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Working Paper

The rise of individual performance pay

CESifo Working Paper, No. 2145

Provided in Cooperation with:

Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

Suggested Citation: Kvaloy, Ola; Olsen, Trond (2007) : The rise of individual performance pay, CESifo Working Paper, No. 2145, Center for Economic Studies and ifo Institute (CESifo), Munich

This Version is available at:

<https://hdl.handle.net/10419/26189>

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THE RISE OF INDIVIDUAL PERFORMANCE PAY

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CESIFO WORKING PAPER NO. 2145
CATEGORY 4: LABOUR MARKETS
NOVEMBER 2007

PRESENTED AT CESIFO AREA CONFERENCE ON EMPLOYMENT AND SOCIAL PROTECTION, MAY 2007

An electronic version of the paper may be downloaded

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THE RISE OF INDIVIDUAL PERFORMANCE PAY

Abstract

Why does individual performance pay seem to prevail in human capital intensive industries? We present a model that may explain this. In a repeated game model of relational contracting, we analyze the conditions for implementing peer dependent incentive regimes when agents possess indispensable human capital. We show that the larger the share of values that the agents can hold-up, the lower is the implementable degree of peer dependent incentives. In a setting with team effects — complementary tasks and peer pressure, respectively — we show that while team-based incentives are optimal if agents are dispensable, it may be costly, and in fact suboptimal, to provide team incentives once the agents become indispensable.

JEL Code: D23, J33, L14.

Keywords: relational contracts, multiagent moral hazard, indispensable human capital.

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November 12, 2007

We thank Derek Clark, Hideshi Itoh, Hideo Owan, Jack Stecher, and seminar participants at the University of Stavanger, Norwegian School of Economics and Business Administration, Hitotsubashi University, Erasmus University, the EIASM Workshop in Accounting and Economics, the CESifo Conference on Employment and Social Protection, the Conference of the European Association of Labour Economists, and the Congress of the European Economic Association for helpful comments.

1 Introduction

Firm value is increasingly dependent on human capital. The share of physical capital in publicly traded corporations has dramatically decreased the last 30 years (see e.g. Blair and Kochan, 2000). At the same time we observe a higher degree of individual performance pay in modern corporations (see e.g. Brown et al., 1998; Brown and Heywood, 2002, and Lemieux et al., 2007). Are these trends related? Several studies indicate so. Long and Shields (2005), Lemieux et al. (2007) and Henneberger et al. (2007) find that individual performance pay is more likely to be found in firms with highly educated employees. A recent study by Barth et al. (2006) shows that the frequency of group-based incentives is decreasing for those with higher education, and increasing for blue-collar workers; while individual performance pay is found to be strongly associated with firms with a highly educated workforce.¹ Tremblay and Chenevert (2004) find that high-tech firms are more likely to use individual performance pay, but not group pay, and Grund and Sliwka (2007) find that individual performance appraisal, such as performance pay, is more common at higher levels of organizations. These studies are supported by research showing that the returns to skills are increasing (see e.g. Junk et al. 1993). Human capital is to a larger extent paid its marginal product, and individual performance pay is a way to that (Lemieux et al. 2007). Group-based incentive schemes (as in partnerships), are still quite common in certain high-skilled professional service industries such as law, accounting, investment banking and consulting, but researchers have noted that there is a trend away from equal sharing partnerships towards productivity-based "eat what you kill" partnerships (Levin and Tadelis, 2005)

One explanation for the increased use of individual performance pay is that advances in information and communication technology has made it easier to measure individual performance (Lemieux et al. 2007). A question then is whether it is has become relatively more easy to asses the performance of high-skilled workers. There is apparently no evidence that this is the case, in fact, MacLeod and Parent (1999) find that incomplete incentive contracts based on looser performance assessments are more common among highly educated. Barth et al. (2006) suggest that one should expect a positive relationship between human capital and individual performance pay because the quality and effort of high-skilled workers have larger impacts on productivity than the quality and effort of other groups of workers. They

¹In addition, several studies show that firms with low union coverage are more willing to use individualized incentive schemes (see e.g. Brown, 1990; Parent, 2002, Long and Shields, 2005, Lemieux et al.), and union coverage is lower among high-skilled workers (Acemoglu et al. 2001).

lend support from Brown (1990) who argues that in high-skilled jobs, worker output is more sensitive to worker quality than in jobs requiring lower skills. Henneberger et al. (2007) show that high-skilled workers tend to self-select into jobs with performance pay, supporting Lazear's (1986) model. Along the same line, studies by Kato (2002) and Torrington (1993) show that workers with more education are particularly interested in receiving rewards tailored to individual performance.

In our view, these are plausible explanations. However, there are some remaining puzzles. Individualized incentives are not desirable when teamwork is important, or when it is difficult to verify each worker's contribution to firm value, but it is hard to see that this applies less to high-skilled than to low-skilled workers. In fact, several HR scholars have argued that knowledge intensive organizations' emphasis on innovation, teamwork and projects calls for incentives that are group-based rather than based on individual performance (see e.g. Balkin and Bannister, 1993). We should thus look for an explanation saying that group-based incentives are desirable, but not feasible. Focusing on firms' inability to fully commit to incentive contracts, the literature has pointed out that group-based incentive schemes are harder to implement – and thus less feasible – than schemes based on relative performance evaluation (Carmichael, 1983; Malcomson, 1984; Levin, 2002, Kvaløy and Olsen 2006). In this paper we focus instead on the workers' lack of ability to commit to incentive contracts, which we believe is a central feature of human capital intensive firms, and show that this feature makes individual performance pay easier to implement than most peer-dependent schemes.

We recognize here two features of human capital that necessitate a high degree of individual performance pay. First, the true performance of high-skilled workers is often difficult to verify by third parties. Objective measures of performance seldom exist, and even if they do, looser assessments of performance also affect compensation (see e.g. MacLeod, 2003). Consequently, incentive contracts specifying criteria for performance pay are seldom fully protected by the court. This non-verifiability problem also applies to low-skilled workers, but as noted above, incomplete incentive contracts are more common in the high-skilled workforce. Second, human capital blurs the allocation of ownership rights. According to the standard view of ownership, it is the owner of an asset who has residual control rights; that is “the right to decide all usages of the asset in any way not inconsistent with a prior contract, custom or law” (Hart, 1995). If the asset involved in the worker's production is his own mind and knowledge, then he is also to decide all non-contractual usages. An indispensable “knowledge worker” can therefore

threaten to walk away with ideas, clients, techniques etcetera.² As noted by Liebeskind (2000), human-capital-intensive firms must induce their employees to stay around long enough so that the firm can establish some intellectual property rights with respect to the ideas generated by these employees, or else these firms run the risk of being expropriated or held-up by their own employees.³

Why do these two features - incomplete contracts and indispensable human capital - prepare the way for individual performance pay? In other words: Why is it difficult to implement *peer-dependent incentives* when performance is unverifiable and workers possess residual control rights? The answer is intuitive when we think of the incentives facing an agent who is a full residual claimant. He simply gets the values he has produced; the market incentives are not linked to what other agents produce. Hence, if a principal wants to implement a peer-dependent incentive contract, she faces a problem if her agents have residual control rights. With relative performance evaluation (RPE) an agent is not paid well if his peer performs better, while with joint performance evaluation (JPE) he is not paid well if his peer's performance is poor. This peer-dependence may lead to contract breach: an agent who is paid a low bonus after realizing a high output, has incentives to hold-up his output and renegotiate payments. Of course, a hold-up strategy is only possible if the agent actually is able to prevent the principal from realizing the agent's value added ex post production. But if hold-up *is* possible, then RPE and JPE schemes are more susceptible to hold-up than incentive schemes based on independent performance evaluation (IPE).

The parties can mitigate the hold-up problem through repeated interaction, i.e. through self-enforcing relational contracting⁴ (also called implicit contracting) where contract breach is punished, not by the court, but by the parties who can refuse to cooperate after a deviation. But since a hold-up will

²A curious example is from Academia, where researchers can threaten to "walk away" with their forthcoming publications. This is particularly relevant in countries where the universities' funding partly depends on publications.

³It should be noted that indispensability is often achieved through investments in firm-specific human capital. Hence, a worker who possesses indispensable human capital is not necessarily highly educated, and education does not guarantee indispensability. However, specific human capital is strongly associated with high levels of formal education (see Blundell et al., 1999).

⁴Influential models of relational contracts include Klein and Leffler (1981), Shapiro and Stiglitz (1984), Bull (1987), Kreps (1990), Baker, Gibbons and Murphy (1994, 2002), Schmidt and Schnitzer (1995). MacLeod and Malcolmson (1989) generalize the case of symmetric information, while Levin (2003) makes a general treatment of relational contracts with asymmetric information, allowing for incentive problems due to moral hazard and hidden information.

be regarded as a deviation from such a relational contract, the self-enforcing range of the contract is limited by the hold-up problem. And since the hold-up problem is most severe under joint or relative performance evaluation, we can expect a larger fraction of independent performance pay when hold-up is feasible for the agents.

Is this a problem? Yes, from the informativeness principle (Holmström, 1979, 1982), we know that an incentive contract should be based on all variables that provide information about the agents' actions. Stochastic and/or technological dependences between the agents then typically call for peer-dependent incentive schemes. By tying compensation to an agent's relative performance, the principal can filter out common noise so that compensation is based more on real effort, and less on random shocks that are outside the agent's control (see Holmström, 1982; and Mookherjee, 1984).⁵ And by tying compensation to the joint performance of a team of agents, the principal can exploit complementarities between the agents' efforts.⁶

Hence, from the informativeness principle it is puzzling that we actually observe incentive schemes based on independent performance evaluation. The drawbacks of JPE and RPE can partly explain it: JPE may be susceptible to free-riding (see e.g. Alchian and Demsetz, 1972; and Holmström, 1982), while RPE is susceptible to collusion (see e.g. Mookherjee, 1984). RPE may also induce sabotage and discourage cooperation (see Lazear, 1995, for a discussion of the costs and benefits of RPE and JPE).

