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Decentralization of contracts with interim side-contracting

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Abstract

This paper gives a new explanation for the phenomena of subcontracting. A model in which a principal contracts two agents who work in a sequence on a project, have soft information and can collude is considered. Side-contracts between agents can be signed at any stage of the game. Due to limited liability and moral hazard agents obtain a rent. The principal's problem is to find the preferable contracting structure. It is shown that in this setting a decentralized contracting structure can be superior to a centralized structure for the principal. The paper derives the conditions under which this holds.

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1 Introduction

Whether organizations should be centralized or decentralized is one of the central questions of economic analysis. Especially, economic theory has had difficulty in explaining the phenomena of subcontracting. To see this, consider a general contractor (or principal) who needs two suppliers (or agents) to realize a project. Either, she can contract directly both of them, or contract only one supplier and let him subcontract the other. Subcontracting obviously implies a loss of control over the subcontractee's contract for the general contractor. However, because she can always replicate the same contracts if she contracts directly with both suppliers, it is not easy to see the advantages of subcontracting. This paper gives a new explanation to explain this phenomena under two quite realistic assumptions. First, it is assumed that agents have more information than the principal but that this information is *soft*. So, contracts cannot be based on it. Second, it restricts the analysis to simple contracts, i.e. follows an incomplete contracting approach. Although complete contracts which allow for message games are theoretically very attractive, they have the inconvenience that message games are rarely observed in reality. Due to Tirole (1999) this is because of legal or institutional restrictions, the costs of writing and enforcing complex contracts, or the lack of information when signing the agreements.

This paper considers a team production problem in which a principal contracts with two agents who work sequentially on a project. The probability of the success of the project depends on the effort choices of the agents which are not observable for the principal. The effort choice of agent 1 is observable but non–verifiable for agent 2. This implies that though agents can collude, ex-ante they cannot sign side-contracts based on agent 1's effort choice. However, the sequential choice of efforts allows to sign side-contracts at an interim stage, *after* agent 1's effort choice and *before* agent 2's effort choice. The paper explores the consequences of this interim side-contracting for the principal's decision how to delegate contracting when agents have limited liability. There are numerous situations to which the model can be applied. Agent 1 might be a basic research department and agent 2 a department in charge of more applied R&D activities (cf. Schmitz, 2005). Or agent 1 might be an architect who delivers a blueprint to a constructor (agent 2) who is in charge of the production process (cf. Baliga and Sjöström, 1998). Finally, agent 1 can be a hospital which takes all investment decisions and agent 2 a physician who provides health services (cf. Jelovac and Macho-Stadler, 2002).

In the paper three different organizational structures are compared: a centralized structure (C), a decentralized structure in which agent 1 is contracted by the principal who then subcontracts agent 2 (D_1), and a decentralized structure in which agent 2 is contracted by the principal who then subcontracts agent 1 (D_2). The principal's problem in a centralized structure is to find the minimum wages she must pay to the two agents to implement full effort with lowest cost. This contract must satisfy, incentive, participation and limited liability constraints. Due to limited liability, agents receive informational rents. Though agents are assumed identical, it is shown that the optimal contract in a centralized structure gives higher rents to agent 2 than to agent 1 when the production process is characterized by supermodularity. In this case, agent 1 has a first mover disadvantage, which will be large when the probability of a success increases much when one of the agents works instead of having both agent shirking. Furthermore, the wage contracts are collusion-proof if agents must agree on side-contracts *before* efforts are chosen. However, though the centralized contract guarantees that both agents prefer to work instead of shirking, agent 1 can credibly thread to shirk at stage one, and then make a side-payment to agent 2 to incite him to work. With this side-payment he improves his welfare compared to the one he receives from the centralized contract and improves agent 2's welfare compared to the situation in which both agents shirk. Agent 2 would never accept such a contract before both efforts are chosen, but once he knows that agent 1 has shirked he prefers this side-contract. Therefore, agent 1 can use the fact that he moves first to obtain a bargaining advantage against agent 2 to redistribute their informational rents. This *rent-redistribution effect* is the greater the more important is his first-mover disadvantage. For the principal this redistribution of rents implies that, generally, full effort cannot be implemented at the same cost as in a centralized structure without collusion at the interim stage.

Contract delegation in a decentralized structure also implies a cost. The principal loses part of the control over the wage of the subcontracted agent. A major problem is that the general contractor often prefers the subcontractor to shirk and to keep his wage when the principal pays the same total wages as in a centralized structure without collusion. This *rent-extraction effect* is the greater the higher is the rent the general contractor can extract. Therefore, again, if the principal wants to implement full effort in these structures, she must increase the wage payments. Once the different optimal wage contracts are obtained, the centralized structure in which agents contract at the interim stage and the different decentralized structures can be compared.

It is shown that: (1) a centralized structure dominates a decentralized structure in which agent 1 is the general contractor, (2) a decentralized structure in which agent 2 is the general contractor dominates a centralized structure when the probability of a success increases much when one of the agent works, otherwise, the centralized structure is preferable for the principal, (3) the three structures implement full effort at the same cost when efforts are submodular. The intuition behind these results is in the allocation of the bargaining power within the different structures. When agent 1 is a general contractor the principal allocates all the bargaining power to him. Similarly, in a centralized structure most of the bargaining power is given to agent 1 because he can make a credible thread to shirk. However, his possibilities to distort full effort are greater when he is the general contractor, which yields result (1). If the probability of a success increases much when one of the agent works instead of having both agent shirking, agent 1's effort can be implemented with much lower cost than agent 2's effort. Therefore, giving the bargaining power to agent 1 is harmful for the principal. If agent 1 is the general contractor he has all the bargaining power and the rent–extracting effect will be high. In this case, in a centralized structure with interim side-contracting the rent–redistribution effect will also be high. Finally, if agent 2 is the general contractor, the rent–extraction effect will be low. Thus, it is optimal to make agent 2 the general contractor, which yields (2). If efforts are submodular, both agents receive the same rent in a centralized structure. Furthermore, this rent is large enough such that both agents always want to implement full effort. This yields result (3).

According to Mookherjee (2006) the literature has taken two approaches to analyze the costs and benefits from delegation: One approach which stays within the framework of the Revelation Principle, and another approach which departs from its assumptions.[1] While the first assumes the absence of (a) any costs like information processing costs, communication costs

[1]Myerson (1982) is the first to show that the revelation principal means that under certain conditions any non-cooperative equilibrium of a decentralized organization can be mimicked by a centralized one.

and contract complexity costs, (b) collusive behavior among the agents and (c) renegotiation of contracts due to limited commitment ability of the principal, the second approach drops one or several of these assumptions. In this paper we follow the second approach and drop assumption (b). The effect of collusion on the principal's decision to delegate contracting has been analyzed from two perspectives.[2] First, in a model with adverse selection, Laffont and Martimort (1998) show that a decentralized structure is always strictly dominated by a centralized structure. Second, in a model with moral hazard, Holmström and Milgrom (1990) and Varian (1990) have obtained the same result.[3] Macho-Stadler and Pérez-Castrillo (1998) show that the advantage of different organizational structures depends on whether it is more easy to avoid coalitional structures between agents (which favors centralization), or between the principal and an agent (which favors a decentralized structure). Baliga and Sjöström (1998) show that a decentralized structure can be superior to a centralized one even when agents can collude if they have limited liability. However, their analysis is based on the important assumption that the effort of the first agent is observable and verifiable for the other agent, which allows to base contracts and enforceable side-contracts on agent 1's effort choice. In this paper side-contracts cannot be based on efforts. As a consequence, the stage of the game at which a collusive agreement is reached becomes important. While agent 2 prefers to reach an agreement before efforts are chosen, agent 1 prefers to wait until agent 2 has observed his effort choice to reach an agreement. Thus, the moment at which an agreement is reached becomes part of the negotiation itself. But since agent 1 can simply decide to wait, his bargaining power is higher than that of agent 2. This allows agent 1 to extract part of agent 2's rent and obliges the principal to increase his wage if she wants to avoid any agreement between the agents. Therefore, apart from the comparison of organizational structures, a main interest of the paper is to show how the position of agents in sequential games can determine endogenously the bargaining power in collusive agreements.

