Cooperation in knowledge-intensive firms

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July 31, 2007

Abstract

The extent to which a knowledge-intensive firm should induce cooperation between its employees is analyzed in a model of relational contracting between a firm (principal) and its employees (two agents). The agents can cooperate by helping each other, i.e. provide effort that increases the performance of their peer without affecting their own performance. We extend the existing literature on agent-cooperation by analyzing the implications of incomplete contracts and agent hold-up. A main result is that if the agents' hold-up power is sufficiently high, then it is suboptimal for the principal to implement cooperation, even if helping effort is productive per se. This implies, contrary to many property rights models, that social surplus may suffer if the investing parties (here the agents) are residual claimants. The model also shows that long-term relationships facilitate cooperation even if the agents cannot monitor or punish each others effort choices.

1 Introduction

There seems to be a consensus among scholars in human resource management (HRM) that teamwork or cooperation is particularly important in knowlegde-intensive organizations. It is argued that teams are essential for knowledge sharing and innovation (see e.g. Cano and Cano, 2006), and that knowledge-intensive firms should therefore adopt compensation plans that reward cooperation (see e.g. Balkin and Banister, 1993). In this paper we argue that, although it may well be the case that teamwork is important in human-capital-intensive firms, one should expect a positive relationship

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between a firm's human-capital-intensity and the costs of implementing cooperation.

It is a well known result from the theory of task allocation that agent cooperation is favorable if there are complementarities between the agents' efforts, see e.g. Drago and Turnbull (1988, 1991), Itoh (1991, 1992), Holmström and Milgrom (1990), Ramakrishnan, and Thakor (1991), Macho-Stadler and Perez-Castrillo, (1993), for static relationships, and Che and Yoo (2001) for the case of repeated peer-monitoring. But these results are deduced from models assuming that contracts are complete and output is verifiable, so that both the principal and the agents can commit to contracts inducing any kind of cooperative behavior. In this paper we show that if output is non-verifiable, and the agents posses some form of ex post hold-up power, then it may be suboptimal to implement cooperation, i.e. induce the agents to help each other, even if it is optimal in the verifiable case. An agent has hold-up power if he is able to prevent the principal from extracting values ex post the agent's production. This is most common in human-capital intensive firms, where agents to a larger extent possess *essential* human capital that makes them ex post indispensable, or possess some kind of ownership rights to ideas, clients or production technologies that make them able to exploit ex post outside opportunities.[1] We show that there can be a critical level of agent hold-up power that determines when it is optimal to implement cooperation. If the agents' hold-up power is sufficiently high, then it is suboptimal to implement cooperation, even if cooperation is productive per se.

The intuition behind this result is quite simple: In order to induce cooperation, the principal must implement some form of group-based incentive schemes that makes it profitable for the agents to help each other, i.e. to provide costly effort that increases the performance of their peers without affecting their own performance. But group-based pay is susceptible to agent hold-up since an agent who performs well in a given period, is tempted to hold-up output and renegotiate his pay if his peers' performances are poor that period. He thereby obstructs the incentive scheme necessary for implementing cooperation. The parties can mitigate this hold-up problem through repeated interaction, i.e. through self-enforcing relational contracting where contract breach is punished, not by the court, but by the parties themselves who can refuse to engage in relational contracting after a deviation.[2] Since

[1] Indispensability is mainly achieved through firm-specific human capital, which is shown to be strongly associated with high levels of education (see Blundell et al., 1999).

[2] Influential models of relatonal contracts include Klein and Leffler (1981), Shapiro and Stiglitz (1984), Bull (1987), Baker, Gibbons and Murphy (2002), MacLeod and Malcomson (1989) generalize the case of symmetric information, while Levin (2003) makes a

a hold-up will be regarded as a deviation from such a relational contract, the self-enforcing range of the contract is limited by the hold-up problem. If the agents' hold-up power is sufficiently high, it may therefore be more costly to implement a relational contract inducing helping effort, than to just implement individualized incentives that trigger non-cooperative effort.

Interestingly, it follows from the analysis that not only the principal's profit, but also the social surplus may decrease if the agents' hold-up power is sufficiently high. This is at variance with the established idea from the property rights approach that the investing parties, the agents in our model, should be residual claimants (Grossman and Hart, 1986, and Hart and Moore, 1990). In our model, residual control rights in the hands of the agents trigger own efforts, but obstruct the principal from implementing socially efficient cooperation.

A secondary result from our analysis is that long-term relationships facilitate agent-cooperation even if the agents cannot monitor or punish each-others effort decisions. This result complements the existing literature on team incentives in repeated settings, such as Che and Yoo (2001) where repeated peer-monitoring makes cooperation easier to sustain.[3] In our model, a higher discount factor eases the implementation of relational contracts, making it less costly for the principal to implement cooperation even if there is no peer sanctioning

To our knowledge, this paper is the first to consider the problem of implementing agent cooperation in a relational contracting model. It is also the first paper to consider the effect of agent hold-up on helping effort. The paper is related to our companion paper (Kvaløy and Olsen, 2006b), where we investigate the problem of implementing peer-dependent incentives schemes when agents are ex post indispensable.[4] But that paper does not consider a multitask situation where the agents are allowed to help each other, which is the main feature of the model presented here. In spirit, the paper is related to Auriol and Friebel (2002) who show how limited principal commitment in a two period model of career concerns can reduce the agents incentives to help each other, since the agents expect that their *relative* productivity in period one will determine their fixed salary in period two. In our model,

general treatment of relational contracts with asymmetric information, allowing for incentive problems due to moral hazard and hidden information.

[3]Radner (1986), Weitzman and Kruse, (1990), and FitzRoy and Kraft (1995) have all pointed out that the folk theorem of repeated games provides a possible answer to the free rider critique of group incentives. But Che and Yoo (2001) is the first to demonstrate this in a repeated game between the agents. See also Ishida (2006).

[4]Kvaløy and Olsen (2006a) analyze peer-monitoring and collusion in a relational contracting model with no agent-hold-up.

their are no internal career concerns, i.e. productivity and expected wage remain the same in all periods. What drives the results is the agents' potential exploitation of ex post outside opportunities.

Broadly speaking, a contribution of the paper, together with our companion paper (Kvaløy and Olsen, 2006b), 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 growing literature dealing with optimal allocation of control rights, the multiagent moral hazard problem is not considered. (This literature begins with Grossman and Hart, 1986; and Hart and More,1990,[5] who analyze static relationships. Repeated relationships are analyzed in particular by Halonen, 2002; and Baker, Gibbons and Murphy, 2002). A contribution of the paper is thus to consider the effect of workers possessing residual control rights when the firm faces a multiagent moral hazard problem.

2 The Model

There are basically two kinds of agent-cooperation. One is where agents cooperate performing a common task, a second is where agents help each other performing each others' tasks. In this paper we focus on the latter since it represents the purest form of cooperative behavior. In particular we assume that an agent who helps his peer does not increase his chance to succeed on his own task, cet par.

We consider a relationship between a principal and two agents ($i = 1, 2$), who each period can either succeed or fail when performing a task for their principal. Success yields high value Q_H , while failure yields low value Q_L. The agents can exert effort in order to increase the probability of success on their own task. In addition they can help each other and thereby increase the probability of success for their peer. Let e_i denote agent i's *own effort* and a_i denote *helping effort.* Efforts can be either high (1) or low (0), where high effort has a cost c for own effort and c_A for helping effort. Low effort is costless. The probabilities for success is then $\Pr(success) = p_i(e_i, a_j)$ for agent i.[6]

[5] 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.

[6] The basic set-up is a simple version of the more general model analyzed by Hideshi Itoh in his seminal 1991- paper. For tractability reasons, our relational contracting extension makes it necessary to simplify Itoh's set up.

Our restrictions on effort levels make it impossible for an agent who exert high effort on his own project, to trade-off helping effort with 'even higher' own effort. This is done for tractability reasons, and is not necessary for our main results to go through. However, it is not entirely unrealistic to assume that there is a limit on how much valuable effort an agent can exert on a given project. If the agent has more time to spend before starting on tomorrow's project, he can spend it on helping others. Proof-reading papers can serve as an example. There is a limit on how many times you can read your own paper, and still find new errors. Reading your colleague's paper, and make him read yours, may though be valuable.

We assume that the 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, not his effort level. Whether or not the agents can observe each others effort choices is not decisive for the analysis presented. However, by assuming that effort is unobservable among the agents, we get stronger results, since we do not need to rely on repeated peer monitoring and peer-sanctions.

We assume that if the parties engage in an incentive contract, agent i receives a bonus vector $\boldsymbol{\beta} \equiv (\beta_{HH}, \beta_{HL}, \beta_{LH}, \beta_{LL})$ where the subscripts refer to respectively agent i and agent j's realization of Q_k and Q_l **,** $k, l \in \{L, H\}$**.**

Agent i's expected wage is then

$$\begin{aligned} \omega^i &= p_i \left[p_j \beta_{HH} + (1-p_j)\beta_{HL}\right] + (1-p_i)\left[p_j \beta_{LH} + (1-p_j)\beta_{LL}\right] \qquad (1) \\ &= p_i \left[p_j \left(\beta_{HH} - \beta_{LH}\right) + (1-p_j)\left(\beta_{HL} - \beta_{LL}\right)\right] + p_j \left(\beta_{LH} - \beta_{LL}\right) + \beta_{LL} \end{aligned}$$

It is assumed that all parties are risk neutral, but that the agents are subject to limited liability: the principal cannot impose negative wages.[7] Ex ante outside options are normalized to zero.