In this paper we provide a new rationale for independent performance evaluation; a rationale that is not based on these classical drawbacks, but rather on the implementability of peer-dependent incentives. Our main result then says that the maximum dependence between agent i 's bonus and agent j 's output that the principal can implement, decreases with the share of values that the agents can hold-up ex post. This result is robust to settings with both stochastic and technological dependence (team effects) between the agents.

With respect to team effects we consider two cases: complementary tasks and peer pressure. We show that a stark JPE contract is optimal only if the agents' hold-up power is sufficiently low. In the case of complementary

⁵See also Lazear and Rosen (1981) Nalebuff and Stiglitz (1983) and Green and Stokey (1983) for analyses of RPE's special form, rank-order tournaments.

⁶In addition, JPE can promote cooperation since an agent is rewarded if his peers perform well (see e.g. Holmström and Milgrom, 1990; Itoh 1993; and Macho-Stadler and Perez-Castrillo, 1993). JPE can also provide implicit incentives not to shirk (or exert low effort), since shirking may have social costs (as in Kandel and Lazear, 1992), or induce other agents to shirk, which again reduces the shirking agent's expected compensation (as in Che and Yoo, 2001).

tasks, the optimal implementable scheme becomes less based on JPE and more based on IPE the larger the share of values the agents can hold-up, and in the case of peer pressure, any JPE scheme becomes suboptimal once the relational contract constraints bind.

Broadly speaking, our contribution is to consider the effect of residual control rights in a multiagent moral hazard model. In the vast literature on multiagent moral hazard it is (implicitly) assumed that residual control rights are exclusively in the hands of the principal. And in the literature dealing with optimal allocation of control rights, the multiagent moral hazard problem is scantily considered.⁷ Our paper also contributes to the literature by introducing other-regarding preferences and team technology in a relational contracting set-up.

Our basic set-up with two agents, binary effort and binary output is similar to Che and Yoo (2001). As shown by these authors, peer monitoring is a rationale for making use of peer-dependent incentives such as JPE. We introduce and explore instead technological complementarities and peer pressure in this setting. And more importantly, we extend and complement their analysis by assuming non-verifiable output, and that agents are able to hold-up values *ex post*.⁸

The paper proceeds as follows. In Section 2 we present the model. Section 3 deduces the optimal relational incentive contract in a simple setting with stochastic and technological independence. In Section 4 we analyze the effect of complementary tasks, common noise and peer pressure, while Section 5 offers some concluding remarks.

2 The Model

Consider an economic environment consisting of one principal and two identical agents ($i = 1, 2$) who each period produce either high, Q_H , or low, Q_L , values for the principal. Each agent's effort level can be either high or low, where high effort has a disutility cost of c and low effort is costless. The

⁷This literature begins with Grossman and Hart, 1986; and Hart and Moore, 1990 who analyze static relationships. Repeated relationships are analyzed in particular by Halonen, 2002; and Baker, Gibbons and Murphy, 2002.

Although Hart and Moore (1990) analyze a model with many agents, they do not consider the classical moral hazard problem that we address, where a principal can only observe a noisy measure of the agents' effort.

⁸Kvaløy and Olsen (2006) analyze a multilateral relational contract with repeated peer-monitoring. But team technology, peer pressure and agent hold-up is not considered in that model. Kvaløy and Olsen (2007) endogenize the agent's hold-up power in a simpler model with no team effects.

principal can only observe the realization of the agents' output, not the level of effort they choose. Similarly, agent i can only observe agent j 's output ($i \neq j, j = 1, 2$), not his effort level.⁹ Moreover, we assume that output is non-verifiable to a third party. Hence, contracts on output cannot be enforced by the court.

The agents' outputs depend on efforts and noise. Like Che and Yoo (2001), we assume that a favorable shock occurs with probability $\sigma \in (0, 1)$, in which case both agents succeed in producing high values for the principal. If the shock is unfavorable, the agents' outputs are stochastically independent, and each agent's success probability depends on the agent's own as well as his peer's effort. Let $q(\kappa, \lambda)$ denote this probability, where $\kappa \in \{H, L\}$ and $\lambda \in \{H, L\}$ refer to the agent's own and his peer's effort, respectively. We assume that there are three levels of the success probability for each agent:

$$\begin{aligned} q(H, H) &= q_H \\ q(H, L) &= q_{HL} \\ q(L, H) &= q(L, L) = q_L, \quad \text{where } q_L \leq q_{HL} \leq q_H, \quad q_L < q_H. \end{aligned} \tag{1}$$

The idea here is that the peer's effort has a positive effect when the agent's own effort is high, but has no effect when own effort is low. Note also that $q_{HL} = q_H$ corresponds to no team effects (independent technology), while $q_{HL} = q_L$ corresponds to perfect complementarity.

Throughout the paper we assume that the value of high effort exceeds its cost, in the sense that

$$(1 - \sigma)\Delta q \Delta Q > c, \tag{2}$$

where $\Delta q = q_H - q_L$ and $\Delta Q = Q_H - Q_L$. It is moreover assumed that all parties are risk neutral, but that the agents are subject to limited liability: the principal cannot impose negative wages.¹⁰ Ex ante reservation wages are assumed to be zero, for convenience.

The principal may offer each agent a wage contract saying that agent i receives a bonus $\beta^i \equiv (\beta_{HH}^i, \beta_{HL}^i, \beta_{LH}^i, \beta_{LL}^i)$ ex post value realizations, where the subscripts refer to agent i and agent j 's realizations of Q_k and Q_l , ($k, l = H, L$), respectively. (We sometimes suppress agent notation in superscripts since the agents are identical.) For each agent, a wage scheme exhibits joint (JPE), relative (RPE) or independent (IPE) performance evalu-

⁹Whether or not the agents can observe each others effort level is not decisive for the analysis presented. However, by assuming that effort is unobservable among the agents, we do not need to model repeated peer-monitoring.

¹⁰Limited liability may arise from liquidity constraints or from laws that prohibit firms from extracting payments from workers.

ation if, respectively, $(\beta_{HH}, \beta_{LH}) > (\beta_{HL}, \beta_{LL})$ ¹¹, $(\beta_{HH}, \beta_{LH}) < (\beta_{HL}, \beta_{LL})$, and $(\beta_{HH}, \beta_{LH}) = (\beta_{HL}, \beta_{LL})$. With JPE an agent is paid more if his peer does well, in RPE he is paid more if his peer does poorly, and in IPE his payment is independent of his peer's performance. Since outputs are not verifiable, a contract must be self-enforcing to be sustainable. We now describe the contracting environment in more detail.

Each period the principal and the agents face the following contracting situation.

1. The principal offers a contract saying that agent i receives a bonus $\beta^i \equiv (\beta_{HH}^i, \beta_{HL}^i, \beta_{LH}^i, \beta_{LL}^i)$ conditional on outputs as described above.
2. The agents simultaneously choose efforts. Provided the contract is honored, agent $i = 1, 2$ then gets an expected wage

$$\pi(\kappa, \lambda, \beta^i) \equiv \sigma \beta_{HH}^i + (1 - \sigma) \{ q(\kappa, \lambda) q(\lambda, \kappa) \beta_{HH}^i + q(\kappa, \lambda) (1 - q(\lambda, \kappa)) \beta_{HL}^i + (1 - q(\kappa, \lambda)) q(\lambda, \kappa) \beta_{LH}^i + (1 - q(\kappa, \lambda)) (1 - q(\lambda, \kappa)) \beta_{LL}^i \} \quad (3)$$

where κ and λ denote, respectively, agent i 's and agent j 's efforts, $\kappa, \lambda \in \{H, L\}$.

3. The agents' value realizations, Q_k and Q_l , ($k, l = H, L$), are revealed. The principal decides whether or not to honor the contract.

4. If the principal reneges on the contract by refusing to pay β^i , she bargains with the agent and pays a spot price s^i for the good. If the principal honors the contract, the agent chooses whether or not to accept the payment β^i . If he accepts, trade takes place according to the contract. If not, he bargains with the principal and obtains a spot price s^i .

We assume that the spot price is determined by Nash bargaining. In stage 4 agent i is able to independently attain θQ_k , $\theta \in [0, 1]$ in an alternative market. In Nash bargaining, agent i will then receive θQ_k plus a share γ of the surplus from trade i.e. $s^i = s_k = \theta Q_k + \gamma(Q_k - \theta Q_k) = \eta Q_k$ where $\eta = \gamma + \theta(1 - \gamma)$. The agent's total hold-up power (η) is then an increasing function of ex post bargaining power, γ , and ex post outside options, θ . The outside option parameter θ depends on the specificity of the agent's value-added. The more firm specific value-added – or the more narrow the agent's skill set – the lower is θ . But, importantly, note that even if $\theta = 0$, the agent can still achieve a share $\eta = \gamma$ ex post. This share γ of the surplus from trade is determined by ex post bargaining power, and will typically increase with the indispensability of the agents: If agents possess essential human capital that makes them indispensable for ex post value extraction, then γ is high. But if values accrue directly to the principal in the process of production,

¹¹The inequality means weak inequality of each component and strict inequality for at least one component.

then the agents have no hold-up power: $\gamma = \theta = 0$, so that $\eta = 0$. So to obtain a positive spot price, the agents must be able to hold up values in stage 3.¹²

2.1 The spot contract

A spot contract is a perfect public equilibrium (PPE) of the contracting game described above. In stage 4, agent i will renege if his promised bonus for the given outputs is lower than the spot price ($\beta_{kl}^i < s_k$), and honor otherwise. In stage 3, the principal will renege if $\beta_{kl}^i > s_k$, and honor otherwise. Hence, at least one party will renege, unless $\beta_{kl}^i = s_k$. The only payment that can be implemented for agent i when he has output Q_k is thus $s_k = \eta Q_k$. Anticipating this, agent i will in stage 2 exert low effort if the cost of high effort exceeds the higher expected spot price induced by this effort, i.e. if $c > (1 - \sigma)\eta(q(H, \lambda) - q(L, \lambda))\Delta Q$. Recalling our assumptions (1) we see that low effort is thus a strictly dominant strategy if

$$(1 - \sigma)\eta\Delta q\Delta Q < c \tag{4}$$

where $\Delta q = q_H - q_L$. Hence, we see that the spot contracting game has a unique continuation equilibrium from stage 2 if (4) holds¹³. Each agent then exerts low effort and receives the expected spot price $E(s) = \eta(Q_L + (\sigma + (1 - \sigma)q_L)\Delta Q)$. If (4) does not hold, there is an equilibrium where each agent exerts high effort and receives the expected spot price $E(s) = \eta(Q_L + (\sigma + (1 - \sigma)q_H)\Delta Q)$.

