta^{HL} < 0. \quad (\text{A20})$$

Obviously, if $\delta^{LL} > 0$, then $\delta^{LH} > 0$. ($\delta^{LH} > 0$ always holds because the nominator is positive for both $p_0 \rightarrow 0$ and $p_0 \rightarrow p_1$ and because it is monotone in p_0 .) If $\delta^{LL} > 0$, (A17)–(A20) show that \mathcal{P}_{LC} is a mean-preserving spread of \mathcal{P}_{FC} . Hence,

$$K(\mathcal{P}_{FC}) = \sum_{ij} \pi^{ij} h(u^{ij}) < K(\mathcal{P}_{LC}) = \sum_{ij} \pi^{ij} h(u^{ij}),$$

and renegotiation is not costless. \mathcal{P}_{FC} characterized by (A13)–(A16) may not be optimal, but it shows that full commitment allows for a better contract than limited commitment.

Case (ii). Since the conditions in (i) and (iii) are sufficient such that renegotiation is costless (i) or costly (iii), for any $p_0 \in \left(\frac{(2q_0 - q_1)p_1}{q_0}, \max\left\{1 - \frac{(1-p_1)q_1}{q_0}, \frac{1+(1-2p_1)(q_1-q_0)}{q_0}\right\}\right)$, renegotiation may be costly or not. It depends on whether raising $(u^{LH} - u^{LL}) = (u^{HH} - u^{HL})$ above their renegotiation-proof level can now relax incentive constraint (7) and, thus, can prove beneficial. As evident from (16), the payment difference $(u^{HH} - u^{HL})$ required to satisfy incentive constraint (7) under limited commitment is increasing in p_0 . (Note that $\nu^{HH} = \nu^{LH} = 0$ under limited commitment.) That is, the incentive constraint is tightened as p_0 increases. Hence, if raising $(u^{LH} - u^{LL}) = (u^{HH} - u^{HL})$ above their renegotiation-proof level becomes optimal for a specific \hat{p}_0 , it must be optimal for any $p_0 \geq \hat{p}_0$.

A.2 | Derivation of payments: Substitutable tasks

A.2.1 | Limited commitment

In this setting, the incentive compatibility constraint(s) relevant for the effort choice in Period 2 (21) is binding. Therefore,

$$(u^{HH} - u^{HL}) = (u^{LH} - u^{LL}) = \frac{c}{(1-p_1)(q_1-q_0)}.$$

Substituting this expression in constraint (6), $(u^{HL} - u^{LL})$ is obtained. By substituting in $(u^{HH} - u^{HL})$, $(u^{HL} - u^{LL})$ and $(u^{LH} - u^{LL})$ into participation constraint (4), payments given in (22)–(25) result. It is readily verified that constraint (7) is slack given these payments. Hence, \mathcal{P}_{LC} given by (22)–(25) is optimal.

A.2.2 | Full commitment

Let $\mathcal{P}_{FC} \equiv \{u^{LL}, u^{LH}, u^{HL}, u^{HH}\}$ be a feasible full-commitment contract that ensures the agent her reservation utility \underline{u} . Assume

$$(u^{HH} - u^{HL}) = \frac{c}{(1-p_1)(q_1-q_0)} + \nu^{HH}, \nu^{HH} > 0, \quad (\text{A21})$$

so that $(u^{HH} - u^{HL})$ is not renegotiation proof. As a consequence, state-contingent payments in contracts \mathcal{P}_{LC} and \mathcal{P}_{FC} differ, which implies

$$u^{LL'} = u^{LL} + \delta^{LL'}, \quad (\text{A22})$$

$$u^{LH'} = u^{LH} + \delta^{LH'}, \quad (\text{A23})$$

$$u^{HL'} = u^{HH} + \delta^{HL'}, \quad (\text{A24})$$

$$u^{HH'} = u^{HH} + \delta^{HH'}. \quad (\text{A25})$$

Given (A21), the δ -terms in (A22)–(A25) can be determined:

$$\delta^{LL'} = -p_0 p_1 q_1 \cdot \nu^{HH} < 0, \quad (\text{A26})$$

$$\delta^{LH'} = \delta^{LL'} < 0, \quad (\text{A27})$$

$$\delta^{HL'} = -(1-p_0)(1-p_1)q_1 \cdot \nu^{HH} < 0, \quad (\text{A28})$$

$$\delta^{HH'} = -(1-p_0)(1-p_1)q_1 + 1 \cdot \nu^{HH} > 0. \quad (\text{A29})$$

Given (A26)–(A29), \mathcal{P}_{FC} represents a mean-preserving spread of \mathcal{P}_{LC} so that $K(\mathcal{P}_{FC}) > K(\mathcal{P}_{LC})$. Hence, setting $\nu^{HH} > 0$ cannot be optimal.