2.1 Optimal contract when output is verifiable

We first consider the least cost incentive contract when output is verifiable. The principal will minimize wages subject to the constraint that the agents must be induced to yield the desired levels of effort and help. Let the prob-

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

ability levels for each agent be denoted:

$$\begin{aligned}
p_i(e_i, a_j) &= q_{11} \text{ if both } e_i, a_j \text{ high } (e_i = a_j = 1) \\
p_i(e_i, a_j) &= q_{10} \text{ if high effort } e_i\text{, but no help } (e_i = 1,\ a_j = 0) \\
p_i(e_i, a_j) &= q_{01} \text{ if low effort, but help } (e_i = 0,\ a_j = 1) \\
p_i(e_i, a_j) &= q_{00} \text{ if neither effort nor help } (e_i = a_j = 0)
\end{aligned}$$

Suppose the principal wants to implement high effort and help from both agents. The incentive compatibility constraints (IC) for each agent can then be written as follows:

IC for not shirking help (ICa):

$$\begin{aligned}
& q_{11}\left[q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{11}\left(\beta_{LH}-\beta_{LL}\right)-c-c_A \\
\geq\ & q_{11}\left[q_{10}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{10}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{10}\left(\beta_{LH}-\beta_{LL}\right)-c
\end{aligned}$$

IC for not shirking own effort, but maintain help (ICe):

$$\begin{aligned}
& q_{11}\left[q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{11}\left(\beta_{LH}-\beta_{LL}\right)-c-c_A \\
\geq\ & q_{01}\left[q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{11}\left(\beta_{LH}-\beta_{LL}\right)-c_A
\end{aligned}$$

In addition there is an IC constraint for not shirking both effort and help. We show in the appendix that this constraint is satisfied when the former two both hold.

A little algebra shows that the constraints above can be written, respectively, as follows:

$$q_{11}\left(\beta_{HH}-\beta_{HL}\right)+\left(1-q_{11}\right)\left(\beta_{LH}-\beta_{LL}\right) \geq \frac{c_A}{\left(q_{11}-q_{10}\right)} \tag{ICa}$$

$$q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right) \geq \frac{c}{\left(q_{11}-q_{01}\right)} \tag{ICe}$$

Using ICe in the expression (1) for the expected wage cost ω^1 for agent 1 yields (since $p_1 = p_2 = q_{11}$)

$$\begin{aligned}
\omega^1 &\geq p_1 \frac{c}{\left(q_{11}-q_{01}\right)}+p_2\left(\beta_{LH}-\beta_{LL}\right)+\beta_{LL} \\
&= q_{11} \frac{c}{\left(q_{11}-q_{01}\right)}+q_{11} \beta_{LH}+\left(1-q_{11}\right) \beta_{LL} \qquad (2)
\end{aligned}$$

Similarly, using ICa in the expression (1) for ω^1 yields

$$\omega^1 \geq q_{11} \frac{c_A}{(q_{11} - q_{10})} + q_{11}\beta_{HL} + (1 - q_{11})\beta_{LL} \tag{3}$$

Due to limited liability ($\beta_{ij} \geq 0$) we clearly have

$$\omega^1 \geq \max\left\{ \frac{c}{(q_{11} - q_{01})}, \frac{c_A}{(q_{11} - q_{10})} \right\} q_{11} \doteq \omega_V(c, c_A, q)$$

Also, this lower bound can be attained by setting $\beta_{LL} = 0$, and either β_{LH} or β_{HL} (or both) to zero. Thus we have:

Lemma 1 *Suppose $\omega_V(c, c_A, q) \geq c + c_A$, which holds e.g. if $q_{11} \leq 2\max\{q_{01}, q_{10}\}$. If output is verifiable, the minimal wage cost (per agent) to implement effort & help is then given by $\omega_V(c, c_A, q)$. This minimal cost is attained by setting $\beta_{LL} = 0$ and $\beta_{LH} \cdot \beta_{HL} = 0$ as follows:*
If $C \doteq \frac{c}{(q_{11}-q_{01})} - \frac{c_A}{(q_{11}-q_{10})} \geq 0$, then $\beta_{LH} = 0$ and ICe is binding, while if $C \leq 0$, then $\beta_{HL} = 0$ and ICa is binding.

In the appendix it is shown that this scheme also satisfies the IC condition for not shirking both effort and help.

As noted in the lemma, there are two cases, depending on whether $C \geq 0$ or $C < 0$. The latter case appears to be the most reasonable; it means that help is less productive (per unit of effort cost) than own effort. Note that a cost minimizing scheme in this case has $\beta_{LL} = 0$ and $\beta_{HL} = 0$, hence it has the feature that an agent never gets a bonus if his partner has a bad outcome. This stimulates cooperation, and is the least costly way to do so when help is less productive than own effort ($C < 0$). The bonus scheme has ICa binding (so $q_{11}\beta_{HH} + (1 - q_{11})\beta_{LH} = \frac{c_A}{q_{11}-q_{10}}$) and must satsify ICe (so $q_{11}(\beta_{HH} - \beta_{LH}) \geq \frac{c}{q_{11}-q_{01}}$). The latter naturally requires that an agent's bonus when both he and his peer succeed must exceed his bonus when he himself fails but his partner succeeds. But the latter bonus may well be positive.

Case: additive probabilities. It will be instructive to consider an additive structure where we have

$$q_{ij} = r_i + s_j, \qquad \text{with} \quad r_1 - r_0 = r > 0 \quad \text{and} \quad s_1 - s_0 = s > 0 \tag{4}$$

This specification implies that the marginal productivity of help ($(q_{i1} - q_{i0})(Q_H - Q_L)$) is independent of the level of effort and vice versa. In this case the first condition in the lemma will always hold, and so $\omega_V(c, c_A, q)$ will indeed be the minimal wage cost to implement effort and help. This holds because we here have $\omega_V = (r + s + q_{00}) \max\left\{\frac{c}{r}, \frac{c_A}{s}\right\} \geq c + c_A$.

We will focus on cases where it is optimal for the firm to implement both effort and help when output is verifiable. The lemma shows that the profit generated by doing so is

$$\Pi_{11} = 2Q_L + 2\left[q_{11}\Delta Q - \omega_V(c, c_A, q)\right],$$

where $\Delta Q = Q_H - Q_L$. For this to be optimal the last term must be positive, and this profit must dominate the profit generated by just implementing effort without help; i.e.[8]

$$\Pi_{11} \geq \Pi_{10} = 2Q_L + 2q_{10}\left[\Delta Q - \frac{c}{(q_{10} - q_{00})}\right]$$

It must also dominate the profit generated by just implementing help without own effort, i.e.

$$\Pi_{11} \geq \Pi_{01} = 2Q_L + 2q_{01}\left[\Delta Q - \frac{c_A}{(q_{01} - q_{00})}\right]$$

All this will hold if ΔQ is sufficiently large, or if $(q_{01} - q_{00})$ and $(q_{10} - q_{00})$ are both 'small' and $(q_{11} - q_{01})$ and $(q_{11} - q_{10})$ are both 'large', i.e. if effort and help are very productive together but not so productive in isolation. More formally we have:

Lemma 2 *For verifiable output, and given $\omega_V(c, c_A, q) \geq c + c_A$, it is optimal to implement effort & help when $q_{11}\Delta Q > \omega_V(c, c_A, q)$, and in addition*

$$\Delta Q \geq \max\left\{\frac{1}{q_{11} - q_{10}}\left(\omega_V - \frac{q_{10}c}{q_{10} - q_{00}}\right), \frac{1}{q_{11} - q_{01}}\left(\omega_V - \frac{q_{01}c_A}{q_{01} - q_{00}}\right)\right\}. \tag{A0}$$

For the additive model these conditions are equivalent to

$$\Delta Q \geq \begin{cases} \frac{c_A}{s} + \frac{r+q_{00}}{s}\left(\frac{c_A}{s} - \frac{c}{r}\right) & if \quad \frac{c_A}{s} > \frac{c}{r} \\ \frac{c}{r} + \frac{s+q_{00}}{r}\left(\frac{c}{r} - \frac{c_A}{s}\right) & if \quad \frac{c_A}{s} \leq \frac{c}{r} \end{cases}$$

[8] An argument similar to that leading to (2) shows that the minimal cost to implement effort without help is $q_{10}c/(q_{10} - q_{00})$.

2.2 Relational contracting

Assume now that output is non-verifiable. The incentive contract must then be self-enforcing, and thus 'relational' by definition. 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 all previous periods. The agents honor the contract only if the principal honored the contract with both agents in all previous periods. 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).[9]

The relational incentive contract is self-enforcing if, for all parties, the present value of honoring is greater than the present value of reneging. Ex post realizations of values, the principal can renege on the contract by refusing to pay the promised wage, while the agents can renege by refusing to accept the promised wage, and instead hold-up values and renegotiate what we can call a spot contract. The spot price is denoted ηQ_k. If values accrue directly to the principal, then $\eta = 0$. But if the agent is able to hold-up values ex-post, then η is determined by bargaining power, ex post outside options and the ability to hold-up values.[10] Assume that there exists an alternative market for the agents' output, and that the agents are able to independently realize values θQ_k, $\theta \in (0,1)$ ex post. If we assume Nash bargaining between principal and agents, each agent will then receive θQ_k plus a share γ from the surplus from trade i.e. $\theta Q_k + \gamma(Q_k - \theta Q_k) = \eta Q_k$ where $\eta = \gamma + \theta(1-\gamma)$.[11]

We will assume that effort is not implementable in a spot contract, which

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

[10] We take η as an exogenous parameter. In Kvaløy and Olsen (2007) we endogenize the agents' hold-up power in a single-task model where relative performance evaluation is optimal.