In our simple model, a contract to motivate high effort is only necessary if the parameters satisfy (4), since if not, the agents' hold-up power provides them with sufficient incentives. Hence, throughout the paper we assume that (4) holds, so that the principal has to implement an incentive contract in

¹²It should be noted that the ability to hold-up values rests on the assumption that agents become indispensable *in the process* of production (as in e.g. Halonen, 2002). We do not analyze the incentives to invest in firm-specific human capital (as in e.g. Kessler and Lülfesmann, 2006). Rather, we just assume that agents become indispensable *ex post*, and then focus on how this affects the multiagent moral hazard problem. We thus follow the relational contracting literature, and abstract from human capital *accumulation*. The level of θQ_i and ηQ_i is therefore assumed to be exogenously given and constant each period. This also allows us to concentrate on stationary relational contracts, where the principal promises the same contingent compensation in each period.

¹³If there are team effects, low effort by both agents is a continuation equilibrium in stage 2 if the weaker condition $(1 - \sigma)\eta(q_{HL} - q_L)\Delta Q < c$ holds. In that case, if $(1 - \sigma)\eta(q_{HL} - q_L)\Delta Q < c \leq (1 - \sigma)\eta(q_H - q_L)\Delta Q$, there are two effort equilibria, namely HH and LL.

order to induce high effort. Since outputs are non-verifiable, such a contract must be self-enforcing.

2.2 Relational contracts

For the principal to implement high effort through a contract, β , the contract must be incentive compatible (IC) and self-enforcing, where a self-enforcing (relational) contract is a PPE of the infinitely repeated game in which the stage game described above is played every period. We consider first the IC constraint.

An implementable incentive scheme, β , is incentive compatible if

$$\pi(H, H, \beta) - c \geq \pi(L, H, \beta) \quad (5)$$

The left hand side (LHS) shows the expected wage minus the cost from exerting high effort, while the right hand side (RHS) shows the expected wage from exerting low effort. The condition (5) ensures that high effort from both agents is an equilibrium, given the contract β . The agents' equilibrium is unique if high effort is a dominant strategy, i.e. if $\pi(H, L, \beta) - c \geq \pi(L, L, \beta)$ holds in addition to (5). The optimal wage schemes we deduce in this paper will ensure either a unique high-effort equilibrium, or a high-effort equilibrium that is not Pareto dominated by a low-effort equilibrium.

Consider now the conditions for the incentive contract to be self-enforcing, i.e. the conditions for implementing a *relational incentive contract*. The relational incentive contract is self-enforcing if all parties honor the contract for all possible values of Q_k and Q_l , $k, l \in \{L, H\}$. As in e.g. Baker, Gibbons and Murphy (2002), we analyze trigger strategy equilibria in which the parties enter into spot contracting forever after one party reneges. We consider a multilateral punishment structure where any deviation by the principal triggers low effort from both agents. The principal honors the contract only if both agents honored the contract in the previous period. The agents honor the contract only if the principal honored the contract with both agents in the previous period. Thus, if the principal reneges on the relational contract, both agents insist on spot contracting forever after. And vice versa: if one of the agents (or both) renege, the principal insists on spot contracting forever after. A natural explanation for this is that the agents interpret a unilateral contract breach (i.e. the principal deviates from the contract with only one of the agents) as evidence that the principal is not trustworthy (see Bewley, 1999, and Levin, 2002).¹⁴

¹⁴Modelling multilateral punishments is also done for convenience. Bilateral punishments will not alter our results qualitatively.

Now, (given that (5) holds) the principal will honor the contract if, for all realizations of output $Q_k, Q_l, k, l \in \{H, L\}$, we have

$$\begin{aligned} & -\beta_{kl} - \beta_{lk} + \frac{2\delta}{1-\delta} [Q_L + (\sigma + (1-\sigma)q_H)\Delta Q - \pi(H, H, \beta)] \quad (\text{EP}) \\ \geq & -\eta(Q_l + Q_k) + \frac{2\delta}{1-\delta} [Q_L + (\sigma + (1-\sigma)q_L)\Delta Q - E(s)], \end{aligned}$$

where δ is a common discount factor. The LHS of the inequality shows the principal's expected present value from honoring the contract, which involves paying out the promised bonuses and then receiving the value associated with high effort in all future periods. The RHS shows the expected present value from renegeing, which involves spot trading of the realized outputs, and then receiving the value associated with low effort and spot trading in all future periods.

Agent i will honor the contract if

$$\beta_{kl} + \frac{\delta}{1-\delta} (\pi(H, H, \beta) - c) \geq \eta Q_k + \frac{\delta}{1-\delta} E(s), \quad \text{all } k, l \in \{H, L\} \quad (\text{EA})$$

where similarly the LHS shows the agent's expected present value from honoring the contract, while the RHS shows the expected present value from renegeing.

3 Independent tasks

In order to highlight the main result from the model in the simplest possible setting, we first consider the case of stochastic and technological independence, i.e. $\sigma = 0$ and $q_{HL} = q_H$. The more general set-up is analyzed in the next section.

In this setting the IC condition (5) for high effort from each agent takes the following form:

$$q_H \beta_{HH} + (1 - q_H) \beta_{HL} - q_H \beta_{LH} - (1 - q_H) \beta_{LL} \geq \frac{c}{\Delta q} \quad (\text{IC})$$

The optimal contract minimizes the associated expected wage costs $\pi(H, H, \beta)$, subject to the constraints given by limited liability, incentive compatibility (IC), and enforceability (EP and EA). By IC and the definition (3) of the wage cost, we have for $\pi = \pi(H, H, \beta)$:

$$\begin{aligned} \pi &= q_H [q_H \beta_{HH} + (1 - q_H) \beta_{HL}] + (1 - q_H) [q_H \beta_{LH} + (1 - q_H) \beta_{LL}] \quad (7) \\ &\geq q_H \frac{c}{\Delta q} + q_H \beta_{LH} + (1 - q_H) \beta_{LL}. \end{aligned}$$

From this inequality and limited liability ($\beta_{LH}, \beta_{LL} \geq 0$), we see that the least cost contract satisfying IC has $\beta_{LH} = \beta_{LL} = 0$ and yields a per agent wage cost $\pi_m = q_H \frac{c}{\Delta q}$. Such a contract would always be feasible, and hence optimal, if outputs were verifiable.

Such a contract will also satisfy the agent's enforceability conditions EA when the hold-up parameter η is small, but generally not so when η is 'large'. (The RHS of EA is increasing in η .) Inserting for EA (applied to β_{LH} and β_{LL}) in (7) now yields

$$\pi \geq q_H \frac{c}{\Delta q} + \eta Q_L + \frac{\delta}{1 - \delta} [E(s) - \pi + c]$$

Collecting terms involving π and substituting for the expected spot price $E(s) = \eta(Q_L + q_L \Delta Q)$ we obtain

$$\pi \geq q_H \frac{c}{\Delta q} + \eta Q_L - \delta \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L$$

Since IC and limited liability ($\beta_{LH}, \beta_{LL} \geq 0$) implies $\pi \geq q_H \frac{c}{\Delta q}$, we see that we have the following lower bound for the wage cost

$$\pi \geq q_H \frac{c}{\Delta q} + \max\{0, \eta Q_L - \delta \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L\} = \pi_{\min} \quad (8)$$

The last term in π_{\min} reflects the influence of the enforceability conditions (EA) for the agent. (We will check the corresponding conditions for the principal (EP) below). When the last term in π_{\min} is positive, it is impossible to implement and enforce a relational contract where the agent is paid $\beta_{LH} = \beta_{LL} = 0$ for a low outcome, and the wage cost for the principal will therefore exceed the cost for the case $\eta = 0$. Higher wages ease implementation by making it less tempting for the agents to renege on the contract.

The additional cost is increasing in η , the share of the value that the agent can hold-up ex post. The cost is naturally decreasing in δ , since higher discount factors ease implementation. We will here restrict attention to cases where the hold-up problem is serious in the sense that the cost is positive for all $\delta < 1$. This will be the case when the hold-up parameter η is sufficiently large, more precisely when it satisfies¹⁵

$$\eta \geq \eta_0 = \frac{c q_L}{\Delta q Q_L + \Delta Q q_L} \quad (9)$$

The derivation of the lower bound π_{\min} above shows that in order to minimize the additional cost associated with the self-enforcement constraint,

¹⁵Note that $\eta_0 \Delta q \Delta Q < c$, so (4) is not violated, given that $\sigma = 0$ here.

EA, the principal must set $\beta_{LH} = \beta_{LL}$, i.e. ensure that an agent's pay for low output is independent of the other agent's output. The 'fixed wage' associated with these outcomes ($\beta_{LH} = \beta_{LL}$) generates the additional cost term in the expression for π_{\min} , and hence we have (for $\eta > \eta_0$):

$$\beta_{LH} = \beta_{LL} = \eta Q_L - \delta \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L > 0 \quad (10)$$

Since the enforceability constraint (EA) is binding for these two bonuses, it follows that we can write this constraint for the other bonuses in the following form:

$$\beta_{Hl} - \eta \Delta Q \geq \beta_{LH} = \beta_{LL}, \quad l = H, L \quad (\text{EA}')$$

This relation says that the bonus increments for high output $\beta_{HH} - \beta_{LH}$ and $\beta_{HL} - \beta_{LL}$ must both exceed $\eta \Delta Q$, which is the additional value of high output for the agent outside the relationship. At the same time the bonuses must be incentive compatible with high effort, and to minimize costs they must satisfy IC with equality, which is to say that we must have

$$q_H(\beta_{HH} - \beta_{LH}) + (1 - q_H)(\beta_{HL} - \beta_{LL}) = \frac{c}{\Delta q} \quad (\text{IC}')$$

Note that an IPE scheme with $\beta_{Hl} - \beta_{Ll} = \frac{c}{\Delta q}$ will certainly fulfill both constraints EA' and IC', given that we have assumed $\frac{c}{\Delta q} > \eta \Delta Q$, see (4). The constraints imply that to generate minimal costs and be implementable a scheme cannot deviate too much from IPE. Figure 1 provides an illustration.