The paper is organized as follows. Section 2 presents the model. Section 3 shows the characteristics of the optimal wage contracts under the different organizational structures. Section 4 compares the different organizational structures and derives the main results. Finally, Section 5 concludes.

2 The model

Consider the situation in which a principal wants to realize a project which requires the effort of two agents.[4] The agents realize their efforts sequentially, beginning with agent 1. The agents' effort e_i is either zero or one, $e_i \in \{0, 1\}$. When $e_i = 0$ we say that agent i shirks and when $e_i = 1$ we say he works. The cost of one unit of effort is c. The project may result either a success (s) or a failure (f). If the project is a success it's value for the principal is v. In case of a failure it's value is zero. The probability of a success is $p_{e_1 e_2}$. We assume $0 < p_{00} < \bar{p} < p_{11} < 1$

[2]Here we refer exclusively to models that include two or more productive agents. Another strand in the literature analyzes models with one principal, a supervisor and one productive agent. Examples of this approach are: Tirole (1986, 1992), Baron and Besanko (1992), Melumad, Mookherjee and Reichelstein (1995), Faure-Grimaud, Laffont and Reichelstein (2003), and Celik (2009).

[3]However, Itoh (1993) shows that side-contracting between agents can be beneficial for the principal when agents cooperate.

[4]Similar models have been applied, among others, by Baliga and Sjöström (1998), Che and Yoo (2001) and Schmitz (2005). See also Laffont and Martimort (2002).

where $\bar{p} = p_{01} = p_{10}$. A distinctive feature of $p_{e_1e_2}$ is the relationship between $\Delta_1 \equiv p_{11} - \bar{p}$ and $\Delta_0 \equiv \bar{p} - p_{00}$. When $\Delta_1 > \Delta_0$ the probability $p_{e_1e_2}$ is supermodular in (e_1, e_2) and an agent's work increases the others productivity gain from work. The values of $(c,\ p_{00},\ \bar{p},\ p_{11})$ are *ex-ante* common knowledge. *Ex-post,* the outcome of the project is commonly observed. The value of the realized effort e_2 is private knowledge of agent 2. Agent 1's effort choice is observed by agent 2. However, we assume that effort is non–verifiable which implies that contracts cannot be based on its observation. Thus, the principal faces a moral hazard problem with each of the two agents.

The agents are compensated for their efforts with payments that depend on the realized outcome of the project. A contract with agent i, $\tilde{w}_i$ is of the form $\tilde{w}_i = (w_{is}, w_{if})$, where w_{is} is the payment agent i receives from the principal if the project results a success, and w_{if} is the one he receives if it is a failure. Denote w_i agent i's wage increment when the project is a success ($w_i = w_{is} - w_{if}$). We assume that agents are risk neutral. If the agents do not accept the contract their wealth is zero. Furthermore, agents have limited liability. In this case it is clearly optimal to set $w_{if} = 0$ and the contract design problem is reduced to find the value of $w_i = w_{is}$. Thus, expected utility of agent i can be written as $Eu_i(e_1, e_2; w_i) = p_{e_1e_2}w_i - ce_i$. We assume that the value of the project in case of a success is sufficiently great such that the principal always wants both agents to work, $e = (e_1, e_2) = (1, 1)$.[5] The principal can decide either to contract both agents directly, or to contract only one of the agents who subcontracts the other agent. Throughout the paper we assume that all parties that sign a contract can credibly commit not to renegotiate the contract. Parties that have not signed a contract can negotiate a contract at any stage of the game. Resuming this, timing of the game is:

1. The principal decides whether to contract both agents or to contract just one agent and delegate subcontracting of the other agent.
2. a) The principal designs the wage contract(s).[6]
   b) If the principal prefers a decentralized structure, the agent contracted by the principal designs himself the wage contract with the other agent.
3. The contracts are publicly observed. The agents accept or refuse the contracts. If both agents accept their contracts the project is realized. Then, agent 1 decides his effort level. Next, after observing agent 1's effort choice, agent 2 himself decides his effort.
4. The success or failure of the project is publicly observed and the agents are paid.

Let us denote $\tilde{w} = (\tilde{w}_1, \tilde{w}_2)$ a vector of wage functions. Furthermore, denote $\Gamma_3 = \Gamma_3\left(e_1, e_2; Eu_1, Eu_2; \tilde{w}\right)$ the extensive form of the subgame played by agents 1 and 2 at stage 3 when the wage function is $\tilde{w}$. Then, the principal's problem at stage 2 is to find a wage function that implements full effort, $e = (1, 1)$, at stage 3 as a subgame perfect equilibrium (SPE) with

[5] The problem of implementing low effort is trivial because if the principal wants agent i to shirk it suffices to pay $w_{is} = w_{if} = 0$.

[6] The principal could also sign the contracts sequentially. However, if she signs first the contract with agent 1 who then chooses his effort and after this she signs the contract with agent 2, this would reduce her commitment capacity against agent 1 to implement working for agent 2. Then she must pay a higher wage to agent 1 and therefore the principal always prefers to sign all contracts before efforts are chosen.

lowest expected total wage cost. At stage 1, the principal chooses the organizational structure that allows her to implement $e = (1,1)$ at stage 3 with lowest w, where $w = w_1 + w_2$.[7] To simplify the exposition of the results the following definition is used:

Definition 1.
Let $\lambda = \left(1 + \sqrt{\left(1 + \frac{4\bar{p}^2}{\Delta_0^2}\right)}\right)$ and $\mu = \sqrt{\left(1 + \frac{4\bar{p}}{\Delta_0}\right)}$.

3 Optimal wage contracts

3.1 The centralized structure

Consider first a centralized structure C, in which the principal contracts both agents directly. The principal's problem is to choose wages w_1 and w_2 that implement $e = (1,1)$ at minimum total cost under two kind of constraints, incentive compatibility constraints which ensure that working for each agent is a SPE and limited liability constraints that ensure that agents cannot be penalized. Consequently, the optimal contracts are the solution to program $[P^C]$:

$$\begin{aligned} \min_{w_1,w_2} \quad & w_1 + w_2 \\ s.t. \quad & 1 = \arg\max_{e_1} Eu_1(e_1, e_2; w_1), \\ & \qquad s.t. \quad 1 = \arg\max_{e_2} Eu_2(1, e_2; w_2) \\ & w_i \geq 0 \qquad i = 1, 2. \end{aligned}$$

The game is solved by backward induction. Notice that the incentive compatibility constraints imply that $e = (1,1)$ is a SPE of Γ_3 which is represented in Figure 1.

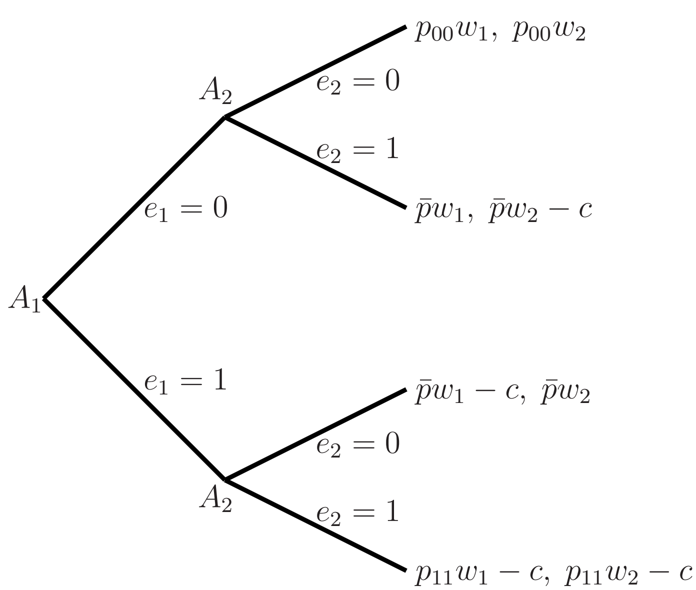

Figure 1.