[11] It 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 expected output realization is therefore assumed to be constant each period. This allows us to concentrate on stationary relational contracts where the principal promises the same contingent compensation in each period.

is the case if $(q_{10} - q_{00})\eta\Delta Q < c$, i.e.

$$\eta < \frac{c}{(q_{10} - q_{00})\Delta Q} \equiv \eta_s \tag{5}$$

This implies that the agent's surplus in the spot contract equals the spot price and is given by

$$u_s = S = \eta Q_L + q_{00}\eta\Delta Q \tag{6}$$

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. I.e. 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.

2.2.1 Optimal relational contract

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, $k, l \in \{L, H\}$. The parties decide whether or not to honor the incentive contract ex post realization of output, but ex ante bonus payments. Agents are treated symmetrically, and thus receive the same contract ($\boldsymbol{\beta}$) and obtain the same expected wage (ω). The principal will honor the contract if

$$-\beta_{kl} - \beta_{lk} + \frac{\delta}{1-\delta}\Pi^R \geq -\eta\left(Q_k + Q_l\right) + \frac{2\delta}{1-\delta}\left[Q_L + q_{00}\Delta Q - S\right], \ \ all\ k, l \in \{L, H\}, \tag{EP}$$

where δ is the discount factor and Π^R is the principal's profit in the relational contract. The LHS of the inequality shows the principal's expected present value from honoring the contract, while the RHS shows the expected present value from reneging.

Each agent will honor the contract if

$$\beta_{kl} + \frac{\delta}{1-\delta}\left(\omega - c - c_A\right) \geq \eta Q_k + \frac{\delta}{1-\delta}u_s, \quad \text{all} \ \ k, l \in \{L, H\}, \tag{EA}$$

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

In the rest of the paper we will assume

$$\frac{q_{11}c_A}{(q_{11}-q_{10})} > \max\left\{\frac{q_{11}c}{(q_{11}-q_{01})}, (c_A+c)\right\} \tag{A1}$$

For the additive model (4) this simply entails assuming $\frac{c_A}{s} > \frac{c}{r}$, i.e. assuming that helping effort is less productive (per unit of effort cost) than own effort Assumption A1 implies that the minimal wage cost to implement effort & help in the verifiable case is $\omega_V = \frac{q_{11}c_A}{(q_{11}-q_{10})}$.

We will now derive a lower bound for the cost (per agent) of implementing help and effort in a releational contract. Using first $\beta_{LL} \geq 0$ and EA for the bonus β_{HL} in (3) (with $\omega^1 = \omega^2 = \omega$) we get

$$\omega \geq q_{11}\frac{c_A}{q_{11}-q_{10}} + q_{11}\left(\eta Q_H + \frac{\delta}{1-\delta}\left[u_s - \omega + c + c_A\right]\right) \tag{7}$$

and hence, collecting terms involving ω:

$$\omega \geq \left(\frac{q_{11}c_A}{q_{11}-q_{10}} + q_{11}\left(\eta Q_H + \frac{\delta}{1-\delta}\left[u_s + c + c_A\right]\right)\right)\frac{1-\delta}{1-\delta+q_{11}\delta} \equiv \omega_m(\delta,\eta) \tag{8}$$

We see that $\omega_m(\delta,\eta)$ defined here is a lower bound for the cost, and will be attained if the two constraints $\beta_{LL} \geq 0$ and EA for the bonus β_{HL} both bind.

Next, using EA for bonuses β_{HL} and β_{LL} in (3) we obtain

$$\omega \geq q_{11}\frac{c_A}{q_{11}-q_{10}} + q_{11}\eta\Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s - \omega + c + c_A\right] \tag{9}$$

and hence

$$\omega \geq (1-\delta)\left[\frac{q_{11}c_A}{q_{11}-q_{10}} + q_{11}\eta\Delta Q + \eta Q_L\right] + \delta\left[u_s + c + c_A\right] \equiv \omega_A(\delta,\eta) \tag{10}$$

The expression $\omega_A(\delta,\eta)$ defined here is also a lower bound for the cost, and will be attained if the EA constraints for the bonuses β_{HL} and β_{LL} both bind.

We have thus obtained two lower bounds for the wage payments that are necessary in order to induce a worker to exert effort on his own task as well as help to his colleague. Note that $\omega_A(\delta,\eta)$ and $\omega_m(\delta,\eta)$ are both increasing in η (the outside value u_s is also increasing in η), reflecting the effect that it generally becomes more costly to induce this behavior when the workers' ex post hold-up power increases.

The cost $\omega_V(c, c_A, q)$ defined for the verifiable case is of course also a lower bound for wage costs in the present case. (This cost is derived from the IC and limited liability conditions, which must also hold in the present case.) So we must have $\omega \geq \max\{\omega_V, \omega_m(\delta,\eta), \omega_A(\delta,\eta)\}$. We can show that the cost defined by this expression is indeed the minimal cost to induce effort and help, subject to IC and EA (and limited liability).

Lemma 3 *Given assumption A1, the minimal cost to implement effort and help, subject to IC and EA (and limited liability) is*

$$\min_{IC,EA} \omega = \max\{\omega_V, \omega_m(\delta,\eta), \omega_A(\delta,\eta)\} \equiv \omega_{11}(\delta,\eta)$$

With agent spot surplus $u_s = \eta Q_L + q_{00}\eta\Delta Q$ *we have the following: For* $\delta \in (0,1]$ *there exists* $\eta_a(\delta) > \eta_m(\delta) > 0$ *such that*

$$\omega_{11}(\delta,\eta) = \begin{cases} \omega_V = \frac{q_{11}c_A}{q_{11}-q_{10}} & for \quad 0 \leq \eta \leq \eta_m(\delta) \\ \omega_m(\delta,\eta) & for \quad \eta_m(\delta) < \eta \leq \eta_a(\delta) \\ \omega_A(\delta,\eta) & for \quad \eta_a(\delta) < \eta \end{cases} \tag{11}$$

Moreover, $\eta_a(\delta), \eta_m(\delta)$ *are increasing in* δ *and satisfy: (i)* $\eta_a(\delta), \eta_m(\delta) \to 0$ *as* $\delta \to 0$*, and (ii)* $\eta_a(1) < \eta_s$ *if and only if*

$$\eta_s Q_L > \eta_s (q_{11} - q_{00}) \Delta Q + [\omega_V - c - c_A] \tag{12}$$

The cost function is piecewise linear (and continous) in η, reflecting increased tightening of the EA constraints as the agent's hold-up power increases. For small η ($\eta < \eta_m$) the cost minimizing bonus scheme for verifiable output does not violate any EA constraint, and neither of these constraints are therefore binding. Each agent gets a rent (since $\omega_V > c + c_A$), and their spot surplus is so low that they are not tempted to renegotiate. This is the case even for the outcome pair Q_H, Q_L, where the agent's own output is high, but his bonus is $\beta_{HL} = 0$. But for $\eta = \eta_m$ the EA constraint for this bonus just starts to bind. The principal is thus forced to modify the inital scheme, where an agent never gets a bonus if his partner fails, into a scheme where an agent gets a bonus if his partner fails, but the agent himself does well ($\beta_{HL} > 0$).

The EA constraint for the bonus β_{HL} continues to bind for larger η, and this implies increased wage costs for the principal, but it is the only binding EA constraint for $\eta < \eta_a$. At this point the constraints start binding also for the outcomes where the agent's own output is low. For $\eta > \eta_a$ the EA constraints for these outcomes are also binding, implying even higher wage costs.

The cost characterized in Lemma 3 will be attainable for the principal if the associated bonuses also satisfy the EP conditions, so that the principal is not tempted to renegotiate ex post. These conditions are more easily satisfied, the larger is δ. The minimal cost given in the lemma will therefore generally be attainable only if δ exceeds some critical level. We will return to this issue below.

2.2.2 Profit in the relational contract

Given that the contract inducing help & effort can be implemented, the profit associated with this contract will be

$$\Pi_{11}^{R}(\delta,\eta) = 2Q_L + 2\left[q_{11}\Delta Q - \omega_{11}(\delta,\eta)\right]$$

Since the wage cost increases with η, the profit decreases with η. For $\eta = 0$ the EA constraints do not bind (we have $S = u_s = 0$ in this case), and the profit for the relational contract is then equal to the profit for the verifiable case (provided implementation, i.e. EP, is feasible). Thus we have

$$\Pi_{11}^{R}(\delta,\eta) \leq \Pi_{11}, \quad \Pi_{11}^{R}(\delta,0) = \Pi_{11} = 2Q_L + 2q_{11}\left[\Delta Q - \frac{c_A}{(q_{11}-q_{10})}\right].$$

(The next-to-last equality presumes that δ is sufficiently large to make ω_V implementable, i.e. to make the associated bonuses compatible with EP.)