Assume now a feasible full-commitment contract $\mathcal{P}_{FC} \equiv \{u^{LL*}, u^{LH*}, u^{HL*}, u^{HH*}\}$ shows

$$(u^{LH*} - u^{LL*}) = \frac{c}{(1-p_1)(q_1-q_0)} + \nu^{LH}, \nu^{LH} > 0, \quad (\text{A30})$$

so that $(u^{LH*} - u^{LL*})$ is not renegotiation proof. Proceeding in the same way as before, the δ -terms amount to

$$\delta^{LL*} = -(1-p_0 p_1)q_1 \cdot \nu^{LH} < 0, \quad (\text{A31})$$

$$\delta^{LH*} = -(1-p_0 p_1)q_1 + 1 \cdot \nu^{LH} > 0, \quad (\text{A32})$$

$$\delta^{HL*} = (1-p_0)(1-p_1)q_1 \cdot \nu^{LH} > 0, \quad (\text{A33})$$

$$\delta^{HH*} = (1-p_0)(1-p_1)q_1 \cdot \nu^{LH} > 0. \quad (\text{A34})$$

Given (A31)–(A34), \mathcal{P}_{FC} represents a mean-preserving spread of \mathcal{P}_{LC} so that $K(\mathcal{P}_{FC}) > K(\mathcal{P}_{LC})$. Hence, setting $\nu^{LH} > 0$ cannot be optimal.

Taken together, neither setting $\nu^{LH} > 0$ nor setting $\nu^{HH} > 0$ is optimal. It follows that $\nu^{LH} = \nu^{HH} = 0$ is optimal, implying the optimal full-commitment contract is identical to the optimal–renegotiation proof–limited-commitment contract.

A.3 | Proof of Proposition 3.2

The proof follows from Appendix A.2.

A.4 | Derivation of payments: Stochastic interdependence

A.4.1 | Limited commitment

The derivation is straightforward and, therefore, omitted. Depending on whether incentive constraints (5)–(7) jointly bind or incentive constraint (5) singly binds, either \mathcal{P}_{LC} given by (33)–(36) is optimal or \mathcal{P}_{LC}

given by (37)–(40). It can be shown that whenever (5) and (6) jointly bind, (7) is binding, too.

A.4.2 | Full commitment

Let $\mathcal{P}_{FC} \equiv \{u^{LL}, u^{LH}, u^{HL}, u^{HH}\}$ represent a feasible full-commitment contract. First, assume incentive constraints (5)–(7) jointly bind. Rearranging incentive constraint (6) gives

$$(u^{HL} - u^{LL}) = \frac{c}{p_1 - p_0} - g_1(u^{HH} - u^{HL}) + b_1(u^{LH} - u^{LL}).$$

Plugging in into the participation constraint (4) gives, after properly rearranging terms,

$$\begin{aligned} u^{LL} &= 2c - p_1 \frac{c}{p_1 - p_0} - b_1(u^{LH} - u^{LL}), \\ u^{HL} &= c - p_1 \frac{c}{p_1 - p_0} - g_1(u^{HH} - u^{HL}), \\ u^{LH} &= 2c - p_1 \frac{c}{p_1 - p_0} + (1 - b_1)(u^{LH} - u^{LL}), \\ u^{HH} &= c - p_1 \frac{c}{p_1 - p_0} + (1 - g_1)(u^{HH} - u^{HL}). \end{aligned}$$

Now, substitute in (31) and (32) to obtain:

$$\begin{aligned} u^{LL} &= 2c - p_1 \frac{c}{p_1 - p_0} - b_1 \frac{c}{(b_1 - b_0)} \cdot \nu^{LH}, \\ u^{HL} &= c - p_1 \frac{c}{p_1 - p_0} - g_1 \frac{c}{(g_1 - g_0)} \cdot \nu^{HH}, \\ u^{LH} &= 2c - p_1 \frac{c}{p_1 - p_0} + (1 - b_1) \frac{c}{(b_1 - b_0)} \cdot \nu^{LH}, \\ u^{HH} &= c - p_1 \frac{c}{p_1 - p_0} + (1 - g_1) \frac{c}{(g_1 - g_0)} \cdot \nu^{HH}. \end{aligned}$$

Let $\delta^{ij} = u^{ij} - u^{ij}$, $i, j = L, H$ denote the differences between state-contingent payments in the full-commitment contract and the limited-commitment contract.

Case 1: Assume $\nu^{HH} > 1$: It is readily verified that

$$\delta^{LL} = 0; \delta^{HL} < 0; \delta^{LH} = 0; \delta^{HH} > 0.$$

Case 2: Assume $\nu^{LH} > 1$: It is readily verified that

$$\delta^{LL} < 0; \delta^{HL} = 0; \delta^{LH} > 0; \delta^{HH} = 0.$$

In both Cases 1 and 2, the feasible full-commitment contract \mathcal{P}_{FC} would be a mean-preserving spread of \mathcal{P}_{LC} so that $K(\mathcal{P}_{FC}) > K(\mathcal{P}_{LC})$ results. Hence, $\mathcal{P}_{FC} \equiv \{u^{LL}, u^{LH}, u^{HL}, u^{HH}\}$ cannot be optimal unless $\nu^{HH} = \nu^{LH} = 1$.

Second, assume incentive constraint (5) singly binds. It implies (6) and (7) are slack and $(u^{HL} - u^{LL}) = 0$. Raising $(u^{LH} - u^{LL}) = (u^{HH} - u^{HL})$ above their renegotiation-proof level can—at best—further relax constraints (6) or (7). However, doing so is unnecessary since the latter two constraints are already slack; additionally, since $(u^{HL} - u^{LL}) = 0$, no relaxation of incentive constraints is possible. Therefore, the optimal full-commitment contract is again identical to the limited-commitment contract.

A.5 | Proof of Proposition 4.1

The proof follows from Appendix A.4.