[7]Notice, that the expected utility of the principal is $p_{11}(v - w)$ if $e = (1,1)$ is implemented. Thus, expected utility is maximized when w is minimized.

The necessary conditions for implementation of $e = (1,1)$ as a SPE of Γ_3 are:

$$p_{11}w_2 - c \geq \bar{p}w_2 \quad \text{and} \quad p_{11}w_1 - c \geq \begin{cases} \bar{p}w_1 & \text{if } \bar{p}w_2 - c \geq p_{00}w_2 \\ p_{00}w_1 & \text{if } \bar{p}w_2 - c < p_{00}w_2. \end{cases}$$

The minimization of the total wage cost implies that at the optimum the constraints are binding. Then, $\tilde{w}_2^C = (\frac{c}{\Delta_1}, 0)$ and $\tilde{w}_1^C = (\frac{c}{\Delta_1}, 0)$ if $\Delta_1 \leq \Delta_0$ and $\tilde{w}_1^C = (\frac{c}{\Delta_1+\Delta_0}, 0)$ if $\Delta_1 > \Delta_0$. When $\Delta_1 > \Delta_0$, agent 1's wage in case of a success of the project is lower than agent's wage. Therefore, agent 1 has a first mover disadvantage in this case, which allows the principal to implement full effort with lower cost. We resume this as:

Proposition 1.
In a centralized structure the principal can implement full effort with lowest total wage cost

$$w^C = \begin{cases} \frac{2c}{\Delta_1} & \text{if } \Delta_1 \leq \Delta_0 \\ \frac{c}{\Delta_1+\Delta_0} + \frac{c}{\Delta_1} & \text{if } \Delta_1 > \Delta_0. \end{cases}$$

Contracts in a centralized structure may be subject to collusive agreements between the agents. Adopting the formulation of Tirole (1986), collusion is a coalition of the two agents which is based on an enforceable side contract, signed after the main contracts but before the actions are taken. We call this kind of side–contracting *ex-ante*. This contract specifies monetary transfers as a function of the verifiable outcome. This implies that, opposite to Baliga and Sjöström (1998), side–payments cannot be made contingent on effort choices because here effort is non–verifiable. We get the following result:

Proposition 2.
The wage function w^C is collusion-proof against ex-ante side–contracting.

Proof:
Agents will engage in side-contracting if both of them can obtain higher expected utility. A necessary condition for this is that the sum of expected utilities is higher when full effort is not implemented as a SPE of Γ_3. With the wage function $\tilde{w}^C$ we get

$$\sum_{i=1,2} \left(Eu_i(1,1;w_i^C) - Eu_i(1,0;w_i^C) \right) = \begin{cases} c > 0 & \text{if } \Delta_1 \leq \Delta_0 \\ \frac{c}{\Delta_1+\Delta_0} > 0 & \text{if } \Delta_1 > \Delta_0. \end{cases}$$

$$\sum_{i=1,2} \left(Eu_i(1,1;w_i^C) - Eu_i(0,1;w_i^C) \right) = \begin{cases} c > 0 & \text{if } \Delta_1 \leq \Delta_0 \\ \frac{c}{\Delta_1+\Delta_0} > 0 & \text{if } \Delta_1 > \Delta_0. \end{cases}$$

$$\sum_{i=1,2} \left(Eu_i(1,1;w_i^C) - Eu_i(0,0;w_i^C) \right) = \begin{cases} 2c\frac{\Delta_0}{\Delta_1} > 0 & \text{if } \Delta_1 \leq \Delta_0 \\ c\frac{\Delta_0}{\Delta_1+\Delta_0} > 0 & \text{if } \Delta_1 > \Delta_0. \end{cases}$$

With wage function $\tilde{w}^C$ there exist no side–payments which make both agents better off. Therefore agents will not engage in side–contracting and the wage function w^C is collusion–proof. ■

The fact that efforts are chosen sequentially and agent 2 can observe agent 1's effort choice before choosing his own, opens the possibility to sign side–contracts also at an interim stage, *after* agent 1's and *before* agents 2's effort choice. The following example shows that this kind of *interim* side–contracting can take place even when contracts are ex–ante collusion–proof.

Example 1.
Let $p_{00} = 0.25$, $\bar{p} = 0.55$, $p_{11} = 0.90$ and $c = 1$. Following proposition 1, the optimal payments which allow to implement full effort in a centralized structure are $w_1^C = 1.5385$ and $w_2^C = 2.8571$. These payments are *ex–ante* collusion-proof, as can be seen in Figure 2.

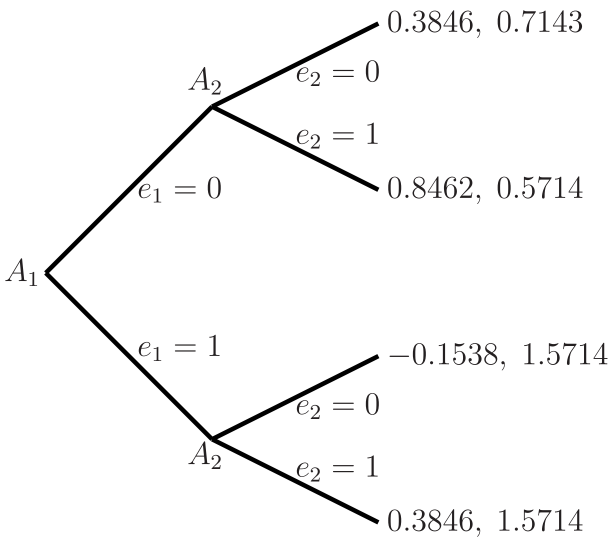

Figure 2

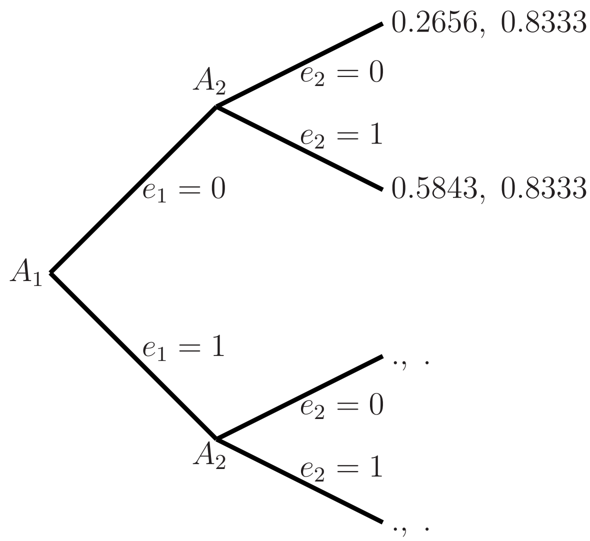

Figure 3

But agent 1 can improve this situation by choosing first $e_1 = 0$ and then offering a payment of $w_2^1 = 0.4762$ to agent 2. Then, as shown in Figure 3, agent 2 would choose to work and agent 1 would obtain higher expected utility than without the side–payment. ■