Alternatively, the principal could seek to implement a contract with effort but no help. We can show (see the appendix) that the wage cost (per agent) for this contract is given by

$$\omega_{10}(\delta,\eta) = \max\left\{\frac{q_{10}c}{q_{10}-q_{00}}, \omega_0(\delta,\eta)\right\} \tag{13}$$

where $\frac{q_{10}c}{q_{10}-q_{00}}$ is the cost to implement effort (and no help) in the verifiable case, and

$$\omega_0(\delta,\eta) = (1-\delta)\left[\frac{q_{10}c}{q_{10}-q_{00}} + \eta Q_L\right] + \delta\left[u_s + c\right], \tag{14}$$

This holds provided that δ is sufficiently large to make the associated bonuses implementable, i.e. compatible with EP. Given these provisions, the profit associated with this contract is

$$\Pi_{10}^R(\delta,\eta) = 2Q_L + 2\left[q_{10}\Delta Q - \omega_{10}(\delta,\eta)\right]$$

As above the profit decreases with η (because the cost $\omega_0(\delta,\eta)$ is increasing in η), and we have (again provided implementation, i.e. EP is feasible):

$$\Pi_{10}^R(\delta,\eta) \leq \Pi_{10}, \quad \Pi_{10}^R(\delta,0) = \Pi_{10} = 2Q_L + 2q_{10}\left[\Delta Q - \frac{c}{(q_{10}-q_{00})}\right]$$

We will now investigate the conjecture that a contract inducing effort&help is optimal for small η, while a contract inducing only effort is optimal for large η. This amounts to the following:

$$\begin{array}{lcll} \Pi_{11}^R(\delta,\eta) & > & \Pi_{10}^R(\delta,\eta) & \text{for 'small' } \eta \text{ (and } \Pi_{11}^R \text{ implementable)} \\ \Pi_{11}^R(\delta,\eta) & < & \Pi_{10}^R(\delta,\eta) & \text{for 'large' } \eta \text{ (or } \Pi_{11}^R \text{ not implementable)} \end{array}$$

Consider first the case of small η. If the effort&help contract is implementable for $\eta = 0$ (or η close to 0), then the conjecture holds true if we just have

$$\Pi_{11} > \Pi_{10} \quad \text{i.e.} \quad q_{11}\left[\Delta Q - \frac{c_A}{(q_{11}-q_{10})}\right] > q_{10}\left[\Delta Q - \frac{c}{(q_{10}-q_{00})}\right]$$

(This inequality is implied by assumption A0.) We can now prove the following result.

Proposition 1 *Given $\Pi_{11} > \Pi_{10}$, then for all η sufficiently small there is $\delta_0 < 1$ such that a contract inducing effort & help is implementable and optimal ($\Pi_{11}^R(\delta,\eta) > \Pi_{10}^R(\delta,\eta)$) for $\delta > \delta_0$.*

The proposition shows that high discount factors, which supports long-term relationships, facilitate agent-cooperation even if the agents cannot monitor or punish each other's effort choices.

Consider next 'large' η. Recall that we have assumed $\eta < \eta_s$, see (5). It can be seen that there is $\eta_0 < \eta_s$ such that the cost to implement own effort only (no help) is given by $\omega_0(\delta,\eta)$ when $\eta \in (\eta_0,\eta_s)$. This can be seen by noting from (14) that we have[12]

$$\begin{aligned}
\omega_0(\delta, \eta) &= \frac{q_{10}c}{q_{10} - q_{00}} + \eta Q_L - \delta \left(\frac{c}{q_{10} - q_{00}} - \eta \Delta Q \right) q_{00} \qquad (15) \\
&\to \frac{q_{10}c}{q_{10} - q_{00}} + \eta_s Q_L \qquad \text{as} \quad \eta \to \eta_s
\end{aligned}$$

Moreover, it follows from the analysis in Kvaløy and Olsen (2006b) that this contract gets easier to implement as η increases. (The critical discount factor for implementation goes to zero as $\eta \to \eta_s$; see the appendix, proof of Proposition 2.)

Consider then the contract with effort & help. We first note that for δ sufficiently large (close to 1) this contract will dominate the contract inducing only own effort even for large η. This is most easily seen when parameters are such that the contract with effort & help has cost given by $\omega_A(\delta, \eta)$ for η large (close to η_s), which by Lemma 3 is the case when (12) holds.[13] The definitions (10) and (14) of the two cost functions then show directly that $\omega_A(\delta, \eta) - \omega_0(\delta, \eta) \to c_A$ when $\delta \to 1$, and from this it follows that we have

$$\Pi^R_{11}(\delta, \eta) - \Pi^R_{10}(\delta, \eta) \to 2\left[(q_{11} - q_{10})\Delta Q - c_A\right] > 0 \quad \text{as} \quad \delta \to 1$$

Since implementation is always guaranteed for δ sufficiently close to 1 (see EP and EA), we can conclude that for such large δ effort & help always dominates, even when the agents' abilities for hold up ex post are large, as represented by a large η. For large δ, where implementation of a relational contract is not particularly challenging, the contract inducing effort and help thus remains optimal, also when the agents' hold up power becomes large.

Having noted this, we next move on to the case of small δ, where implementation of a relational contract is more of a challenge. The smaller is δ, the harder it generally is to implement a relational contract. We will show that at least under some assumptions, it becomes relatively harder to implement a contract inducing both effort and help than a contract inducing effort alone when δ becomes small.

To verify this statement, consider first the limiting case $\delta \to 0$, for which

[12] We see from (15) that $\omega_0(\delta, \eta)$ is decreasing in δ for $\eta < \eta_s$ and is thus larger than $\frac{q_{10}c}{q_{10}-q_{00}}$ for all $\delta \leq 1$ if $\eta > \eta_0$ given by $\eta_0 Q_L = \left(\frac{c}{q_{10}-q_{00}} - \eta_0 \Delta Q \right) q_{00}$

[13] When (12) holds we have $\eta_a(\delta) \leq \eta_a(1) < \eta_s$ and the minimal cost is thus $\omega_A(\delta, \eta)$ for $\eta_a(1) < \eta < \eta_s$.

we obtain, from (10) and (14);

$$\omega_A(\delta,\eta)-\omega_0(\delta,\eta)\rightarrow\left(\frac{q_{11}c_A}{q_{11}-q_{10}}+q_{11}\eta\Delta Q\right)-\frac{q_{10}c}{q_{10}-q_{00}}\quad\text{as}\quad\delta\rightarrow 0$$

(For δ small, the relevant cost functions for a given η are indeed $\omega_A(\delta,\eta)$ and $\omega_0(\delta,\eta)$. This follows from Lemma 3 by noting that $\eta_a(\delta)\rightarrow 0$ as $\delta\rightarrow 0$, and from (14) by noting that $\omega_0(\delta,\eta)>\frac{q_{10}c}{q_{10}-q_{00}}$ for δ small.) We are here interested in situations where the agents' hold up power, as represented by η, is large. So consider η close to the upper bound η_s introduced above, see (5). Noting that the definition of η_s implies $q_{11}\eta_s\Delta Q=\frac{q_{11}c}{q_{10}-q_{00}}$, we see that for $\eta=\eta_s$ we have

$$\omega_A(\delta,\eta_s)-\omega_0(\delta,\eta_s)\rightarrow\frac{q_{11}c_A}{q_{11}-q_{10}}+\frac{(q_{11}-q_{10})\,c}{q_{10}-q_{00}}\quad\text{as}\quad\delta\rightarrow 0$$

and consequently

$$\left(\Pi^R_{11}(\delta,\eta_s)-\Pi^R_{10}(\delta,\eta_s)\right)\frac{1}{2}\rightarrow(q_{11}-q_{10})\Delta Q-\left(\frac{q_{11}c_A}{q_{11}-q_{10}}+\frac{(q_{11}-q_{10})\,c}{q_{10}-q_{00}}\right)=D_0 \tag{16}$$

We see that, for given probability and cost parameters, this profit difference is positive for ΔQ large, but negative otherwise. A large ΔQ will in this model imply that help as well as effort are quite productive. We have previously seen (Lemma 2) that a contract inducing effort and help is optimal in the verifiable case only if ΔQ is not too small, i.e. only if both effort and help are sufficiently productive. The interesting question now is therefore whether there is a range of intermediate $\Delta Q's$ such that effort and help is optimal in the verifiable case, but not optimal in the non-verifiable case, and in particular such that the profit difference is negative ($D_0<0$) while the assumptions of Lemma 2 still hold.

To examine this issue, consider first the additive specification (4), for which we obtain

$$\frac{D_0}{q_{11}-q_{10}}=\Delta Q-\left(\frac{1}{s}\frac{(s+r+q_{00})\,c_A}{s}+\frac{c}{r}\right)=\Delta Q-\left(\left(1+\frac{r+q_{00}}{s}\right)\frac{c_A}{s}+\frac{c}{r}\right)$$

Comparing with the conditions in Lemma 2, we see that there is indeed a range of $\Delta Q's$ such that these conditions hold and yet $D_0<0$. (Assumption A1 implies here $\frac{c_A}{s}>\frac{c}{r}$, and the range is then defined by $\frac{r+q_{00}}{s}(\frac{c_A}{s}-\frac{c}{r})<\Delta Q-\frac{c_A}{s}<\frac{r+q_{00}}{s}\frac{c_A}{s}+\frac{c}{r}$.) There is thus a range of intermediate $\Delta Q's$ for which a contract inducing effort and help is optimal when output is verifiable, but not necessarily so when output is non-verifiable.

We have so far not considered the implementability conditions EP for the principal. The condition $D_0 < 0$ is therefore not sufficient to conclude that the contract inducing effort alone is optimal. It must also be verified that this contract can indeed be implemented at cost $\omega_0(\delta, \eta)$. Now, from the analysis in Kvaløy and Olsen (2006b) it follows that for large η (close to η_s) such implementation is indeed feasible even for δ very small (see the appendix for details). Based on this we can therefore conclude that the condition $D_0 < 0$ will imply that for η large (close to η_s) and δ small the relational contract inducing effort alone is indeed optimal. Stated formally we have the following.

Proposition 2 *When*

$$\Delta Q < \frac{q_{11}c_A}{(q_{11} - q_{10})^2} + \frac{c}{(q_{10} - q_{00})}$$

and (A0,A1) and (12) hold, there exists a $\eta_1 < \eta_s$ *such that for every* $\eta \in (\eta_1, \eta_s)$ *there is an interval* $(\underline{\delta}(\eta), \bar{\delta}(\eta))$ *such that for* $\delta \in (\underline{\delta}(\eta), \bar{\delta}(\eta))$ *we have* $\Pi_{11}^R(\delta, \eta) < \Pi_{10}^R(\delta, \eta)$*, so that in relational contracting effort & help is dominated by effort alone.*

The conditions in Proposition 2 are not particularly strict. A0 and A1 are plausible assumptions, and (12) is compatible with the other conditions in the proposition, since it is the only condition involving Q_L. This condition holds in addition to the other ones if Q_L is sufficiently large. The main insight from the proposition is that if the agents have hold-up power, there exists parameters where productive cooperation is not implemented in the relational contract equilibrium.