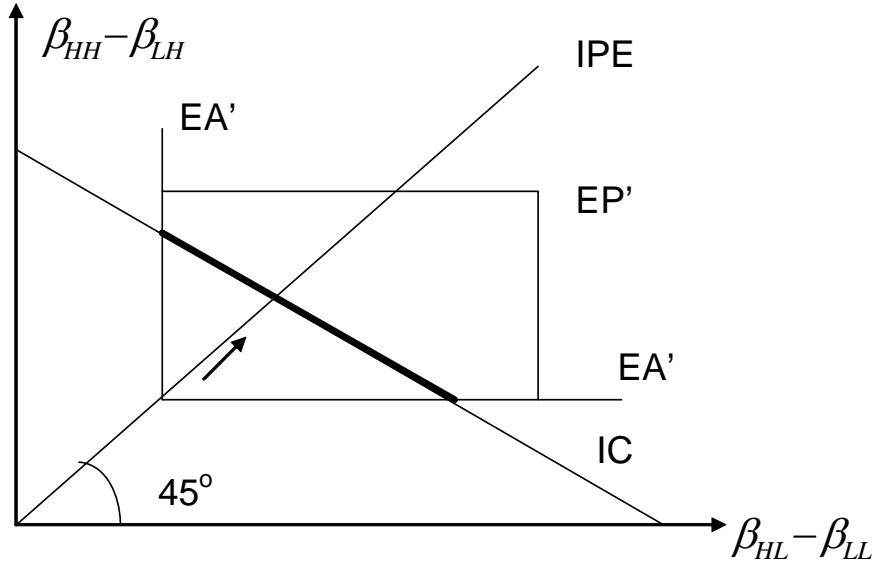


Figure 1

The figure depicts the IC constraint and the reduced form dynamic enforceability constraints for the agents (EA') as functions of the bonus increments $\beta_{HL} - \beta_{LL}$ and $\beta_{HH} - \beta_{LH}$ (where $\beta_{LH} = \beta_{LL}$). Here points above, on and below the diagonal represent, respectively, JPE, IPE and RPE contracts. The figure illustrates that only a limited set of contracts on IC satisfies the agents' enforceability constraints.

To be fully feasible a contract must also satisfy the dynamic enforceability constraint for the principal (EP). As we demonstrate in the appendix, this constraint can here be written as

$$\max \{2(\beta_{HH} - \beta_{LH} - \eta\Delta Q), (\beta_{HL} - \beta_{LL} - \eta\Delta Q)\} \leq \frac{2\delta}{1-\delta} [\Delta q\Delta Q - c] \quad (\text{EP}')$$

This reduced form EP constraint can be represented as the curve marked EP' in Figure 1. The curve has a kink at $\beta_{HH} - \beta_{LH} = \frac{1}{2}(\beta_{HL} - \beta_{LL} + \eta\Delta Q)$, and its position depends on δ . For given bonuses, the constraint requires that the discount factor δ must be sufficiently large to guarantee implementability. Conversely, for given δ the constraint limits the set of bonuses that can be implemented; in particular we see that the bonus increments $\beta_{HL} - \beta_{LL}$ cannot be too large.

Defining $\hat{\delta} \in (0, 1)$ by

$$\frac{1 - \hat{\delta}}{\hat{\delta}} = \frac{[\Delta q\Delta Q - c]}{c - \eta\Delta Q\Delta q} \Delta q(2 - q_H) \quad (11)$$

we obtain the following result.

Proposition 1 (i) For $\eta \geq \eta_0$ and $\delta \geq \hat{\delta}$ a wage scheme satisfying (10), IC', EA' and EP' is optimal. The minimal wage cost is given by π_{\min} , and any other implementable wage scheme yields a higher cost. (ii) No wage scheme yielding high effort can be implemented for $\delta < \hat{\delta}$

Remark. In the appendix we verify that the optimal wage schemes ensure either a unique high-effort equilibrium (for RPE schemes), or a high-effort equilibrium that is not Pareto dominated by a low-effort equilibrium (for JPE or IPE schemes). Moreover, we show that these schemes satisfy the following conditions

$$\pi(H, H, \beta) - c \geq E(s) \quad (12)$$

$$\Delta q\Delta Q \geq \pi(H, H, \beta) - E(s) \quad (13)$$

The first shows that the agents' expected payment from the incentive contract exceeds the expected spot price, and the second shows that the

principal's expected surplus from the contract exceeds the surplus from spot contracting. All parties are therefore better off with the relational contract than with a spot contract.

Proposition 1 shows that an optimal wage scheme satisfies IC and is bounded by the dynamic implementability constraints EA' and EP'. Consider now variations in η . As η increases (for δ fixed), the curve representing EA' in Figure 1 moves outwards along the 45 degree line with the EP'-curve 'attached to it'. The IC curve remains fixed, and thus a smaller set of bonuses remains admissible. Hence, the agents' ability to hold-up values ex post calls for incentive schemes that come close to schemes based on independent performance evaluation. We have:

Proposition 2 *The maximum dependence between agent i 's bonus and agent j 's output that the principal can implement, decreases with the share of values, η , that the agents can hold-up. In particular, for an optimal and feasible wage scheme, we have $\beta_{LH} = \beta_{LL}$ and $|\beta_{HH} - \beta_{HL}| \leq (\frac{c}{\Delta q} - \eta\Delta Q)m$, where $m = \max\{\frac{1}{q_H}, \frac{1}{1-q_H}\}$*

Note that for a sufficiently large η only IPE remains feasible, since $|\beta_{HH} - \beta_{HL}| \rightarrow 0$ as $\eta \rightarrow \frac{c}{\Delta q\Delta Q}$. Finally note also that a higher η eases implementation of high effort. This is seen in the expression for the critical factor $\hat{\delta}$, which shows that $\hat{\delta} \rightarrow 0$ as $\eta \rightarrow \frac{c}{\Delta q\Delta Q}$.

Proposition 2 highlights how agent hold-up affects the implementability of peer dependent incentives. An agent who realizes a high output, but is paid a low bonus only because his peer performs better (RPE) or worse (JPE), has incentives to hold-up his output and renegotiate payments. This obstructs the implementation of relational incentive contracts.

In the simple setting presented in this section, there is no inherent reason for the principal to offer peer-dependent incentives, since IPE, RPE and JPE are equally profitable. However, once we allow for technological or stochastic dependence between the agents' tasks, RPE or JPE become desirable. But as we shall see in the next section, even if peer-dependent incentives become desirable, the basic insight from Proposition 2 remains valid, and implies that the most desirable schemes may well not be implementable.

4 Team incentives

We will now demonstrate the importance of agent-hold up in a setting where there are team effects. Such effects can take many forms; here we analyze two cases: Complementary tasks and peer pressure.

4.1 Complementary tasks

Consider now the general formulations (1) - (3) incorporating complementary tasks and common noise. For expositional simplicity we will assume perfect complementarity, so that high effort from one agent is productive only if the other agent also exerts high effort, and thus

$$q(H, H) = q_H > q_L = q(H, L) = q(L, H) = q(L, L)$$

In this setting we have:

$$\begin{aligned}\pi(H, H, \boldsymbol{\beta}) &= \sigma\beta_{HH} + (1 - \sigma) \{q_H^2\beta_{HH} + q_H(1 - q_H)(\beta_{HL} + \beta_{LH}) + (1 - q_H)^2\beta_{LL}\} \\ \pi(L, H, \boldsymbol{\beta}) &= \sigma\beta_{HH} + (1 - \sigma) \{q_L^2\beta_{HH} + q_L(1 - q_L)(\beta_{HL} + \beta_{LH}) + (1 - q_L)^2\beta_{LL}\}\end{aligned}$$

To illustrate the forces at play here, consider first three 'extreme' contracts; a stark JPE scheme $(\beta_{HH}, 0, 0, 0)$, a pure IPE scheme $(\beta, \beta, 0, 0)$ and a stark RPE scheme $(0, \beta_{HL}, 0, 0)$. In all contracts an agent is paid a bonus only if he has a success. The JPE (RPE) contract pays the bonus when the success occurs together with a success (failure) by the other agent, while in the IPE contract the payment is independent of the other agent's outcome. We will now show that if we ignore enforceability conditions, the least cost contract is either the stark JPE scheme or the stark RPE scheme. We will then show that (i) while these contracts can be feasible (enforceable) when the agents' hold-up power is sufficiently small, they become unfeasible when this hold-up power exceeds some threshold, and (ii) that the optimal contract then moves towards an IPE scheme as the hold-up power increases beyond the threshold.

For the JPE scheme $(\beta_{HH}, 0, 0, 0)$, the IC constraint $\pi(H, H, \boldsymbol{\beta}) - c \geq \pi(L, H, \boldsymbol{\beta})$ yields $(1 - \sigma)(q_H^2 - q_L^2)\beta_{HH} \geq c$ and thus (minimal) expected costs $\pi_J = \left[\frac{\sigma}{1-\sigma} + q_H^2\right] \frac{c}{q_H^2 - q_L^2}$. For the IPE scheme the IC constraint yields $(1 - \sigma)(q_H - q_L)\beta \geq c$ and thus expected costs $\pi_I = \left[\frac{\sigma}{1-\sigma} + q_H\right] \frac{c}{q_H - q_L}$, while for the RPE scheme the IC constraint yields $(1 - \sigma)(q_H - q_L)(1 - q_H - q_L)\beta_{HL} \geq c$ and thus expected costs $\pi_R = q_H(1 - q_H) \frac{c}{(q_H - q_L)(1 - q_H - q_L)}$ (assuming $1 - q_H - q_L > 0$). The RPE contract here filters out the common noise factor, and yields a cost that is completely independent of this factor.