The example shows that agent 1 can use side–payments after his effort choice to influence the effort choice of agent 2. When does this kind of side–payments take place and how must the principal design collusion-proof wages w_1^{CP} and w_2^{CP} to avoid side-contracting at an interim stage? First, notice that only agent 1 can offer side-payments to agent 2. Since agent 2 chooses his effort after agent 1 he must offer side–payments before all effort choices. But then, as we have seen in proposition 2, both agents cannot gain from side–payments. Second, agent 1 can bribe agent 2 only when agent 2 is supposed to shirk. Only then, a positive payment can induce agent 2 to change his effort choice. Therefore, the only case in which agent 1 may induce agent 2 to change his effort choice is when p_{e_1,e_2} is supermodular ($\Delta_1 > \Delta_0$). In order to make agent 2 work, agent 1 must pay at least the amount t, given by:

$$p_{00}(w_2^{CP} + t) \leq \bar{p}(w_2^{CP} + t) - c \tag{1}$$

where $w_2^{CP} \geq w_2^C$ is the payment agent 2 receives from the principal. Agent 1 himself is interested in paying this amount if his resulting expected utility is higher than when he decides to work. Therefore, a collusion-proof payment must satisfy that

$$\bar{p}(w_1^{CP} - t) \leq p_{11} w_1^{CP} - c \tag{2}$$

where $w_1^{CP} \geq w_1^C$ is the payment agent 1 receives from the principal. The principal must choose the payments w_1^{CP} and w_2^{CP} that fulfill the above conditions and yield lowest total cost.

Proposition 3.
In a centralized structure with interim side-contracting, the principal can implement full effort with lowest total wage cost:

$$w^{CP} = \begin{cases} \frac{2c}{\Delta_1} & if \quad \Delta_1 \leq \Delta_0 \\ \frac{2\Delta_1\Delta_0 - \Delta_1\overline{p} + \Delta_0\overline{p}}{\Delta_1^2\Delta_0}c & if \quad \Delta_0 < \Delta_1 < \frac{\Delta_0^2}{2\overline{p}}\lambda \\ \frac{c}{\Delta_1+\Delta_0} + \frac{c}{\Delta_1} & if \quad \frac{\Delta_0^2}{2\overline{p}}\lambda \leq \Delta_1. \end{cases}$$

Proof:
Utility maximization implies that (1) is binding, which determines t. Cost minimization implies that (2) is binding and that $w_2^{CP} = w_2^C$. Then, we find that $w_1^{CP} = \frac{\bar{p}^2 - p_{11}p_{00}}{(p_{11}-\bar{p})^2(\bar{p}-p_{00})}c = \frac{\Delta_1\Delta_0 - \Delta_1\overline{p} + \Delta_0\overline{p}}{\Delta_1^2\Delta_0}c$ which must fulfill the condition $w_1^{CP} > w_1^C$. Otherwise, w_1^C is sufficient to implement full effort. For $\Delta_1 \leq \Delta_0$ we have $w_1^{CP} = w_1^C$ and therefore $w^{CP} = w^C$. For $\Delta_1 > \Delta_0$ the condition $w_1^{CP} > w_1^C$ implies:

$$w_1^{CP} = \frac{\Delta_1\Delta_0 - \Delta_1\overline{p} + \Delta_0\overline{p}}{\Delta_1^2\Delta_0}c > \frac{c}{\Delta_1 + \Delta_0} = w_1^C \quad \text{or} \quad \Delta_0 < \Delta_1 < \frac{\Delta_0^2}{2p}\lambda.$$

Therefore, for $\Delta_0 < \Delta_1 < \frac{\Delta_0^2}{2\overline{p}}\lambda$ we have $w^{CP} = \frac{\Delta_1\Delta_0 - \Delta_1\overline{p} + \Delta_0\overline{p}}{\Delta_1^2\Delta_0}c + w_2^C$, and for $\Delta_1 \geq \frac{\Delta_0^2}{2\overline{p}}\lambda$ we have $w^{CP} = w_1^C + w_2^C = w^C$. ■

From proposition 3 we see that the conditions under which interim side–contracting takes place are that p_{e_1,e_2} is supermodular and that $2\overline{p}/\Delta_0$ is small (because the size of the second region is decreasing in $2\overline{p}/\Delta_0$). This expression achieves its smallest value when $p_{00} \to 0$. The intuition here is that the more important A1's first-mover disadvantage, which increases in Δ_0 and decreases in p_{00}, the more agent 2 has to lose when agent 1 does not work at stage 1. Thus, agent 1's bargaining power increases which allows to negotiate a redistribution of rents. I call this the *rent–redistribution effect*, which means:

Corollary 1.
In a centralized structure, interim side-contracting can take place to redistributed rents from agent 2 to agent 1. This rent–redistribution effect requires that $w^{CP} > w^C$ iff $\Delta_0 < \Delta_1 < \frac{\Delta_0^2}{2\overline{p}}\lambda$, where the size of this interval is decreasing in p_{00}. Else, there will be no rent redistribution and $w^{CP} = w^C$.

Example 1.
With $p_{00} = 0.25$, $\bar{p} = 0.55$, $p_{11} = 0.90$, and $c = 1$ we have $w^{CP} = 4.9660 > w^C = 4.3956$. To see that this payment is collusion-proof against interim contracting consider the expected utility levels of the agents displayed in Figure 4 and Figure 5.

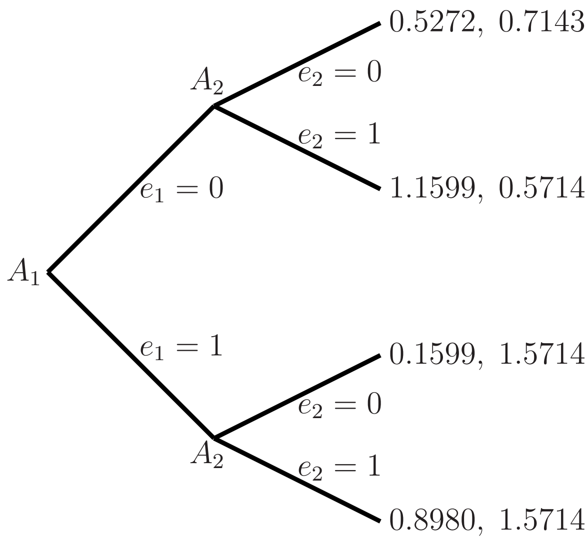

Figure 4

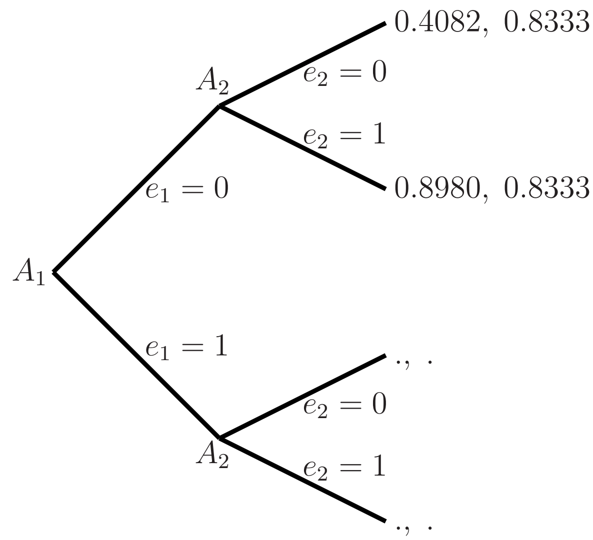

Figure 5

As can be seen from Figure 4, agent 1 still prefers $e = (0, 1)$ to full effort. However, if he shirks, agent 2 will work only if he gets the transfer $t = 0.4762$ from agent 1. But after paying this transfer agent 1 is better off working himself. ■