Proposition 2 shows that if the agents' hold up power η is high, then there are discount factor intervals where effort & help is dominated by effort alone. To complete the analysis, and verify our initial conjecture, we will also show that for a *given* discount facor, it is optimal to induce cooperation when η is small, but not so if η is large.

Proposition 3 *There is a set of parameters satisfying (A0, A1) and (12), and for which the following is true. There is an interval* (δ_1, δ_0) *such that for* δ *in this interval the contract inducing effort & help is implementable and optimal for* η *sufficiently small (*η *close to* 0*), while the contract inducing only own effort and no help is implementable and optimal for* η *sufficiently large (*η *close to* η_s*).*

This proposition has an interesting corollary. Since own effort without help yields a lower social surplus than own effort and help together, a higher η may reduce the social surplus:

Corollary: *There is a set of parameters satisfying (A0, A1) and (12), and for which the following is true. There is an interval* (δ_1, δ_0) *such that for* δ *in this interval the social surplus is smaller when* η *is large (*η *close to* η_s*) than when* η *is small (*η *close to* 0*).*

This result is not in line with the established idea from the property rights approach that the investing parties should be the residual claimants. In our model - where the principal does not make any investment decisions - this principle would indicate that the social surplus should increase when the agents' ex post share of value added (η) increases. But we see that the opposite happens here: If η is sufficiently high, then social surplus suffers since the principal cannot implement efficient cooperation (helping effort). If we interpret η as proxy for asset ownership, where a high η implies that the agents own assets, then the corollary has implications for the theory of the firm: It implies that if cooperation is valuable (and output is non-verifiable), then the firm and not the agents should own the assets (at least for some parameter configurations). The result is thus related to Holmström's (1999) claim - building on Alchian and Demsetz (1972) - that firms will arise in situations where it is important to mitigate individual incentives and foster cooperative behavior.

3 Concluding remarks

In so-called knowledge-intensive industries we often hear managers stress the importance of cooperation, team-work and knowledge sharing. And these claims are not only accompanied by dry complementarity arguments. The updated HR-manager would say that cooperation and helping-on-the job increase job satisfaction, and she will even find scientific support for her claim (Heywood et al. 2005). In contrast to these observations, empirical findings suggest that the use individual incentives, as opposed to team incentives, is higher in knowledge intensive firms (see e.g. Long and Shields, 2005, and Barth et al. 2006), and some empirical findings also suggest that people with more education are less satisfied with their job than people with lower levels of education (Clark and Oswald, 1996).[14]

[14] And the layman reads magazines about stress, burning-out and pushy behaviour in the high-skilled workforce.

Our paper responds to these findings by showing that cooperation can be more costly to implement in human capital-intensive industries. The reason is that human capital blurs the allocation of ownership rights. As noted by Liebeskind (2000), if human-capital intensive firms are unable to establish intellectual property rights with respect to the ideas generated by their employees, they run the risk of being expropriated or held-up by their own employees. Our point is that this hold-up problem increases if the firm encourages cooperation between its employees, since the incentive regimes that are necessary to encourage cooperation are susceptible to employee hold-up.

As noted, a higher hold-up power, η, decreases not only the firm's surplus, but also social surplus if it prevents the agents from helping each other. This contrasts with the standard property rights argument that the investing party (the agents in our paper) should own assets. We thus present a cost of providing agents with ownership rights that can be explored further within the modelling framework presented in this paper

An interesting corollary that follows from the model is that long-term relationships foster cooperation between agents even if the agents cannot monitor or punish colleagues who free-ride, or refuse to cooperate. That is; a higher discount factor eases implementation of relational contracts, making it less costly for the principal to implement cooperation. This adds to the literature, since peer-monitoring has been more or less the "folk explanation" of why repeated interaction foster cooperation at the workplace.

Appendix

Proof of Lemma 1

We first show that a joint deviation, i.e. shirking both own effort and helping effort, is not profitable for the agent. This holds if

$$\begin{aligned} & q_{11}\left[q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right)\right] \\ & +q_{11}\left(\beta_{LH}-\beta_{LL}\right)-c-c_A \\ \geq\ & q_{01}\left[q_{10}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{10}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{10}\left(\beta_{LH}-\beta_{LL}\right) \end{aligned} \tag{IC-ae}$$

We have from first ICa and then ICe

$$
\begin{aligned}
& q_{11}\left[q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{11}\left(\beta_{LH}-\beta_{LL}\right)-c-c_A \\
\geq\ & q_{11}\left[q_{10}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{10}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{10}\left(\beta_{LH}-\beta_{LL}\right)-c \\
\geq\ & \left(q_{11}-q_{01}+q_{01}\right)\left[q_{10}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{10}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{10}\left(\beta_{LH}-\beta_{LL}\right) \\
& -\left(q_{11}-q_{01}\right)\left[q_{11}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{11}\right)\left(\beta_{HL}-\beta_{LL}\right)\right] \\
=\ & \left(q_{11}-q_{01}\right)\left(q_{10}-q_{11}\right)\left[\left(\beta_{HH}-\beta_{LH}\right)-\left(\beta_{HL}-\beta_{LL}\right)\right] \\
& +q_{01}\left[q_{10}\left(\beta_{HH}-\beta_{LH}\right)+\left(1-q_{10}\right)\left(\beta_{HL}-\beta_{LL}\right)\right]+q_{10}\left(\beta_{LH}-\beta_{LL}\right)
\end{aligned}
$$

Since $\left(q_{11}-q_{01}\right)\left(q_{10}-q_{11}\right)<0$ we see that IC-ae will indeed hold if $\left(\beta_{HH}-\beta_{LH}\right)-\left(\beta_{HL}-\beta_{LL}\right)\geq 0$. Now, the cost-minimizing bonuses must satisfy this inequlity. For instance, if $C=\frac{c}{q_{11}-q_{01}}-\frac{c_A}{q_{11}-q_{10}}\geq 0$, then $\beta_{LL}=\beta_{LH}=0$, ICe binds and ICa must hold. This implies $\beta_{HH}\geq\beta_{HL}$ because the two IC conditions are now $q_{11}\beta_{HH}+(1-q_{11})\beta_{HL}=\frac{c}{q_{11}-q_{01}}$ and $q_{11}\left(\beta_{HH}-\beta_{HL}\right)\geq\frac{c_A}{q_{11}-q_{10}}$, respectively. This proves IC-ae for the case $C\geq 0$. The other case is proved similarly.

The scheme in Lemma 1 ensures participation if

$$
\max\left\{\frac{c}{\left(q_{11}-q_{01}\right)},\frac{c_A}{\left(q_{11}-q_{10}\right)}\right\}q_{11}\geq c+c_A
$$

The latter holds if e.g. $q_{11}\leq 2\max\left\{q_{01},q_{10}\right\}$. This follows because we have $\omega_V\geq 2\max\left\{c,c_A\right\}$ under this assumption.

Proof of Lemma 2.

Condition A0 is just a different way of writing $\Pi_{11}\geq\Pi_{10}$ and $\Pi_{11}\geq\Pi_{01}$. For the additive model (4) consider the case $\frac{c_A}{q_{11}-q_{10}}>\frac{c}{q_{11}-q_{01}}$, i.e. $\frac{c_A}{s}>\frac{c}{r}$. (The case $\frac{c_A}{s}\leq\frac{c}{r}$ can be analysed similarly.) For this case we have $\omega_V=\frac{c_A}{s}q_{11}$, and the condition $q_{11}\Delta Q>\omega_V$ is then equivalent to $\Delta Q>\frac{c_A}{s}$. Condition A0 is now

$$
\Delta Q\geq\max\left\{\frac{1}{s}\left(\frac{q_{11}c_A}{s}-\frac{q_{10}c}{r}\right),\frac{1}{r}\left(\frac{q_{11}c_A}{s}-\frac{q_{01}c_A}{s}\right)\right\}
$$

Using $q_{11}=s+q_{10}=r+q_{01}$, this is equivalent to

$$
\Delta Q\geq\max\left\{\frac{1}{s}\left(c_A+q_{10}\left(\frac{c_A}{s}-\frac{c}{r}\right)\right),\frac{1}{r}\left(\frac{rc_A}{s}\right)\right\}=\frac{c_A}{s}+\frac{q_{10}}{s}\left(\frac{c_A}{s}-\frac{c}{r}\right)
$$

which coincides with the condition stated in the lemma, since $q_{10}=r+q_{00}$.

Proof of Lemma 3.

The proof entails showing that the asserted minimum cost can be attained by nonnegative bonuses that satisfy IC and EA. We first prove (11).

By construction of the functions $\omega_m(\delta,\eta)$ and $\omega_A(\delta,\eta)$ they satisfy, respectively, (7) and (9) with equalities, thus;

$$\omega_m(\delta,\eta) = \omega_V + q_{11}\left[\eta\Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s - \omega_m(\delta,\eta) + c + c_A\right]\right], \quad (17)$$

$$\omega_A(\delta,\eta) = \omega_V + q_{11}\eta\Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s - \omega_A(\delta,\eta) + c + c_A\right]. \quad (18)$$

Hence we have $\omega_m(\delta,\eta) = \omega_V$ for $\eta = \eta_m > 0$ that solves

$$\eta\Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s(\eta) - \omega_V + c + c_A\right] = 0 \quad (19)$$

Substituting for $u_s(\eta) = \eta Q_L + q_{00}\eta\Delta Q$ this yields

$$\eta_m = \frac{\delta\left[\omega_V - c - c_A\right]}{Q_L + (1-\delta)\Delta Q + \delta q_{00}\Delta Q} > 0$$

Since $\omega_m(\delta,\eta)$ is increasing (linearly) in η, we have $\omega_m(\delta,\eta) > \omega_V$ iff $\eta > \eta_m$.