Comparing the three contracts, we see that for $\sigma = 0$ the JPE contract yields the lowest cost, and that we then have $\pi_J < \pi_I < \pi_R$. For σ close to 1, on the other hand, the RPE contract yields the lowest cost. Indeed, (assuming $1 - q_H - q_L > 0$) there is critical $\hat{\sigma} \in (0, 1)$ such that for $\sigma < \hat{\sigma}$ we have $\pi_J < \pi_I < \pi_R$, while for $\sigma > \hat{\sigma}$ we have $\pi_J > \pi_I > \pi_R$. The critical $\hat{\sigma}$ is given by the condition $\pi_J = \pi_R$, which after a little algebra yields $\hat{\sigma} = \frac{q_H q_L}{(1 - q_H)(1 - q_L)}$.

The reason behind these results are as follows: When tasks are complements, low effort from agent i yields a negative externality on agent j . With JPE, the agent is punished for this, i.e. JPE internalizes the externality to some extent. If there is no or little common noise ($\sigma < \hat{\sigma}$), this makes it less costly to implement high effort under JPE than under IPE or RPE. Indeed, the stark JPE scheme will then, if it is feasible, dominate all other schemes. But the JPE scheme, which pays out bonuses when both agents have high outputs, is vulnerable to common shocks. So when the common noise factor is sufficiently large ($\sigma > \hat{\sigma}$) this scheme is dominated by the RPE scheme, which here is immune to such shocks. Thus we see that there is a tension here between (i) using JPE to internalize the externality induced by the complementarity between tasks, and (ii) using RPE to filter out and neutralize the effect of the common shocks.

This can be illustrated by Figure 2, which is similar to Figure 1. (The position of the IC constraint will be different from that in Figure 1 due to the complementarity and noise factors.) The three contracts discussed above are here represented by points J, I, and R, respectively. The dotted lines are iso-cost lines for the principal. Their slope depend on σ , and the critical value $\hat{\sigma}$ is precisely the value for which they are parallel to the IC line. For $\sigma < \hat{\sigma}$ the iso-cost lines are steeper than the IC line, as indicated in the figure. It is clear from the figure that the JPE contract then yields a lower cost than the two other contracts. It is also clear that for the opposite case $\sigma > \hat{\sigma}$ the lowest cost will be obtained by the RPE contract, since the iso-cost lines then are less steep than the IC line.

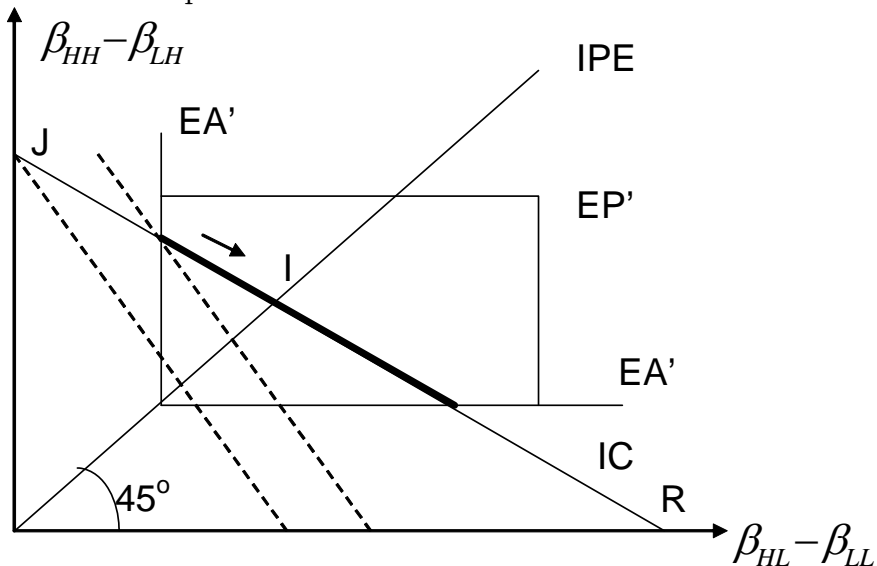


Figure 2
Regarding enforceability, we see by checking the EA constraints that the

three contracts do satisfy these constraints if the agents have no hold-up power (since the RHS of EA is zero for $\eta = 0$). Checking the EP constraints, we see that the three contracts also satisfy these for $\eta = 0$, provided the discount factor δ is sufficiently close to 1. This implies that each of these contracts is enforceable if the agents' hold-up power is sufficiently small (η close to zero), and δ is sufficiently close to 1. Intuitively, each contract gives both agents a rent ($\pi_i - c > 0$), and for η small no agent can gain by renegeing. Also, each contract gives the principal a surplus exceeding her spot surplus for η small (one can check that $(1 - \sigma)\Delta q\Delta Q - \pi_i > 0$), and hence neither the principal has incentives to renege when future surpluses are sufficiently important for her (δ is large).

The stark JPE or RPE contracts discussed above will, however, typically not be feasible when the agents' hold-up power (η) is 'large', since they will then typically violate the agents' enforceability constraints (EA). As we will show below, these constraints can be represented by lines such as EA' in Figure 2. This is similar to the independence case illustrated in Figure 1, and we will see that the principal's constraints (EP) can be represented in a similar way as well. The unique optimal contract for the case illustrated in Figure 2 ($\sigma < \hat{\sigma}$) will then be the contract given by the north-west intersection point of IC and EA'. This is a JPE contract, but it is less stark than the JPE contract discussed above. As η increases, the principal will be forced to move the contract in the direction of the 45 degree line, and hence move it towards an IPE contract.

Proceeding to the formal analysis, note that the IC constraint $\pi(H, H, \beta) - c \geq \pi(L, H, \beta)$, can here be written:

$$[q_H + q_L] \beta_{HH} + [1 - q_H - q_L] (\beta_{HL} + \beta_{LH}) - [2 - q_H - q_L] \beta_{LL} \geq \frac{c}{(1 - \sigma)\Delta q} \quad (IC_t)$$

where $\Delta q = q_H - q_L$. Consider first the case $\sigma < \hat{\sigma} = \frac{q_H q_L}{(1 - q_H)(1 - q_L)}$. Substituting for β_{HH} from the IC constraint (IC_t) into the expression for $\pi(H, H, \beta)$ we obtain the following inequality (see the appendix)

$$\pi \geq \pi_J + \frac{p}{2}(\beta_{HL} + \beta_{LH}) + (1 - p)\beta_{LL}, \quad (14)$$

where

$$\pi_J = \frac{\sigma + (1 - \sigma)q_H^2}{q_H^2 - q_L^2} \frac{c}{1 - \sigma} \quad \text{and} \quad p = 2 \frac{q_H q_L - \sigma(1 - q_H)(1 - q_L)}{q_H + q_L} \in (0, q_H)$$

We recognize π_J as the cost associated with the stark JPE contract discussed above. The inequality in (14) shows that this is the lowest cost to implement

high effort, subject to limited liability. But for $\eta > 0$ the bonuses must also satisfy the enforceability conditions. Using EA for $\beta_{HL}, \beta_{LH}, \beta_{LL}$ in (14) now yields (see the appendix):

$$\pi \geq \pi_J + \frac{p}{2}\eta\Delta Q + \underline{\beta}(\eta, \delta) = \pi_m(\eta, \delta) \quad (15)$$

where

$$\underline{\beta}(\eta, \delta) = \eta Q_L - \delta \left(\frac{c}{(1-\sigma)\Delta q} - \eta\Delta Q \right) \frac{\sigma + (1-\sigma)q_L^2}{q_H + q_L}$$

As in Section 3, we will also here restrict attention to cases where the hold-up problem is serious in the sense that $\pi_m(\eta, \delta) > \pi_J$ for all $\delta < 1$. This will occur when the hold-up parameter η exceeds some threshold. Define η_1 as the smallest value of η that makes the expression for $\underline{\beta}(\eta, \delta)$ positive for all $\delta < 1$, i.e.¹⁶

$$\eta_1 = \frac{c}{(1-\sigma)\Delta q} \frac{1}{\frac{q_H + q_L}{\sigma + (1-\sigma)q_L^2} Q_L + \Delta Q}$$

Reasoning as in the previous section we then obtain the following result (see the appendix):

Lemma 1 *For $\sigma < \hat{\sigma} = \frac{q_H q_L}{(1-q_H)(1-q_L)}$ we have: For $\eta \geq \eta_1$ the minimal wage cost subject to IC and EA is given by $\pi_m(\eta, \delta)$. This is attained when IC binds, and when EA binds for $\beta_{HL}, \beta_{LH}, \beta_{LL}$. The unique bonuses are given by*

$$\begin{aligned} \beta_{HH} &= \beta_{HL} + \frac{1}{q_H + q_L} \left(\frac{c}{(1-\sigma)\Delta q} - \eta\Delta Q \right) > \beta_{HL} = \beta_{LL} + \eta\Delta Q, \\ \beta_{LH} &= \beta_{LL} = \underline{\beta}(\eta, \delta) \end{aligned} \quad (16)$$

Remark. In the appendix we show that the optimal wage scheme given in the lemma ensures a high-effort equilibrium that is not Pareto dominated by a low-effort equilibrium.

The given wage scheme is JPE, but has a less stark form than the optimal scheme for verifiable output. And we see that the larger is the agent's ex post share η , the closer the scheme is to an IPE scheme; specifically we see that $\beta_{HH} - \beta_{HL} \rightarrow 0$ as $\eta \rightarrow \frac{c}{(1-\sigma)\Delta q\Delta Q}$. Note moreover that, since EA is

¹⁶ $\eta > \eta_1$ is sufficient, but not strictly necessary for $\pi_m(\eta, \delta) > \pi_J$. We restrict attention to $\eta > \eta_1$ to simplify the exposition.

binding for β_{LH} and β_{LL} , the EA constraints for the other bonuses take the form $\beta_{HI} - \beta_{LI} \geq \eta\Delta Q$, and these constraints can hence be represented as indicated in Figure 2. For the same reason the EP constraints can also be represented as indicated in that figure.