3.2 Delegation to agent 1

Consider first a decentralized structure in which the principal contracts only agent 1 who contracts separately with agent 2. Denote this structure by D_1. When the principal designs the payment scheme w_1 she must take into account that it is now agent 1 who implements the effort level of agent 2 with his own contract. If the principal wants both agents to work, in equilibrium, she must design her contract such that agent 1 wants to work, and such that agent 1 also wants agent 2 to work. Therefore, to design her contract, the principal must know how agent 1 will solve his contract design problem with agent 1. Since agent 2 observes agent 1's effort choice before choosing himself his effort, agent 1's contracting problem seems to have a simple solution. Given that agent 1 works, the contract must provide sufficient incentives to agent 2 to work, too. However, from the principal's point of view the solution is more complex. To guarantee that both agents work in equilibrium implies that she must consider all alternatives: agent 2 works and incites agent 1 to shirk, agent 2 shirks and incites agent 1 either to work or also to shirk. In each of these cases the contract offered by agent 1 to agent 2 will be different. Denote the optimal contract agent 1 offers to agent 2 and which allows agent 1 to implement (e_1, e_2) as a SPE of Γ_3 for a given wage w_1, by $w_2(e_1, e_2)$. Formally, if agent 1 wants to implement $e = (e_1, e_2)$ he must choose the contract with agent 2 to solve $[P^1]$:

$$\begin{aligned}
(e_1^*, e_2^*, w_2(e_1^*, e_2^*)) \in \arg \max_{e_1, e_2, w_2} \quad & Eu_1(e_1, e_2; w_1 - w_2) \\
s.t. \quad & e_2 = \arg\max_{\tilde{e}_2} Eu_2(e_1, \tilde{e}_2; w_2), \\
& w_2 \geq 0.
\end{aligned}$$

The principal herself, if she wants both agents to work hard, solves the problem $[P^{D_1}]$:

$$\min_{w_1} \; w_1 \qquad s.t. \qquad (1,1,w_2(1,1)) \text{ solves } P^1$$
$$w_1 - w_2(1,1) \geq 0.$$

The solution of P^{D_1} yields:

Proposition 4.
In a decentralized structure in which contracting is delegated to agent 1, the principal can implement full effort with total wage cost

$$w_1^{D_1} = \begin{cases} \frac{2}{\Delta_1} c & \text{for} \quad \Delta_1 \leq \Delta_0 \\ \frac{p_{11}}{\Delta_1^2} c & \text{for} \quad \Delta_0 < \Delta_1 \leq \frac{\Delta_0}{2}(1+\mu) \\ \frac{2\Delta_1 + \bar{p}}{\Delta_1(\Delta_1+\Delta_0)} c & \text{for} \quad \frac{\Delta_0}{2}(1+\mu) < \Delta_1. \end{cases}$$

Example 1.
Let $p_{00} = 0.25$, $\bar{p} = 0.55$, $p_{11} = 0.90$ and $c = 1$. Suppose the principal pays a wage of $w_1^{D_1} = w^C = 4.3956$. Does this wage allow to implement full effort in equilibrium? To see this, we must compare agent 1's expected utility under different alternatives. If agent 1 works and wants agent 2 also to work, he must pay him $w_2(1,1) = 2.8571$ and gets an expected utility of $Eu^1(1,1;1.5385) = 0.3847$. If only agent 1 works, he pays nothing to agent 2 and gets an expected utility of $Eu^1(1,0;4.3956) = 1.4176$. Similarly, if agent 1 shirks and agent 2 works, $w_2(0,1) = 3.3333$ and $Eu_1(0,1;1.0623) = 0.5843$. Finally, if both agents shirk, agent 2 is paid nothing and $Eu_1(0,0;4.3956) = 1.0989$. Thus, agent 1 prefers agent 2 to shirk and himself to work. Therefore, full effort cannot be implemented at wage cost w^C. To implement full effort the principal must increase her payment to agent 1.

Now, let $w_1^{D_1} = 7.3469$. Then, paying the same wages as before to agent 2, agent 1's expected utility levels are $Eu_1(1,1;4.4898) = 3.0408$, $Eu_1(1,0;7.3469) = 3.0408$, $Eu(0,1;4.0136) = 1.2075$, and $Eu(0,0;7.3469) = 1.8367$, respectively. We conclude that the principal can implement full effort under contract delegation to agent 1 with minimum total wage cost $w_1^{D_1} = 7.3469$. ■

As can be seen from the example and as it is shown in the appendix, the cost of delegating contracting to agent 1 compared to the collusion–free centralized structure (C) consists in that agent 1 might prefer agent 2 to shirk and to keep his payment instead of giving part of the payment received from the principal to agent 2 to incite him to work. We call this the *rent extraction effect*. Due to this effect, the principal must avoid that only agent 1 works or that both agents shirk, which might require to increase the payment to A1 when the project is a success. The cost of delegation decreases in p_{00} and in $\overline{p}$, because then, the probability for a success when both agents do not work is lower and agent 1 will be more interested in inciting agent 2 to work. Furthermore, the cost of delegation also decreases in Δ_1 because in this case A1's productivity gain from working is larger when A2 also works.

Corollary 2.
In structure D_1, agent 1 can extract part of the rent that agent 2 receives in structure C. To implement full effort, this rent–extraction effect requires that $w^{D_1} > w^C$ iff $\Delta_0 < \Delta_1$. Else, there is no rent extraction and $w^{D_1} = w^C$.

3.3 Delegation to agent 2

Consider now the case in which the principal contracts agent 2 who subcontracts agent 1. Denote this structure by D_2. Again, the implementation of full effort as a SPE of Γ_3 requires that the principal incites with her payment w_2 first, agent 2 to work, and second, agent 2 himself to incite agent 1 to work. To find the optimal payment $w_2^{D_2}$ the principal must consider first agent 2's implementation problem. Denoted $w_1(e_1, e_2)$ the optimal contract between agent 2 and agent 1 when agent 2 wants to implement (e_1, e_2) as a SPE of Γ_3. To find this contract, agent 2 must solve problem $[P^2]$:

$$\begin{aligned} (e_1^*, e_2^*, w_1(e_1^*, e_2^*)) \in \arg \max_{e_1,e_2,w_1} \quad & Eu_2(e_1, e_2; w_2 - w_1) \\ s.t. \quad & e_1 = \arg\max_{\tilde{e}_1} Eu_1(\tilde{e}_1, e_2; w_1), \\ & s.t. \quad e_2 = \arg\max_{\tilde{e}_2} Eu_2(\tilde{e}_1, \tilde{e}_2; w_2 - w_1), \\ & w_1 \geq 0. \end{aligned}$$

The principal herself if she wants both agents to work, solves the problem $[P^{D_2}]$:

$$\begin{aligned} \min_{w_2} \ w_2 \qquad s.t. \quad & (1, 1, w_1(1, 1)) \text{ solves } P^2 \\ & w_2 - w_1(1, 1) \geq 0. \end{aligned}$$

The solution of P^{D_2} yields:

Proposition 5.
In a decentralized structure in which contracting is delegated to agent 2, the principal can implement full effort with total wage cost

$$w_2^{D_2} = \begin{cases} \frac{2}{\Delta_1} c & \text{for} \quad \triangle_1 \leq \triangle_0 \\ \frac{p_{11}}{\Delta_1^2} c & \text{for} \quad \triangle_0 < \Delta_1 < \frac{1}{2}\Delta_0 (\mu - 1) \ \text{ and } \overline{p} > 2\Delta_0 \\ \frac{p_{11}}{(\Delta_1 + \Delta_0)\Delta_1} c & \text{for} \quad \frac{1}{2}\Delta_0 (\mu - 1) \leq \Delta_1 < \min\left\{\overline{p} - \Delta_0, \sqrt{\overline{p}\Delta_0}\right\} \ \text{ and } \overline{p} > 2\Delta_0 \\ \frac{2p_{11} - p_{00}}{(\Delta_1 + \Delta_0)^2} c & \text{for} \quad \max\left\{\sqrt{\overline{p}\Delta_0}, \frac{\Delta_0^2}{\overline{p} - 2\Delta_0}\right\} \leq \Delta_1 \text{ and } \overline{p} > 2\Delta_0 \\ \frac{c}{\Delta_1 + \Delta_0} + \frac{c}{\Delta_1} & \text{for} \quad \max\left\{\overline{p} - \Delta_0, \triangle_0\right\} < \Delta_1 \text{ and } \left(\overline{p} - 2\Delta_0\right)\Delta_1 < \Delta_0^2 \end{cases}$$