Similarly we see from (18) that we have $\omega_A(\delta,\eta) = \omega_V$ for $\eta = \eta_a'$ given by $q_{11}\eta\Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s(\eta) - \omega_V + c + c_A\right] = 0$. Comparing with (19) we see that, since $q_{11} < 1$, this yields $\eta_a' > \eta_m$, and hence $\omega_A(\delta,\eta) < \omega_V$ for $\eta < \eta_m$.

We now claim that $\omega_A(\delta,\eta) = \omega_m(\delta,\eta)$ for the unique $\eta = \eta_a$ that solves $\omega_A(\delta,\eta) = \omega_V + q_{11}\eta\Delta Q$, i.e. for $\eta = \eta_a$ that solves (see (18))

$$\eta Q_L + \frac{\delta}{1-\delta}\left[u_s(\eta) - (\omega_V + q_{11}\eta\Delta Q) + c + c_A\right] = 0 \quad (20)$$

The claim is verified by noting from (17) that this η also solves $\omega_m(\delta,\eta) = \omega_V + q_{11}\eta\Delta Q$, and hence solves $\omega_m(\delta,\eta) = \omega_A(\delta,\eta)$. Substituting for $u_s(\eta) = \eta Q_L + q_{00}\eta\Delta Q$ in (20) we obtain

$$\eta_a = \frac{\delta\left[\omega_V - c - c_A\right]}{Q_L - \delta\left(q_{11} - q_{00}\right)\Delta Q} \qquad (\text{for } \; Q_L - \delta\left(q_{11} - q_{00}\right)\Delta Q > 0)$$

We have here tacitly assumed $Q_L - \delta\left(q_{11} - q_{00}\right)\Delta Q > 0$; otherwise we will have $\omega_m(\delta,\eta) > \omega_A(\delta,\eta)$ for all $\eta > 0$.

We see that $\eta_a > \eta_m$, that η_a and η_m are both increasing in δ, and that $\eta_a < \eta_s$ for $\delta = 1$ iff (12) holds. This proves (11) and the ensuing statement in the lemma.

Now we will show that the asserted minimum cost can be attained by nonnegative bonuses that satisfy IC and EA.

First, for $\eta \leq \eta_m$ let the bonuses β_{kl} be given by the optimal scheme for verifiable output. This scheme satisfies IC and yields wage cost $\omega_V = \frac{q_{11}c_A}{q_{11}-q_{10}} > 0$. The scheme has nonnegative bonuses ($\beta_{HH} > \beta_{LH} \geq \beta_{HL} = \beta_{LL} = 0$) and satisfies EA, since we for $\eta \leq \eta_m$ by definition of η_m (see (19)) have

$$\eta \Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s(\eta) - \omega_V + c + c_A\right] \leq 0 \leq \beta_{kl}$$

This shows that for for $\eta \leq \eta_m$ the lower bound ω_V is attainable.

For $\eta > \eta_m$ the EA constraint is violated if $\beta_{HL} = 0$, hence the above scheme is no longer feasible. Note that by definition of $\omega_m(\delta, \eta)$, a set of bonuses will yield wage cost $\omega = \omega_m(\delta, \eta)$ if (i) ICa is binding, which yields equality in (3), and (ii) $\beta_{LL} = 0$ and EA binds for β_{HL}, which yields equality in (8). Define such a set of bonuses, specifically; let $\beta_{LH} = \beta_{LL} = 0$, and let β_{HL}, β_{HH} be given by EA and ICa; thus

$$\beta_{HL} = \eta \Delta Q + \eta Q_L + \frac{\delta}{1-\delta}\left[u_s(\eta) - \omega_m(\delta, \eta) + c + c_A\right] \tag{EA$_m$}$$

$$q_{11}\left(\beta_{HH} - \beta_{HL}\right) = \frac{c_A}{(q_{11} - q_{10})} \tag{ICa}$$

These bonuses then yield cost $\omega = \omega_m(\delta, \eta)$. The bonus β_{HL} satisfies EA by construction, and since $\beta_{HH} > \beta_{HL}$, so does β_{HH}. From the definition of β_{HL} and (17) we see that $\omega_m(\delta, \eta) - \omega_V = q_{11}\beta_{HL}$, and hence that $\beta_{HL} > 0$, since $\eta > \eta_m$. Moreover, the bonuses satisfy ICe, since we have

$$\begin{aligned} & q_{11}\left(\beta_{HH} - \beta_{LH}\right) + (1 - q_{11})\left(\beta_{HL} - \beta_{LL}\right) \\ = \; & q_{11}\left(\beta_{HL} + \frac{c_A}{(q_{11} - q_{10})\, q_{11}}\right) + (1 - q_{11})\beta_{HL} \\ > \; & \frac{c_A}{(q_{11} - q_{10})} \end{aligned}$$

and $\frac{c_A}{q_{11}-q_{10}} > \frac{c_E}{q_{11}-q_{01}}$ by assumption A1.

It remains to verify that $\beta_{LH} = \beta_{LL} = 0$ satisfy EA. We show that this is the case for $\eta \leq \eta_a$. Recall that $\omega_m(\delta, \eta) \leq \omega_V + q_{11}\eta\Delta Q$ for $\eta \leq \eta_a$, and hence that (17) then implies

$$\eta Q_L + \frac{\delta}{1-\delta}\left[u_s - \omega_m(\delta, \eta) + c + c_A\right] \leq 0$$

This shows that $\beta_{LH} = \beta_{LL} = 0$ satisfy EA for $\eta \leq \eta_a$. Hence we have shown that for $\eta_m < \eta \leq \eta_a$ there is a set of non-negative bonuses that satisfies EA and IC, and which yields wage costs $\omega = \omega_m(\delta, \eta)$ on this interval.

Finally consider $\eta > \eta_a$. We now derive a set of bonuses that yield the cost $\omega_A(\delta, \eta)$, satisfy EA for all outcomes, and satisfy IC. The first requirement follows by definition of $\omega_A(\delta, \eta)$ once ICa is binding and EA binds for the bonuses β_{LL} and β_{HL}. So define the bonuses as follows:

$$\beta_{LL} = \beta_{LH} = \eta Q_L + \frac{\delta}{1-\delta}\left[u_s - \omega_A(\delta, \eta) + c + c_A\right], \quad \beta_{HL} = \eta \Delta Q + \beta_{LL} \qquad (\text{EA}_A)$$

$$q_{11}\left(\beta_{HH} - \beta_{HL}\right) + (1 - q_{11})\left(\beta_{LH} - \beta_{LL}\right) = \frac{c_A}{(q_{11} - q_{10})} \qquad (\text{ICa})$$

This yields $\beta_{HH} = \beta_{HL} + \frac{c_A}{(q_{11}-q_{10})q_{11}} > \beta_{HL} = \eta \Delta Q + \beta_{LH}$, and shows that β_{HH} also satisfies EA.

To verify that the bonuses are positive, note from the definition of β_{LL} and (18) that we have $\omega_A(\delta, \eta) = \omega_V + q_{11}\eta\Delta Q + \beta_{LL}$. This shows that $\beta_{LL} > 0$, since we have $\omega_A(\delta, \eta) > \omega_V + q_{11}\eta\Delta Q$ for $\eta > \eta_a$. (We showed that $\omega_A(\delta, \eta) = \omega_V + q_{11}\eta\Delta Q$ for $\eta = \eta_a$, and the inequality then follows from linearity and $\omega_A(\delta, \eta) < \omega_V$ for η small.)

It then only remains to verify that the given bonuses satisfy ICe. We have now

$$\begin{aligned} & q_{11}\left(\beta_{HH} - \beta_{LH}\right) + (1 - q_{11})\left(\beta_{HL} - \beta_{LL}\right) \\ = \; & q_{11}\left(\beta_{HL} + \frac{c_A}{(q_{11} - q_{10})\, q_{11}} - \beta_{LH}\right) + (1 - q_{11})\eta\Delta Q \\ = \; & \frac{c_A}{q_{11} - q_{10}} + \eta\Delta Q \end{aligned}$$

which exceeds $\frac{c}{q_{11}-q_{01}}$ according to assumption A1. The given bonuses thus satisfy IC, they are positive and satisfy EA, and they yield the cost $\omega_A(\delta, \eta)$for $\eta > \eta_a$. This completes the proof.

Proof of (13).

By an argument similar to that leading to (2) one sees that the cost to implement effort alone (with no help) must satisfy

$$\omega_{10} \geq \frac{q_{10}c}{q_{10} - q_{00}} + q_{11}\beta_{LH} + (1 - q_{11})\beta_{LL} \qquad (21)$$

Limited liability ($\beta_{kl} \geq 0$) shows that $\omega_{10} \geq \frac{q_{10}c}{q_{10}-q_{00}}$. Substituting next from the EA constraints for the bonuses β_{LH} and β_{LL} (with $\omega = \omega_{10}$ and $c_A = 0$)

in (21) we obtain

$$\omega_{10} \geq \frac{q_{10}c}{q_{10}-q_{00}} + \eta Q_L + \frac{\delta}{1-\delta}(u_s - \omega_{10} + c)$$

Collecting terms involving ω_{10} yields the inequality $\omega_{10} \geq \omega_0(\delta, \eta)$ with $\omega_0(\delta, \eta)$ defined in (14). This proves (13).