To be implementable, a wage scheme must also satisfy EP. We show in the appendix that the scheme given in Lemma 3 satisfies this constraint for $\delta \geq \delta_2$ defined by

$$\frac{1 - \delta_2}{\delta_2} = \frac{[(1 - \sigma)\Delta q\Delta Q - c]}{c/(1 - \sigma) - \eta\Delta q\Delta Q}(q_H + q_L)\Delta q$$

Note that δ_2 is decreasing in η . Hence, we have the following result.

Proposition 3 *For $\sigma < \hat{\sigma}$ we have: For $\eta \geq \eta_1$ and $\delta \geq \delta_2$ the JPE wage scheme given by (16) is implementable and uniquely optimal. As the share of values (η) that the agents can hold-up ex post increases, the scheme approaches an IPE scheme.*

For given $\eta \geq \eta_1$ and for discount factors smaller than the critical factor δ_2 , the scheme (16) will no longer be implementable. For $\delta = \delta_2$ the dynamic enforceability constraint for the principal (EP) is binding for β_{HH} (and only for this bonus), while the agent's constraint EA is binding for the other bonuses. The least costly way for the principal to adapt to a lower δ (and hence a stricter EP) will then be to reduce β_{HH} , and by that reduce the difference $\beta_{HH} - \beta_{HL}$. Note as well that a lower δ will also increase $\beta_{LH}, \beta_{LL}, \beta_{HL}$ when EA binds, see (16). Thus, a lower δ will force the principal to modify the scheme towards an IPE scheme. *To sum up: the possibility for the agents to hold-up values forces the principal to offer a greater extent of individualized incentives at the expense of team incentives, even when the agents' tasks are perfect complements*

So far we have only analyzed the case of a 'small' common shock; $\sigma < \hat{\sigma}$. The case $\sigma > \hat{\sigma}$ can be analyzed similarly. (Note that this case is only relevant if $q_H + q_L < 1$, since otherwise $\hat{\sigma} \geq 1$.) The reasoning leading to Lemma 1 and the discussion following Figure 2 indicates that for η exceeding some lower bound the minimal cost contract will be a modified RPE contract, graphically given by the south-east intersection of EA' and IC in Figure 2. This can be verified formally, and it can also be verified that this contract will satisfy EP and hence be fully implementable when δ exceeds some critical value $\delta'_2 < 1$ (cfr Proposition 3). Moreover, as η increases the contract will move towards an IPE contract.¹⁷ Formal proofs of these assertions are available from the authors.

¹⁷In the case $\sigma > \hat{\sigma}$ considered here, it turns out that the least-cost contract is not

4.2 Peer pressure

A more striking demonstration of the JPE hold-up problem can be made in a setting with peer pressure. In order to highlight the effects of this feature, we return to the case of stochastic and technological independence, i.e. $\sigma = 0$ and $q_{HL} = q_H$, as assumed in Section 3. To model peer pressure in this framework, we assume that there are costs associated with lowering the peer's wage by realizing low output, i.e. that agents experience disutility from being the "weakest link". Such an event will occur with probability $(1 - q_H)q_H$ if $\beta_{HH} > \beta_{HL}$. We represent this disutility by $d = \max\{\nu(\beta_{HH} - \beta_{HL}), 0\}$, where ν is a cost parameter.

This assumption is in some sense in the spirit of Kandell and Lazear (1992). They distinguish between internal peer pressure, or guilt, when effort is unobservable among the agents, and external pressure, or shame, when effort is observable. In our model, effort is unobservable, so our assumption can be interpreted as guilt. However, output is observable, so the weakest link effect can also be interpreted as shame. A point here is that our assumption is not directly related to the disutility from low effort. It is output that matters. Low effort gives no disutility if it leads to high output (which it does with probability q_L .) And high effort may induce disutility if it leads to low output. The shame interpretation is therefore most appropriate.

Let D denote the expected disutility associated with being the weakest link:

$$D = (1 - q_H)q_H d = (1 - q_H)q_H \max\{\nu(\beta_{HH} - \beta_{HL}), 0\}$$

In a high effort equilibrium, each agent's expected utility is now

$$\begin{aligned} \pi - D - c &= q_H [q_H \beta_{HH} + (1 - q_H) \beta_{HL}] \\ &\quad + (1 - q_H) [q_H (\beta_{LH} - d) + (1 - q_H) \beta_{LL}] - c \end{aligned}$$

where $\pi = \pi(H, H, \beta)$. This yields an IC constraint just as (IC) in Section 3, except that β_{LH} is replaced by $\beta_{LH} - d$. From this constraint and the definition of π we then obtain

$$\begin{aligned} \pi &= q_H [q_H \beta_{HH} + (1 - q_H) \beta_{HL}] + (1 - q_H) [q_H \beta_{LH} + (1 - q_H) \beta_{LL}] \\ &\geq \underline{q_H \left[\frac{c}{\Delta q} + q_H (\beta_{LH} - d) + (1 - q_H) \beta_{LL} \right] + (1 - q_H) [q_H \beta_{LH} + (1 - q_H) \beta_{LL}]} \end{aligned}$$

unique, as there is some leeway in specifying the bonuses β_{HL} and β_{LH} . The modified RPE contract is one optimal contract, and any optimal contract moves towards an IPE contract when η increases.

Hence, since $d = \max\{\nu(\beta_{HH} - \beta_{HL}), 0\}$:

$$\pi \geq q_H \frac{c}{\Delta q} - q_H^2 \max\{\nu(\beta_{HH} - \beta_{HL}), 0\} + q_H \beta_{LH} + (1 - q_H) \beta_{LL} \quad (17)$$

Ignoring enforceability constraints for the moment, we now see that if $\nu > 0$, the least costly contract has $\beta_{HL} = \beta_{LH} = \beta_{LL} = 0$ and $\beta_{HH} = \frac{c}{q_H \Delta q (1 + \nu)}$. (The latter value follows from the IC constraint, which for a contract $(\beta_{HH}, 0, 0, 0)$ here requires $q_H \beta_{HH} - q_H(-d) \geq \frac{c}{\Delta q}$.) The associated minimal wage cost is $\pi_m = q_H \frac{c}{\Delta q} \frac{1}{\nu + 1}$. We see that this wage cost is decreasing in ν , and hence lower than the cost for the case $\nu = 0$. This shows that, by offering incentives based on JPE, the principal can exploit the disutility effect of being the weakest link.

The minimal wage cost $\pi_m = q_H \frac{c}{\Delta q} \frac{1}{\nu + 1}$ is achievable if output is verifiable, or if the enforceability constraints (EA and EP) do not bind.¹⁸ Interestingly, we will now see that once the agent's enforceability constraints bind for low output (β_{LL} and β_{LH}), which will occur for η above some threshold, then the optimal scheme is not only a less stark JPE scheme; it is a pure IPE scheme. In fact, any JPE contract is then dominated by this IPE scheme.

The dynamic enforceability constraint EA for the agents here takes the form

$$\min\{\beta_{HH} - \eta Q_H, \beta_{HL} - \eta Q_H, \beta_{LH} - d - \eta Q_L, \beta_{LL} - \eta Q_L\} \geq \frac{\delta}{1 - \delta} [E(s) - \pi + D + c]$$

Using (17), which follows from the present IC-constraint, and EA for bonuses β_{LH} and β_{LL} , we get:

$$\pi \geq q_H \frac{c}{\Delta q} - q_H^2 d + \left(\eta Q_L + \frac{\delta}{1 - \delta} [E(s) - \pi + D + c] + q_H d \right)$$

Note that $-q_H^2 d + q_H d = D$. Collecting terms involving $\pi - D$ and substituting for $E(s) = \eta(Q_L + q_L \Delta Q)$ we then obtain

$$\pi \geq q_H \frac{c}{\Delta q} + \eta Q_L - \delta \left[\frac{c}{\Delta q} - \eta \Delta Q \right] q_L + D$$

We see that to minimize π , the principal will want to set D as small as possible i.e. make $d = \max\{\nu(\beta_{HH} - \beta_{HL}), 0\}$ as small as possible. This means setting $\beta_{HH} - \beta_{HL} = 0$, provided this is feasible by EP. It follows that

¹⁸It can be checked that for η and ν sufficiently small and for δ sufficiently large this least cost contract is implementable even if output is non-verifiable.

the IPE wage scheme together with the feasible RPE schemes satisfying the IC constraint with equality, are optimal once the enforceability conditions EA bind for low outputs (bonuses β_{LH} and β_{LL}).

We see that for $\eta \geq \eta_0$ given by (9) we have $\eta Q_L - \delta \left[\frac{c}{\Delta q} - \eta \Delta Q \right] q_L > 0$ for all $\delta < 1$, and so EA will indeed bind at outcomes LL and LH. Provided $\beta_{HH} - \beta_{HL} = 0$ is feasible (EP is satisfied), then EA' and IC' will hold. EP will be satisfied for this solution if EP' holds for $\beta_{HH} = \beta_{HL}$, which is the case if $2(\beta_{HH} - \beta_{LH} - \eta \Delta Q) \leq \frac{2\delta}{1-\delta} [\Delta q \Delta Q - c]$. From EA' and IC' we see that this holds if $\delta \geq \bar{\delta}$ given by

$$\frac{1 - \bar{\delta}}{\bar{\delta}} = \frac{[\Delta q \Delta Q - c]}{\frac{c}{\Delta q} - \eta \Delta Q}$$

For $\delta \geq \bar{\delta}$ an IPE wage scheme ($\beta_{HH} = \beta_{HL}$) is thus optimal.¹⁹ We have the following result:

Proposition 4 *When there is peer pressure ($\nu > 0$) and agent hold-up ($\eta \geq \eta_0$) we have: For $\delta \geq \bar{\delta}$ an IPE wage scheme (with $\beta_{HH} = \beta_{HL}$) satisfying (10), IC and EA' is feasible and optimal. The minimal wage cost is π_{\min} given in (8). Any wage scheme with $\beta_{HH} - \beta_{HL} > 0$ yields a strictly larger cost, thus any JPE scheme is strictly inferior to IPE (and feasible RPE schemes).*

The intuition for this result goes as follows: If the agents can renegotiate a spot price, they are able to avoid the disutility effects from peer pressure, since a spot price is equivalent to an IPE scheme. In order to implement JPE, the principal then has to compensate the agents for the peer pressure effect. But then JPE becomes more expensive than IPE or RPE, where no such effects exist. In other words: once the spot price becomes sufficiently tempting, the principal can no longer use JPE to exploit the effects of peer pressure, but has to compensate the agents for any disutility effects that team incentives provide.