Example 1.
Let $p_{00} = 0.25$, $\bar{p} = 0.55$, $p_{11} = 0.90$ and $c = 1$ and suppose the principal pays a wage of $w_2^{D_2} = w^C = 4.3956$ to agent 2. Suppose agent 2 wants to implement full effort. Then, he must pay agent 1 a wage of $w_1(1, 1) = 1.5385$. As we have seen in the centralized structure, in this case agent 1 chooses to work. Furthermore, agent 2 also prefers to work in this case and his expected utility is $Eu_2(1, 1; 2.8571) = 1.5714$. The question which arises is whether agent 2 really wants to implement full effort.

Consider the case in which only agent 1 works. Whether $e = (1, 0)$ can be implemented as a SPE depends crucially on what effort agent 1 expects agent 2 to choose. This choice is determined by agent 2's residual wage. If this wage is such that agent 2 prefers to work when agent 1 shirks, then agent 1 will never work because this reduces his expected utility. With $w_1(1, 0) = 3.3333$ we find that $Eu_2(0, 1; 1.0623) = -0.4157 < Eu_2(0, 0; 1.0623) = 0.2656$

and $Eu_2(1,1;1.0623) = -0.04393 < Eu_2(1,0;1.0623) = 0.5843$. Thus, agent 1 expects agent 2 to shirk. Then, he himself prefers to work because with $w_1(1,0) = 3.3333$ we have $Eu_1(1,0;3.3333) = 0.8333 \geq Eu_1(0,0;3.3333) = 0.8333$. Thus, agent 2 can implement $e = (1,0)$ with lowest wage cost by paying agent 1 the wage $w_1(1,0) = 3.3333$ obtaining an expected utility of $Eu_2(1,0) = 0.5843$.

Now consider the case that agent 2 wants agent 1 to shirk. Then, he pays him nothing. If agent 1 works he gets an expected utility of $Eu_2(0,1;4.3945) = 1.4176$, and if he shirks he gets $Eu_2(0,0;4.3956) = 1.0989$. We conclude that agent 2 is best off when he implements full effort. Thus, the principal can implement full effort with minimum total wage cost $w_2^{D_2} = w^C = 4.3956$ if she delegates the contracting of agent 1 to agent 2. ■

The cost of delegation to agent 2 compared to the collusion–free centralized structure C, is similar to the case of delegation to agent 1. Agent 2 might prefer agent 1 to shirk and to pay him nothing. If the principal wants to avoid this, she must increase the payment to agent 2 if the project is a success to make him more interested in obtaining a high outcome. However, compared to structure D_1, there is a main difference. If the productivity gains from having both agent working instead of having one of them shirking are high enough, full effort can be implemented under structure D_2 with the same cost as under structure C. This is because when Δ_0 is large, agent 1's rent in a centralized structure is low. Therefore, agent 2's gain from extracting this rent is inferior to his gain from having a successful project with higher probability because it is relatively cheap for agent 2 in this case to incite agent 1 to work. Then, delegation to agent 2 has the same cost as a centralized structure without collusion and therefore is cheaper for the principal than delegation to agent 1.

Corollary 3.
In structure D_2, agent 2 can extract part of the rent agent 1's receive in structure C. This rent–extraction effect requires that $w^{D_2} > w^C$ iff $\max\left\{\sqrt{\overline{p}\Delta_0}, \frac{\Delta_0^2}{\overline{p}-2\Delta_0}\right\} \leq \Delta_1$ and $\overline{p} > 2\Delta_0$, where the size of this interval is increasing in p_{00}. Else, there is no rent extraction and $w^{D_2} = w^C$.

4 Comparison of structures

In this section the centralized structure with interim contracting C^{CP} and the two decentralized structures D_1 and D_2, are compared. First, structures C^{CP} and D_1 are compared. From propositions 3 and 4 we get:

Proposition 6.
Full effort can be implemented at lower cost in a centralized hierarchy than in a decentralized hierarchy in which contracting is delegated to agent 1 when $\Delta_1 > \Delta_0$. Else, full effort can be implemented at the same cost in both structures.

This result means that the principal never gains from delegating contracting to agent 1. When p_{e_1,e_2} is supermodular the implementation of full effort is more costly for the principal. In a centralized structure in which agents collude and in a structure in which contracting is delegated to agent 1, payments between agents go from agent 1 to agent 2. If the principal wants to avoid these payments, she must distort the implementation of full effort for both agents. As we have seen before, under collusion the principal must avoid that agent 1 shirks and that agent 2 works instead of having both agents working. Under delegation to agent 1, the principal must avoid that any other combination of efforts which is not having both agents working is implemented. Therefore, delegation to agent 1 cannot be less costly than a centralized structure in which agents collude because in both cases it is agent 1 that distorts the effort decisions and under structure D_1 his possibilities to do so are greater.

Now, consider structures C^{CP} and D_2. From propositions 3 and 5 we get:

Proposition 7.
Full effort can be implemented with strictly lower cost in a decentralized hierarchy in which contracting is delegated to agent 2 than in a centralized hierarchy iff

$$\max\{p_{00}, \Delta_0\} < \Delta_1 < \frac{\Delta_0^2}{2\overline{p}}\lambda \text{ and } (\overline{p} - 2\Delta_0)\,\Delta_1 < \Delta_0^2.$$

Full effort can be implemented at the same cost in both hierarchies iff

a) $\max\left\{p_{00}, \frac{\Delta_0^2}{2\overline{p}}\lambda\right\} \leq \Delta_1 < \frac{\Delta_0^2}{\overline{p}-2\Delta_0}$,

b) $\frac{\Delta_0^2}{2\overline{p}}\lambda \leq \Delta_1$ *and* $\overline{p} \leq 2\Delta_0$, *or*

c) $\Delta_1 \leq \Delta_0$.

The interesting result in proposition 7 is that the principal might prefer a decentralized structure in which contracting is delegated to agent 2 to a centralized structure in which agents can collude. Under delegation to agent 2 and in a centralized structure the bargaining power is distributed to different agents. In the first case, it is agent 2 who distorts the effort decisions while in the second case it is agent 1 that can distort them. In both cases agents are interested in distorting the effort levels when the productivity gains from working both are not too high. However, in a centralized structure in which agents can collude, agent 1 is more likely to distort the second-best effort decision when p_{00} is small (and the rent-redistribution effect is large, corollary 1), while in a decentralized structure in which agent 2 is the general contractor, agent 2 is more likely to distort efforts when p_{00} is large (and the rent-extraction effect is large, corollary 3). Therefore, when p_{00} is small, we have a large rent-redistribution effect in structure C^{CP} and a small rent-extraction effect in structure D_2. In this case, structure D_2 is superior to structure C^{CP}.

5 Conclusions

The study of organizational structures is important for our understanding of many economic phenomena. Since Myerson's (1982) article an important challenges for economic theory has been to explain the existence of contract delegation. While economic theory suggests that decentralized structures in most circumstances cannot be superior to a centralized structure, we find that contract delegation is a pervasive feature that can be found in many organizations.