Proof of Proposition 1.

Consider the limiting case $\eta = 0$. Then the EA constraints do not bind, and the optimal bonuses for the verifiable case can be implemented if they satisfy EP. From Lemma 1 and assumption A1 these bonuses satisfy $\beta_{LL} = \beta_{HL} = 0$ and ICa binding, hence we have $q_{11}\beta_{HH} + (1-q_{11})\beta_{LH} = \frac{c_A}{(q_{11}-q_{10})}$. In addition ICe holds, i.e. $q_{11}\left(\beta_{HH} - \beta_{LH}\right) \geq \frac{c}{(q_{11}-q_{01})}$.

These bonuses are easiest to implement when β_{HH} is minimal, which is obtained when ICe binds. This yields

$$\beta_{HH} - \beta_{LH} = \frac{c}{q_{11}\left(q_{11}-q_{01}\right)}, \quad \beta_{LH} = \frac{c_A}{(q_{11}-q_{10})} - \frac{c}{(q_{11}-q_{01})} \tag{22}$$

For $\eta = 0$ EP takes the following form

$$\beta_{kl} + \beta_{lk} \leq \frac{2\delta}{1-\delta}\left[\frac{1}{2}\Pi_{11} - Q_L - q_{00}\Delta Q\right]$$

(By assumption the latter square bracket, which equals $q_{11}\left[\Delta Q - \frac{c_A}{(q_{11}-q_{10})}\right] - q_{00}\Delta Q$ is positive.) For the bonuses given above we have $\beta_{HH} > \beta_{LH} > \beta_{HL} = \beta_{LL} = 0$. Hence EP for outcome HH is the critical condition for implementation, thus we must have

$$2\beta_{HH} \leq \frac{2\delta}{1-\delta}\left[\frac{1}{2}\Pi_{11} - Q_L - q_{00}\Delta Q\right] \tag{23}$$

Substituting for β_{HH}, we see that there is a critical $\delta_0 < 1$ such that this condition holds for all $\delta > \delta_0$. The other EP conditions are then also satisfied, hence we have shown that the bonuses that yield wage costs ω_V and profits Π_{11} are implementable for $\delta > \delta_0$. This proves the proposition for $\eta = 0$. By continuity the result will also hold for $\eta > 0$ sufficiently close to zero.

Proof of Proposition 2.

First note that condition (12) ensures that for η close to η_s the cost function for the contract inducing effort and help is given by $\omega_A(\delta, \eta)$ for all $\delta \leq 1$. (More precisely; taking also EP into account, that effort and help can not be implemented at a cost lower than $\omega_A(\delta,\eta)$.) This can be seen from Lemma 3, since (12) implies that $\eta_a(\delta) \leq \eta_a(1) < \eta_s$, and hence that for $\eta_a(1) < \eta < \eta_s$ the minimal cost is given by $\omega_A(\delta,\eta)$ for all $\delta < 1$.

Now consider the comparison of the two contracts. Regarding the effort-alone contract, it follows from the analysis in Kvaløy and Olsen (2006b) that the following statement holds true. *There is $\eta_0 < \eta_s$ such that for every $\eta \in (\eta_0, \eta_s)$ there is a critical $\underline{\delta}(\eta)$ such that effort-alone can be implemented at minimal cost $\omega_0(\delta,\eta)$ for $\delta \geq \underline{\delta}(\eta)$, and moreover that $\underline{\delta}(\eta) \to 0$ as $\eta \to \eta_s$.* For completeness we give a proof of this statement below.

Taking the statement for granted, consider $\eta > \max\{\eta_0, \eta_a(1)\}$, where the relevant costs are $\omega_A(\delta,\eta)$ and $\omega_0(\delta,\eta)$, respectively. Define

$$D(\eta) \equiv \Pi_{11}^R(\underline{\delta}(\eta),\eta) - \Pi_{10}^R(\underline{\delta}(\eta),\eta).$$

Since $\underline{\delta}(\eta) \to 0$ as $\eta \to \eta_s$, it follows from (16) that $D(\eta) \to D_0 < 0$ as $\eta \to \eta_s$. Hence by continuity there is $\eta_1 < \eta_s$ such that for every $\eta \in (\eta_1, \eta_s)$ we have $D(\eta) < 0$. For such a η, we thus have $\Pi_{11}^R(\delta,\eta) < \Pi_{10}^R(\delta,\eta)$ for $\delta = \underline{\delta}(\eta)$. Hence by continuity there is $\bar{\delta}(\eta) > \underline{\delta}(\eta)$ such that $\Pi_{11}^R(\delta,\eta) < \Pi_{10}^R(\delta,\eta)$ for $\delta \in (\underline{\delta}(\eta), \bar{\delta}(\eta))$. This verifies the statement in Proposition 2, provided we check that the principal prefers the relational contract inducing effort alone to the spot contract (which under the given assumptions induces no effort)

To check this, note that for $\eta \to \eta_s$ the profit (per agent) associated with the relational contract becomes (see (15))

$$\begin{aligned}
\Pi_{10}^R(\delta,\eta_s)\frac{1}{2} &= Q_L + q_{10}\Delta Q - \left(\frac{q_{10}c}{q_{10}-q_{00}} + \eta_s Q_L\right) \\
&= (1-\eta_s)\,Q_L + q_{10}\left(\Delta Q - \frac{c}{q_{10}-q_{00}}\right) \\
&= (1-\eta_s)\,(Q_L + q_{10}\Delta Q)
\end{aligned}$$

In a spot contract (with no effort) the profit would be $(1-\eta_s)(Q_L + q_{00}\Delta Q)$, so the relational contract is better. By continuity the same holds for η close to η_s.

We finally give the proof of the claim regarding the effort-alone contract stated above. As noted in the text, the minimal wage cost, subject to EA and IC for the effort-alone contract is $\omega_0(\delta,\eta)$ defined in (14), provided that this cost $\omega_0(\delta,\eta)$ exceeds $\frac{q_{10}c}{q_{10}-q_{00}}$, which is the cost to implement effort (and no help) in the verifiable case. From (14) and (15) we have

$$\omega_0(\delta,\eta) - \frac{q_{10}c}{q_{10}-q_{00}} = \eta Q_L - \delta\left(\frac{c}{q_{10}-q_{00}} - \eta\Delta Q\right) q_{00}$$

This expression is positive for all $\delta < 1$ if $\eta > \eta_0 = \frac{c}{q_{10}-q_{00}} \frac{1}{\Delta Q + Q_L/q_{00}}$. We see that $\eta_0 < \eta_s = \frac{c}{q_{10}-q_{00}} \frac{1}{\Delta Q}$. Hence for $\eta \in (\eta_0, \eta_s)$ we have $\omega_0(\delta, \eta) > \frac{q_{10}c}{q_{10}-q_{00}}$ for all $\delta < 1$, and $\omega_0(\delta, \eta)$ is then indeed the minimal cost to implement effort-alone, subject to the relevant IC and EA constraints.

The associated bonuses satisfy ICe with equality and EA with equality for β_{LL} and β_{LH}, and thus we have from ICe and EA (with effort-alone):

$$q_{10} (\beta_{HH} - \beta_{LH}) + (1 - q_{10}) (\beta_{HL} - \beta_{LL}) = \frac{c}{q_{10} - q_{00}} \tag{ICe'}$$

$$\beta_{LL} = \beta_{LH} = \eta Q_L + \frac{\delta}{1-\delta} [u_s - \omega_0 + c] . \tag{24}$$

The bonuses β_{HH} and β_{HL} must further satisfy EA (with effort-alone), thus

$$\beta_{HH} \geq \eta \Delta Q + \beta_{LH} \quad \text{and} \quad \beta_{HL} \geq \eta \Delta Q + \beta_{LL} \tag{25}$$

Consider then EP. Substituting for $\Pi^R = \Pi_{10} = 2 [Q_L + q_{10} \Delta Q - \omega_0]$ EP becomes here

$$\max \{2\beta_{HH} - 2\eta Q_H, \beta_{HL} + \beta_{LH} - \eta(Q_H + Q_L), 2\beta_{LL} - 2\eta Q_L\} \leq \frac{2\delta}{1-\delta} [(q_{10} - q_{00}) \Delta Q + S - \omega_0]$$

Substituting from (24) and noting that $S = u_s$, we see that this constraint is equivalent to

$$\max \{2(\beta_{HH} - \beta_{LH} - \eta \Delta Q), (\beta_{HL} - \beta_{LL} - \eta \Delta Q)\} \leq \frac{2\delta}{1-\delta} [(q_{10} - q_{00}) \Delta Q - c] \tag{EP'}$$

The minimal discount factor $\delta = \underline{\delta}$ for which a bonus scheme satisfying ICe' and (24-25) also satisfies EP' is obtained when when ICe', EP' and $2(\beta_{HH} - \beta_{LH} - \eta \Delta Q) = \beta_{HL} - \beta_{LL} - \eta \Delta Q$ hold jointly. This yields the following condition for $\underline{\delta} = \underline{\delta}(\eta)$

$$\frac{1}{\underline{\delta}} - 1 = \frac{[\Delta q \Delta Q - c]}{c - \eta \Delta Q \Delta q} \Delta q (2 - q_{10})$$

where $\Delta q = q_{10} - q_{00}$.

We see that, since $c - \eta \Delta Q \Delta q \to 0$ as $\eta \to \eta_s$, then so does the critical discount factor, i.e. $\underline{\delta}(\eta) \to 0$ as $\eta \to \eta_s$. This proves the claim, and thus completes the proof.

Proof of Proposition 3.