5 Concluding remarks

In an interesting review of the history of employment relationships, Peter Cappelli (2000) argues that the last twenty years have seen a dramatic shift from traditional bureaucratic employment structures to "inside contracting

¹⁹It can be seen that for sufficiently low discount factors the "commitment advantage" of RPE dominates the peer-dependence effect, making RPE optimal. The commitment advantage of RPE (with no agent hold-up) is analyzed in Kvaløy and Olsen (2006).

systems (...) shaped by individualized incentives and pressures from outside labor markets. Along the same lines, Levin and Tadelis (2005) argue that greater competition in the labour market and changes in market information has made it less valuable to commit to the profit sharing plans of professional partnerships.

In this paper we offer a model that elucidates these developments. We have shown that compensation tied to peer performance can induce employee hold-up and obstruct the implementation of relational incentive contracts. The model presented may thus explain the tendency to use individual performance pay in human-capital-intensive industries. Tremblay and Chenevert (2004) and Appelbaum (1991) note that even if knowledge-based industries are characterized by teamwork, the challenge to retain the most critical resources increases the pertinence of rewarding individual performance. Our model supports this conjecture.

In addition, the model can contribute to explain why relative performance evaluation is used less in CEO compensation than agency theory suggests.²⁰ Even though our model has a multilateral feature, i.e. one principal contracting with two agents, what drives our result is the agents' temptations to renegotiate when not being paid according to absolute output. A CEO interpretation is therefore not unreasonable since they are in the position of holding up values ex post if not being paid a "fair share" of their value added.

There is a large literature discussing human capital and problems of expropriation in modern corporations. Recent papers include Kessler and Lulfesmann (2006) who show how the firm can balance incentive provision between general and firm specific investments in human capital in order to mitigate the hold-up problem; and Rajan and Zingales (2001) who argue that human-capital-intensive industries will develop flat organizations with distinctive technologies and cultures in order to avoid expropriation. We complement this literature by showing how indispensable human capital affects the firm's feasible incentive design.

Our model also complements the seminal paper by Holmström and Milgrom (1994). They show how asset ownership gives a firm the ability to restructure the incentives of those who join the firm (the employees). In particular, they show how a firm - by giving up control rights - loses the ability to balance incentives between various tasks. We show how the firm - by giving up control rights - loses the ability to exploit the advantages that

²⁰See Murphy (1999) who states that 'the paucity of RPE in options and other components of executive compensation remains a puzzle worth understanding'. See also Aggarwal and Samwick (1999).

lie in designing peer-dependent incentives.

Appendix

Proof of Proposition 1

Consider first the principal's enforceability constraint EP. The constraint binds when $\beta_{kl} + \beta_{lk} - \eta(Q_k + Q_l)$ is maximal. We can thus write the constraint as

$$\begin{aligned} \max \{2\beta_{HH} - 2\eta Q_H, \beta_{HL} + \beta_{LH} - \eta(Q_H + Q_L), 2\beta_{LL} - 2\eta Q_L\} \\ \leq \frac{2\delta}{1-\delta} [\Delta q \Delta Q + E(s) - \pi(H, H, \boldsymbol{\beta})] \quad (\text{EP}) \end{aligned}$$

When the EA constraints are binding for β_{LH} and β_{LL} , we have $\beta_{LH} = \beta_{LL} = \frac{\delta}{1-\delta} [E(s) - \pi(H, H, \boldsymbol{\beta}) + c]$. Subtracting $2\beta_{LL} - 2\eta Q_L$ on both sides then yields (recalling $\beta_{LH} = \beta_{LL}$):

$$\max \{2(\beta_{HH} - \beta_{LH} - \eta \Delta Q), (\beta_{HL} - \beta_{LL} - \eta \Delta Q), 0\} \leq \frac{2\delta}{1-\delta} [\Delta q \Delta Q - c]$$

We see that this is equivalent to the condition EP' given in the text, because the EA constraints for β_{HH} and β_{HL} are here equivalent to $\beta_{Hl} - \beta_{Ll} - \eta \Delta Q \geq 0$, $l = H, L$.

Consider now statement (i) in Proposition 1. It follows from the geometry of Figure 1 that the minimal discount factor $\delta = \hat{\delta}$ for which a bonus scheme satisfying IC and EA' also satisfies EP' is obtained when the kink of the EP' curve in Figure 1 is positioned on IC, i.e. when EP', IC and $2(\beta_{HH} - \beta_{LH} - \eta \Delta Q) = \beta_{HL} - \beta_{LL} - \eta \Delta Q$ hold jointly. The last two conditions yield

$$q_H(\beta_{HH} - \beta_{LH}) + (1 - q_H)(2(\beta_{HH} - \beta_{LH}) - \eta \Delta Q) = \frac{c}{\Delta q}$$

and hence $(2 - q_H)(\beta_{HH} - \beta_{LH}) = \frac{c}{\Delta q} + (1 - q_H)\eta \Delta Q$. Inserting this in EP' yields the following condition for $\hat{\delta}$

$$\left(\frac{c}{(2 - q_H)\Delta q} + \frac{1 - q_H}{2 - q_H} \eta \Delta Q \right) - \eta \Delta Q = \frac{\hat{\delta}}{1 - \hat{\delta}} [\Delta q \Delta Q - c]$$

This coincides with (11), and hence proves statement (i).

It remains to prove statement (ii). By definition of δ no wage scheme can satisfy IC and EP' for $\delta < \hat{\delta}$. The statement then follows when we show that EP' is a necessary condition for implementability. To prove this, first note that EA implies

$$\beta_{Lj} - \eta Q_L \geq \frac{\delta}{1-\delta} [E(s) - \pi + c], \quad j = H, L, \quad (\pi = \pi(H, H, \boldsymbol{\beta})).$$

Condition EP implies

$$\begin{aligned} 2(\beta_{HH} - \beta_{LH} - \eta\Delta Q) + 2(\beta_{LH} - \eta Q_L) &= 2(\beta_{HH} - \eta Q_H) \\ &\leq \frac{2\delta}{1-\delta} [\Delta q \Delta Q - \pi + E(s)] \end{aligned}$$

and

$$\begin{aligned} (\beta_{HL} - \beta_{LL} - \eta\Delta Q) + (\beta_{LH} - \eta Q_L) + (\beta_{LL} - \eta Q_L) \\ = (\beta_{HL} + \beta_{LH} - \eta Q_H - \eta Q_L) \\ \leq \frac{2\delta}{1-\delta} [\Delta q \Delta Q - \pi + E(s)] \end{aligned}$$

Using these three inequalities we see that EP' follows. This completes the proof.

Remark Proposition 1

We here verify the statements made in the remark to Proposition 1. For any contract $\boldsymbol{\beta}$ with $\beta_{LH} = \beta_{LL}$ we have $\pi(\lambda, \kappa, \boldsymbol{\beta}) = q_\lambda [q_\kappa \beta_{HH} + (1 - q_\kappa) \beta_{HL}] + (1 - q_\lambda) \beta_{LL}$ and hence

$$\begin{aligned} \pi(H, H, \boldsymbol{\beta}) - \pi(H, L, \boldsymbol{\beta}) + \pi(L, L, \boldsymbol{\beta}) - \pi(L, H, \boldsymbol{\beta}) \\ = q_H ([q_H \beta_{HH} + (1 - q_H) \beta_{HL}] - [q_L \beta_{HH} + (1 - q_L) \beta_{HL}]) \\ + q_L ([q_L \beta_{HH} + (1 - q_L) \beta_{HL}] - [q_H \beta_{HH} + (1 - q_H) \beta_{HL}]) \\ = (q_H - q_L)^2 (\beta_{HH} - \beta_{HL}) \end{aligned}$$

When IC binds ($\pi(H, H, \boldsymbol{\beta}) - c = \pi(L, H, \boldsymbol{\beta})$) we thus have

$$\pi(L, L, \boldsymbol{\beta}) - (\pi(H, L, \boldsymbol{\beta}) - c) = (q_H - q_L)^2 (\beta_{HH} - \beta_{HL})$$

This is negative for RPE contracts, hence efforts HH is then a unique equilibrium for the given contract. The expression is however non-negative for JPE or IPE contracts, hence efforts LL is then another equilibrium.

Next compare equilibrium payoffs. Note that for $\beta_{LH} = \beta_{LL}$ we have

$$\begin{aligned} \pi(L, L, \boldsymbol{\beta}) - \pi(L, H, \boldsymbol{\beta}) &= q_L ([q_L \beta_{HH} + (1 - q_L) \beta_{HL}] - [q_H \beta_{HH} + (1 - q_H) \beta_{HL}]) \\ &= -q_L (q_H - q_L) (\beta_{HH} - \beta_{HL}) \end{aligned}$$

Hence for a JPE or IPE contract with IC binding we have

$$\pi(L, L, \boldsymbol{\beta}) \leq \pi(L, H, \boldsymbol{\beta}) = \pi(H, H, \boldsymbol{\beta}) - c$$

with strict inequality for JPE. Thus the HH equilibrium yields a higher payoff than the LL equilibrium, and strictly so for a JPE contract.

Verification of (12 - 13).