This paper contributes to our understanding of why decentralized structure can perform as well as a centralized structure or even better.

The first message of this paper is that decentralized structures can perform as well as a centralized structure when efforts are submodular. A second result is that a decentralized structure can perform strictly better than a centralized structure. This happens when efforts are supermodular and low efforts from both agents are unlikely to yield a successful project. Furthermore, in this case the principal always delegates contracting to the agent at the final production stage. This result shows that the assumption of Baliga and Sjöström (1998) that agents can side-contract on agent 1's effort is unnecessarily strong to find a decentralized structure superior to a centralized structure. For this result it is sufficient that agents can collude and sign side-contracts at an interim stage, after agent 1's effort choice and before agent 2 chooses his effort. This means that a decentralized structure can be superior to a centralized structure in many circumstances.

Appendix

Proof of Proposition 4.
Define $E_{e_1 e_2} = \{w_1, w_2\}$ the set of wage-tuples that allow the implementation of (e_1, e_2) as a SPE of Γ_3. Then we have:

$E_{11} = \{w_1, w_2\}$ such that: (1) $w_2 \geq c/\Delta_1$ and (2) $w_1 - w_2 \geq c/\Delta_1$ if $w_2 \geq c/\Delta_0$ and (3) $w_1 - w_2 \geq c/(\Delta_1 + \Delta_0)$ if $w_2 < c/\Delta_0$.

$E_{10} = \{w_1, w_2\}$ such that: (1) $w_2 < c/\Delta_1$ and (2) $w_2 < c/\Delta_0$ and (3) $w_1 - w_2 \geq c/\Delta_0$.

$E_{01} = \{w_1, w_2\}$ such that: (1) $w_2 \geq c/\Delta_0$ and (2) $w_1 - w_2 < c/\Delta_1$ if $w_2 \geq c/\Delta_1$.

$E_{00} = \{w_1, w_2\}$ such that: (1) $w_2 < c/\Delta_0$ and (2) $w_1 - w_2 < c/\Delta_0$ if $w_2 < c/\Delta_1$ and (3) $w_1 - w_2 < c/(\Delta_1 + \Delta_0)$ if $w_2 \geq c/\Delta_1$.

Furthermore, in all cases the limited liability constraint $w_1 \geq w_2$ must be satisfied. Let us define $\alpha = \frac{c}{\Delta_1} + \frac{c}{\Delta_1+\Delta_0}$, $\beta = \frac{c}{\Delta_0} + \frac{c}{\Delta_1+\Delta_0}$, $\gamma = \frac{c}{\Delta_0} + \frac{c}{\Delta_1}$ and $\theta = \frac{c}{\Delta_0}$, where $\theta < \beta < \gamma$. In Figures A1 and A2 we display the sets which allow the implementation of the different equilibria.

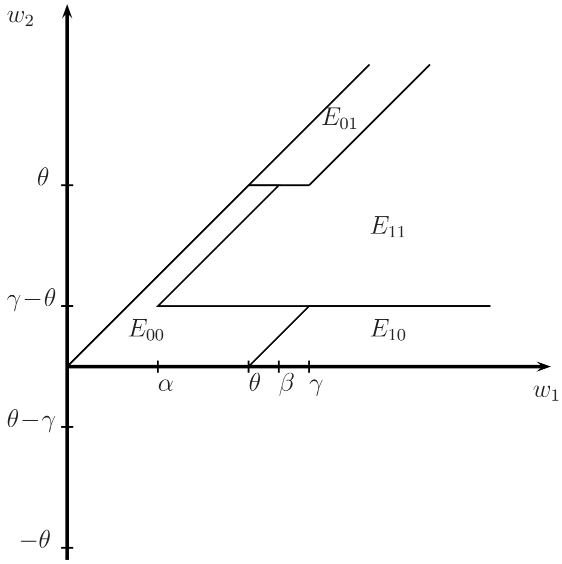

Figure A1. Implementable equilibria for $\triangle_1 > \triangle_0$ which implies that $\beta > \alpha$. In the Figure $\theta > \alpha$, which is not necessarily the case.

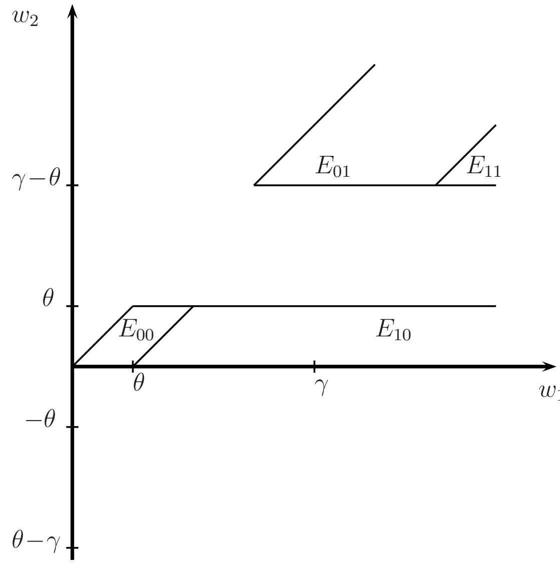

Figure A2. Implementable equilibria for $\triangle_1 \leq \triangle_0$.

Consider first the case $\Delta_1 > \Delta_0$. Then, from Figure A1 we see that agent 2 chooses the following wages to maximize his expected utility, i.e. the solutions of P^1 are:

$$\begin{aligned} w_2(1,1) &= \gamma-\theta && \text{for} \quad \alpha \leq w_1 \\ w_2(1,0) &= 0 && \text{for} \quad \theta \leq w_1 \\ w_2(0,1) &= \begin{cases} \theta+\epsilon & \text{for} \quad \theta < w_1 \leq \gamma \\ w_1-\gamma+\theta+\epsilon & \text{for} \quad \gamma < w_1 \end{cases} \\ w_2(0,0) &= \begin{cases} 0 & \text{for} \quad 0 \leq w_1 \leq \theta \\ w_1-\theta+\epsilon & \text{for} \quad \theta < w_1 < \gamma \end{cases} \end{aligned}$$

where ϵ is an amount infinitesimally small. Denoting $Eu_1(e_1,e_2;w_1) = Eu_1(e_1,e_2;w_1 - w_2(e_1,e_2))$, the maximal expected utility of agent 1 is:

$$\begin{aligned} Eu_1(1,1;w_1) &= p_{11}\left(w_1-\gamma+\theta\right)-c && \text{for} \quad \alpha \leq w_1 \\ Eu_1(1,0;w_1) &= \bar{p}w_1 - c && \text{for} \quad \theta \leq w_1 \\ Eu_1(1,0;w_1) &= \begin{cases} \bar{p}\left(w_1-\theta-\epsilon\right) & \text{for} \quad \theta < w_1 \leq \gamma \\ \bar{p}(\gamma-\theta-\epsilon) & \text{for} \quad \gamma < w_1 \end{cases} \\ Eu_1(0,0;w_1) &= \begin{cases} p_{00}w_1 & \text{for} \quad 0 \leq w_1 \leq \theta \\ p_{00}(\theta-\epsilon) & \text{for} \quad \theta < w_1 < \gamma \end{cases} \end{aligned}$$

To find the minimum wage $w_1^{D_1}$ that induces agent 1 to implement $e=(1,1)$ as a SPE of Γ_3 we must guarantee that $Eu_1(1,1;w_1^{D_1}) \geq Eu_1(e_1,e_2;w_1^{D_1})$, where $w^{D_1} \in E_{11}$. First, we show that $Eu_1(1,0;w_1) > Eu_1(0,1;w_1), \quad \forall w_1 \in E_{01}$:

$$Eu_1(1,0;w_1) - Eu_1(0,1;w_1) = \begin{cases} \frac{p_{00}}{\bar{p}-p_{00}}c + \bar{p}\epsilon > 0 & \text{for} \quad \theta \leq w_1 \leq \gamma \\ \bar{p}(w_1-\gamma) + \frac{p_{00}}{\bar{p}-p_{00}}c + \bar{p}\epsilon > 0 & \text{for} \quad \gamma < w_1. \end{cases}$$