From Proposition 1 we know that there is a critical $\delta(\eta) < 1$ such that for η sufficiently small and $\delta > \delta(\eta)$ the contract inducing effort and help is implementable and optimal;

$$\Pi_{11}^R(\delta,\eta) - \Pi_{10}^R(\delta,\eta) > 0 \qquad \text{for} \quad 0 \le \eta < \eta_1 \text{ and } \ \delta > \delta(\eta). \tag{26}$$

Letting $\eta \to 0$, then by continuity $\delta(\eta) \to \delta_0$, where δ_0 is the critical factor corresponding to $\eta = 0$ defined in the proof of Proposition 1. From that proof (see (23)) we have δ_0 defined by

$$\beta_{HH} = \frac{\delta_0}{1-\delta_0}\left[\frac{1}{2}\Pi_{11} - Q_L - q_{00}\Delta Q\right] = \frac{\delta_0}{1-\delta_0}\left[(q_{11}-q_{00})\Delta Q - \frac{q_{11}c_A}{(q_{11}-q_{10})}\right]$$

where we have substituted for Π_{11}, and where β_{HH} is given by (see (22)):

$$\begin{aligned}\beta_{HH} &= \frac{c}{q_{11}\,(q_{11}-q_{01})} + \beta_{LH} = \frac{c}{q_{11}\,(q_{11}-q_{01})} + \frac{c_A}{(q_{11}-q_{10})} - \frac{c}{(q_{11}-q_{01})} \\ &= \frac{(1-q_{11})c}{q_{11}\,(q_{11}-q_{01})} + \frac{c_A}{(q_{11}-q_{10})}\end{aligned}$$

The critical factor δ_0 is thus given by the following equation

$$\left[\frac{(1-q_{11})c}{q_{11}\,(q_{11}-q_{01})} + \frac{c_A}{(q_{11}-q_{10})}\right] = \frac{\delta_0}{1-\delta_0}\left[(q_{11}-q_{00})\Delta Q - \frac{q_{11}c_A}{(q_{11}-q_{10})}\right] \tag{d0}$$

From Proposition 2 we know that, under the stated assumptions the contract inducing effort only is implementable and optimal for η sufficiently large, and for $\delta \in (\underline{\delta}(\eta), \bar{\delta}(\eta))$:

$$\Pi_{11}^R(\delta,\eta) - \Pi_{10}^R(\delta,\eta) < 0 \qquad \text{for} \quad \eta_2 < \eta < \eta_s \text{ and } \ \delta \in (\underline{\delta}(\eta), \bar{\delta}(\eta)). \tag{27}$$

Here $\underline{\delta}(\eta)$ is the critical factor for implementing the 'only effort' contract, and we know that $\underline{\delta}(\eta) \to 0$ as $\eta \to \eta_s$. Since $\Pi_{11}^R(\delta,\eta) - \Pi_{10}^R(\delta,\eta)$ is linear in δ, and positive for $\delta = 1$, it must be the case that (the largest) $\bar{\delta}(\eta)$ is defined by $\Pi_{11}^R(\delta,\eta) - \Pi_{10}^R(\delta,\eta) = 0$ for $\delta = \bar{\delta}(\eta)$. Hence, letting $\eta \to \eta_s$, then by continuity $\bar{\delta}(\eta) \to \delta_1$ defined by

$$0 = \Pi_{11}^R(\delta_1,\eta_s) - \Pi_{10}^R(\delta_1,\eta_s) = 2\left[(q_{11}-q_{10})\Delta Q - (\omega_A(\delta_1,\eta_s) - \omega_0(\delta_1,\eta_s))\right] \tag{d1}$$

The proof is then complete if we show that (for a set of parameters) $\delta_1 > \delta_0$, because for given $\delta \in (\delta_0, \delta_1)$ we can then by continuity find $\eta_1 > 0$ and $\eta_2 < \eta_s$ such that both (26) and (27) hold for the given δ.

Consider the equation (d1) defining δ_1. From (10), (6) and (5) we obtain

$$\begin{aligned}
\omega_A(\delta, \eta_s) &= (1-\delta)\left[\frac{q_{11}c_A}{(q_{11}-q_{10})} + q_{11}\eta_s\Delta Q + \eta_s Q_L\right] + \delta\left[(\eta_s Q_L + q_{00}\eta_s\Delta Q) + c + c_A\right] \\
&= \eta_s Q_L + (1-\delta)\left[\frac{q_{11}c_A}{(q_{11}-q_{10})} + \frac{q_{11}c}{(q_{10}-q_{00})}\right] + \delta\left[\frac{q_{00}c}{(q_{10}-q_{00})} + c + c_A\right] \\
&= \frac{q_{11}c_A}{(q_{11}-q_{10})} + \frac{q_{11}c}{(q_{10}-q_{00})} + \eta_s Q_L - \delta\left[\frac{(q_{11}-q_{10})c}{(q_{10}-q_{00})} + \frac{q_{10}c_A}{(q_{11}-q_{10})}\right] \qquad (28)
\end{aligned}$$

Substituting this and $\omega_0(\delta, \eta_s)$ from (14) in the equation (d1) defining δ_1, this equation becomes

$$0 = (q_{11}-q_{10})\Delta Q - \left(\frac{q_{11}c_A}{(q_{11}-q_{10})} + \frac{(q_{11}-q_{10})\,c}{(q_{10}-q_{00})}\right) + \delta_1\left[\frac{(q_{11}-q_{10})c}{(q_{10}-q_{00})} + \frac{q_{10}c_A}{(q_{11}-q_{10})}\right] \qquad \text{(d1)}$$

We will consider the additive model (4). The equations defining δ_0 and δ_1 then take the following form

$$\left[\frac{1-q_{11}}{q_{11}}\frac{c}{r} + \frac{c_A}{s}\right] = \frac{\delta_0}{1-\delta_0}\left[(r+s)\Delta Q - \frac{q_{11}c_A}{s}\right] \qquad \text{(d0)}$$

$$0 = s\Delta Q - \left(\frac{q_{11}c_A}{s} + \frac{sc}{r}\right) + \delta_1\left[\frac{sc}{r} + \frac{q_{10}c_A}{s}\right] \qquad \text{(d1)}$$

where $q_{11} = r + s + q_{00}$ and $q_{10} = r + q_{00}$, and the assumptions A0 and A1 entail

$$\frac{c_A}{s} > \frac{c}{r} \quad \text{and} \quad \frac{r+q_{00}}{s}\left(\frac{c_A}{s} - \frac{c}{r}\right) < \Delta Q - \frac{c_A}{s} < \frac{r+q_{00}}{s}\frac{c_A}{s} + \frac{c}{r} \qquad \text{(A)}$$

Condition (12) involves Q_L, and can be fullfilled independently of the other conditions. For the additive model we have $\eta_s = \frac{c}{r\Delta Q}$, and we see that the condition is then (for $\frac{c_A}{s} > \frac{c}{r}$) equivalent to

$$Q_L > (r+s)\,\Delta Q + \left[q_{11}\frac{c_A}{s} - c - c_A\right]/\eta_s = (r+s)\,\Delta Q + \left[(r+q_{00})\,\frac{c_A}{s}/\frac{c}{r} - r\right]\Delta Q \qquad (29)$$

Define

$$\gamma = \frac{\Delta Q}{c_A/s} > 1, \quad \alpha = \frac{c/r}{c_A/s} < 1$$

and note that $q_{10} = r + q_{00} = q_{11} - s$. Then the conditions above are

$$0 = s\gamma - (q_{11} + s\alpha) + \delta_1 [s\alpha + (q_{11} - s)] \tag{d1}$$

$$\left[\frac{1 - q_{11}}{q_{11}}\alpha + 1\right] = \frac{\delta_0}{1 - \delta_0} [(r + s)\gamma - q_{11}] \tag{d0}$$

where

$$1 > \alpha \quad \text{and} \quad \frac{q_{11} - s}{s}(1 - \alpha) < \gamma - 1 < \frac{q_{11} - s}{s} + \alpha \tag{A}$$

We will now show that, keeping q_{11}, γ and r fixed, then for s sufficiently small there is α close to 1 such that A holds and $0 < \delta_0 < \delta_1$. To see this, let $\alpha \to 1$ and $s \to 0$ such that $\frac{1-\alpha}{s} \leq k$, where $q_{11}k < \gamma - 1$, and $\gamma > q_{11}/r$. Then we obtain

$$\delta_1 = \frac{(q_{11} + s\alpha) - s\gamma}{[s\alpha + q_{11} - s]} \to 1$$

$$\delta_0 = \frac{\left[\frac{1-q_{11}}{q_{11}}\alpha + 1\right]}{\left[\frac{1-q_{11}}{q_{11}}\alpha + 1\right] + [(r + s)\gamma - q_{11}]} \to \frac{1}{1 + [r\gamma - q_{11}]} < 1$$

Moreover, condition A will clearly hold for s small and α close to 1 since $\frac{q_{11}-s}{s}(1 - \alpha) \leq q_{11}k + (1 - \alpha) < \gamma - 1$ and $\frac{q_{11}-s}{s} + \alpha \to \infty$. This completes the proof.

Remark. The following is an example of parameters that yield $\delta_0 < \delta_1$:

$$q_{11} = 0.9, \;\; r = 0.45, \;\; s = 0.1, \;\; \gamma = \frac{\Delta Q}{c_A/s} = 3, \quad \alpha = \frac{c/r}{c_A/s} = 0.9$$

For these parameters we find $\delta_0 = 0.746$ and $\delta_1 = 0.775$. Checking condition A, we see that $\frac{q_{11}-s}{s}(1 - \alpha) = 0.8 < \gamma - 1 < \frac{q_{11}-s}{s} + \alpha = 8.9$, and hence this condition is satisfied.

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