We verify here that (12 - 13) hold for the schemes stated in Proposition 1 when $\delta \geq \hat{\delta}$. We have

$$\begin{aligned} \pi - E(s) &= \left(q_H \frac{c}{\Delta q} + \eta Q_L - \delta \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L \right) - \eta (Q_L + \Delta Q q_L) \\ &= q_L \frac{c}{\Delta q} + c - \delta \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L - \eta \Delta Q q_L \\ &= (1 - \delta) \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L + c \end{aligned}$$

This shows that $\pi - E(s) > c$, hence (12) holds. We further have

$$\pi - E(s) - c < (1 - \delta) \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L$$

$$\begin{aligned}
&= \hat{\delta} \frac{[\Delta q \Delta Q - c]}{c - \eta \Delta Q \Delta q} \Delta q (2 - q_H) \left(\frac{c}{\Delta q} - \eta \Delta Q \right) q_L \\
&= \hat{\delta} [\Delta q \Delta Q - c] (2 - q_H) q_L < [\Delta q \Delta Q - c]
\end{aligned}$$

where the last inequality follows from $\hat{\delta} < 1$ and $(2 - q_H)q_L < (2 - q_H)q_H < 1$. Hence we see that (13) holds.

Verification of (14 - 15).

Substituting from β_{HH} from (IC_t) in the expression for $\pi = \pi(H, H, \beta)$ yields

$$\begin{aligned}
\pi \geq & \frac{\sigma + (1 - \sigma)q_H^2}{q_H + q_L} \left(\frac{c}{(1 - \sigma)\Delta q} - [1 - q_H - q_L](\beta_{HL} + \beta_{LH}) + [2 - q_H - q_L]\beta_{LL} \right) \\
& + (1 - \sigma) \{ q_H(1 - q_H)(\beta_{HL} + \beta_{LH}) + (1 - q_H)^2\beta_{LL} \}
\end{aligned}$$

Hence, defining $\pi_J = \frac{\sigma + (1 - \sigma)q_H^2}{q_H + q_L} \frac{c}{(1 - \sigma)\Delta q}$ we have

$$\begin{aligned}
\pi \geq & \pi_J + \left((1 - \sigma)q_H(1 - q_H) - [\sigma + (1 - \sigma)q_H^2] \left(\frac{1}{q_H + q_L} - 1 \right) \right) (\beta_{HL} + \beta_{LH}) \\
& + \left((1 - \sigma)(1 - 2q_H + q_H^2) + [\sigma + (1 - \sigma)q_H^2] \left(\frac{2}{q_H + q_L} - 1 \right) \right) \beta_{LL} \\
= & \pi_J + \left(\sigma + (1 - \sigma)q_H - \frac{\sigma + (1 - \sigma)q_H^2}{q_H + q_L} \right) (\beta_{HL} + \beta_{LH}) \\
& + \left(1 - 2\sigma - 2(1 - \sigma)q_H + 2 \frac{\sigma + (1 - \sigma)q_H^2}{q_H + q_L} \right) \beta_{LL}
\end{aligned}$$

This verifies (14), since the coefficient for $(\beta_{HL} + \beta_{LH})$ equals $\frac{q_H q_L - \sigma(1 - q_H)(1 - q_L)}{q_H + q_L} = \frac{p}{2}$.

Substituting then from EA for $\beta_{HL}, \beta_{LH}, \beta_{LL}$ in (14) we get

$$\pi \geq \pi_J + \frac{p}{2} \eta \Delta Q + \left(\eta Q_L + \frac{\delta}{1 - \delta} (E(s) - (\pi - c)) \right)$$

Collecting terms involving π and substituting for $E(s) = \eta(Q_L + (\sigma + (1 - \sigma)q_L) \Delta Q)$ then yields

$$\begin{aligned}
\pi \geq & (1 - \delta) \left(\pi_J + \frac{p}{2} \eta \Delta Q \right) + (1 - \delta) \eta Q_L + \delta [\eta(Q_L + (\sigma + (1 - \sigma)q_L) \Delta Q) + c] \\
= & \left(\pi_J + \frac{p}{2} \eta \Delta Q + \eta Q_L \right) - \delta \left[(\pi_J - c) + \frac{p}{2} \eta \Delta Q - \eta(\sigma + (1 - \sigma)q_L) \Delta Q \right] \\
= & \pi_J + \frac{p}{2} \eta \Delta Q + \eta Q_L - \delta \left(\frac{\sigma + (1 - \sigma)q_L^2}{(q_H^2 - q_L^2)(1 - \sigma)} c - \frac{\sigma + (1 - \sigma)q_L^2}{q_H + q_L} \eta \Delta Q \right)
\end{aligned}$$

where the last equality follows from $\pi_J - c = \frac{\sigma + (1 - \sigma)q_H^2}{q_H^2 - q_L^2} \frac{c}{1 - \sigma} - c = \frac{\sigma + (1 - \sigma)q_L^2}{(q_H^2 - q_L^2)(1 - \sigma)} c$

and

$$(\sigma + (1 - \sigma)q_L) - \frac{p}{2} = (\sigma + (1 - \sigma)q_L) - \frac{q_H q_L - \sigma(1 - q_H)(1 - q_L)}{q_H + q_L} = \frac{\sigma + (1 - \sigma)q_L^2}{q_H + q_L}$$

Hence we have

$$\pi \geq \pi_J + \frac{p}{2}\eta\Delta Q + \eta Q_L - \delta \left(\frac{c}{\Delta q(1 - \sigma)} - \eta\Delta Q \right) \frac{\sigma + (1 - \sigma)q_L^2}{q_H + q_L}$$

This verifies (15).

Proof of Lemma 1

Note first that $\eta_1 \Delta q \Delta Q (1 - \sigma) < c$ for $Q_L > 0$, hence (4) is satisfied. The derivation of (15) shows that for $\eta \geq \eta_1$ the minimal wage cost is given by $\pi_m(\eta, \delta)$, and that the minimum is attained when IC binds and EA binds for $\beta_{HL}, \beta_{LH}, \beta_{LL}$.

To verify the expression for β_{LL} note that (14) may be written as $\pi \geq \pi_J + \frac{p}{2}((\beta_{HL} - \beta_{LL}) + (\beta_{LH} - \beta_{LL})) + \beta_{LL}$. When EA binds for $\beta_{HL}, \beta_{LH}, \beta_{LL}$ the RHS equals $\pi_m(\eta, \delta)$, and we thus have $\pi_m(\eta, \delta) = \pi_J + \frac{p}{2}\eta\Delta Q + \beta_{LL}$. This yields the stated expression for β_{LL} . Next, substituting for $\beta_{LH} = \beta_{LL} = \beta_{HL} - \eta\Delta Q$ in (IC_t) and solving this for β_{HH} when the constraint binds then yields the stated expression for β_{HH} . To see this, note that the substitution yields

$$[q_H + q_L]\beta_{HH} + [1 - q_H - q_L](2\beta_{HL} - \eta\Delta Q) - [2 - q_H - q_L](\beta_{HL} - \eta\Delta Q) = \frac{c}{(1 - \sigma)\Delta q}$$

Solving this for β_{HH} yields the stated expression.

Remark to Lemma 1

We here verify the statements made in the remark to Lemma 1. From the assumption of perfect complementarity we have now $\pi(H, L, \beta) = \pi(L, L, \beta) = \pi(L, H, \beta)$, and for a contract with $\beta_{LH} = \beta_{LL}$ we have then

$$\begin{aligned} \Delta\pi &\equiv \{\pi(H, H, \beta) - \pi(H, L, \beta) + \pi(L, L, \beta) - \pi(L, H, \beta)\} / (1 - \sigma) \\ &= q_H [q_H \beta_{HH} + (1 - q_H)\beta_{HL}] + (1 - q_H)\beta_{LL} \\ &\quad - q_L [q_L \beta_{HH} + (1 - q_L)\beta_{HL}] - (1 - q_L)\beta_{LL} \\ &= (q_H - q_L)^2 (\beta_{HH} - \beta_{HL}) + (q_H - q_L)(\beta_{HL} - \beta_{LL}) \end{aligned}$$

The expression is positive for the JPE contract given in Lemma 1. When IC binds ($\pi(H, H, \beta) - c = \pi(L, H, \beta)$) we thus have

$$\pi(L, L, \beta) - (\pi(H, L, \beta) - c) = \Delta\pi > 0,$$

hence efforts LL is then another equilibrium.

Comparing equilibrium payoffs, we have $\pi(L, L, \beta) = \pi(L, H, \beta)$ by perfect complementarity and $\pi(L, H, \beta) = \pi(H, H, \beta) - c$ when IC binds. Hence $\pi(L, L, \beta) = \pi(H, H, \beta) - c$ for the contract given in Lemma 1. The two effort equilibria thus yield equal payoffs. (We may note that with less than perfect complementarity; $q_H > q_{HL} > q_L$, we would have $\pi(L, L, \beta) < \pi(L, H, \beta)$ and $\Delta\pi > 0$ for the optimal JPE contract, and hence a strictly higher payoff for efforts HH than for efforts LL.)

Proof of Proposition 3

We must show that the bonuses given by (16) satisfy EP for $\delta \geq \delta_2$. These bonuses satisfy $\beta_{HH} > \beta_{HL} = \beta_{LL} + \eta\Delta Q$ and $\beta_{LH} = \beta_{LL}$. This implies $2\beta_{HH} - 2\eta Q_H > 2\beta_{HL} - 2\eta Q_H = \beta_{HL} + \beta_{LH} - \eta(Q_H + Q_L) = 2\beta_{LL} - 2\eta Q_L$. We moreover have from EA $\frac{\delta}{1-\delta} (E(s) - \pi(H, H, \beta) + c) = \beta_{LL} - \eta Q_L$. So EP is here

$$\beta_{HH} - \eta Q_H \leq \frac{\delta}{1-\delta} [(1-\sigma)\Delta q\Delta Q - c] + \beta_{LL} - \eta Q_L$$

Thus from (16) this inequality is

$$\frac{1}{q_H + q_L} \left(\frac{c}{(1-\sigma)\Delta q} - \eta\Delta Q \right) \leq \frac{\delta}{1-\delta} [(1-\sigma)\Delta q\Delta Q - c]$$

We see that δ_2 is defined as the minimal δ satisfying this inequality. This completes the proof.

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