Thus, if agent 1 must choose between SPE's in which only one of the two agents works, he always prefers a SPE in which he works himself. Next, define $Eu_1(.,0;w_1) =$

$sup\{Eu_1(0,0;w_1), Eu_1(1,0;w_1)\}$ the highest expected utility agent 1 can obtain if he decides to implement a SPE where agent 2 shirks. Then, we have:

$$Eu_1(.,0;w_1) = \begin{cases} p_{00}w_1 & \text{for } \; 0 \le w_1 < \theta \\ \bar{p}w_1 - c & \text{for } \; \theta \le w_1 \end{cases}$$

Finally, if the principal wants to implement $e = (1,1)$ she chooses $w_1^{D_1}$ the lowest w_1 such that $Eu_1(1,1;w_1) = Eu_1(.,0;w_1)$. We get:

$$\begin{array}{rcll} w_1^{D_1} & = & \alpha & \text{for } \; Eu_1(1,1;\alpha) \ge p_{00}\alpha \quad \text{and} \quad \alpha < \theta \\ Eu_1(1,1;w_1^{D_1}) & = & p_{00}w_1^{D_1} & \text{for } \; Eu_1(1,1;\alpha) < p_{00}\alpha, \quad Eu_1(1,1;\theta) > \frac{p_{00}}{\Delta_0}c \quad \text{and} \quad \alpha < \theta \\ Eu_1(1,1;w_1^{D_1}) & = & \bar{p}w_1^{D_1} - c & \text{for } \; Eu_1(1,1;\theta) \le \frac{p_{00}}{\Delta_0}c \quad \text{and} \quad \alpha < \theta \\ Eu_1(1,1;w_1^{D_1}) & = & \alpha & \text{for } \; Eu_1(1,1;\alpha) \ge \bar{p}\alpha - c \quad \text{and} \quad \alpha \ge \theta \\ Eu_1(1,1;w_1^{D_1}) & = & \bar{p}w_1^{D_1} - c & \text{for } \; Eu_1(1,1;\alpha) < \bar{p}\alpha - c \quad \text{and} \quad \alpha \ge \theta \end{array}$$

Solving for $w_1^{D_1}$ and using $\alpha < \theta \Leftrightarrow \Delta_1 > \frac{1+\sqrt{5}}{2}\Delta_0$ we can rewrite the conditions as:

$$w_1^{D_1} = \begin{cases} \frac{c}{\Delta_1} + \frac{c}{\Delta_1+\Delta_0} & \text{for } \; 0 \ge \frac{p_{00}}{\Delta_1} \quad \text{and} \quad \Delta_1 > \frac{1+\sqrt{5}}{2}\Delta_0 \\ \frac{2\Delta_1+\bar{p}}{\Delta_1(\Delta_1+\Delta_0)}c & \text{for } \; 0 < \frac{p_{00}}{\Delta_1} \quad \text{and} \quad \Delta_1 > \frac{\Delta_0}{2}(1+\mu) \quad \text{and} \quad \Delta_1 > \frac{1+\sqrt{5}}{2}\Delta_0 \\ \frac{p_{11}}{\Delta_1^2}c & \text{for } \; 0 < \Delta_1 \le \frac{\Delta_0}{2}(1+\mu) \quad \text{and} \quad \Delta_1 > \frac{1+\sqrt{5}}{2}\Delta_0 \\ \frac{c}{\Delta_1} + \frac{c}{\Delta_1+\Delta_0} & \text{for } \; \Delta_1 \ge \frac{\bar{p}}{2}\left(1+\sqrt{\left(1+\frac{4\Delta_0}{\bar{p}}\right)}\right) \quad \text{and} \quad \Delta_1 \le \frac{1+\sqrt{5}}{2}\Delta_0 \\ \frac{p_{11}}{\Delta_1^2}c & \text{for } \; 0 < \Delta_1 < \frac{\bar{p}}{2}\left(1+\sqrt{\left(1+\frac{4\Delta_0}{\bar{p}}\right)}\right) \quad \text{and} \quad \Delta_1 \le \frac{1+\sqrt{5}}{2}\Delta_0 \end{cases}$$

Notice, that the first condition in the first line yields a contradiction. The first condition in the second line is fulfilled trivially. The second condition in the second line implies both the third condition and $\Delta_1 > \Delta_0$. The second condition in the third line implies $\Delta_1 > \Delta_0$. The conditions in the fourth line yield a contradiction. Finally, the first condition in line five is implied by the second condition. This allows to rewrite the conditions as in proposition 4.

Now consider the case $\Delta_1 \le \Delta_0$. Then, from Figure A2 we see that agent 1 chooses the following wages to maximize his expected utility:

$$\begin{array}{rcll} w_2(1,1) & = & \frac{c}{\Delta_1} & \text{for} \quad \frac{2c}{\Delta_1} \le w_1 \\ w_2(0,1) & = & \begin{cases} \frac{c}{\Delta_1} \\ w_1 - \frac{c}{\Delta_1} \end{cases} & \begin{array}{ll} \text{for} & \frac{c}{\Delta_1} \le w_1 < \frac{2c}{\Delta_1} \\ \text{for} & \frac{2c}{\Delta_1} \le w_1 \end{array} \\ w_2(1,0) & = & 0 & \text{for} \quad \frac{c}{\Delta_1} \le w_1 \\ w_2(0,0) & = & \begin{cases} 0 \\ w_1 - \frac{c}{\Delta_1} \end{cases} & \begin{array}{ll} \text{for} & 0 \le w_1 < \frac{c}{\Delta_1} \\ \text{for} & \frac{c}{\Delta_1} \le w_1 \le \frac{c}{\Delta_0} + \frac{c}{\Delta_1} \end{array} \end{array}$$

The maximal expected utility of agent 2 is:

$$\begin{array}{rcll} Eu_1(1,1;w_1) & = & p_{11}\left(w_1 - \frac{c}{\Delta_1}\right) - c & \text{for} \quad \frac{2c}{\Delta_1} \le w_1 \\ Eu_1(0,1;w_1) & = & \begin{cases} \bar{p}\left(w_1 - \frac{c}{\Delta_1}\right) \\ \frac{\bar{p}c}{\Delta_1} \end{cases} & \begin{array}{ll} \text{for} & \frac{c}{\Delta_1} \le w_1 < \frac{2c}{\Delta_1} \\ \text{for} & \frac{2c}{\Delta_1} \le w_1 \end{array} \\ Eu_1(1,0;w_1) & = & \bar{p}w_1 - c & \text{for} \quad \frac{c}{\Delta_1} \le w_1 \\ Eu_1(0,0;w_1) & = & \begin{cases} p_{00}w_1 \\ \frac{p_{00}c}{\Delta_1} \end{cases} & \begin{array}{ll} \text{for} & 0 \le w_1 < \frac{c}{\Delta_1} \\ \text{for} & \frac{c}{\Delta_1} \le w_1 \le \frac{c}{\Delta_0} + \frac{c}{\Delta_1} \end{array} \end{array}$$

First, notice that $E_{11} \cap E_{00} = \emptyset$. Second, $\forall w_1 \in E_{11}$:

$$Eu_1(1,1;w_1) - Eu_1(0,1;w_1) = p_{11}\left(w_1 - \frac{2c}{\Delta_1}\right) \geq 0.$$

Thus, the wage $w_1^{D_1}$ which allows the implementation of $e = (1,1)$ with lowest cost is the lowest w_1 such that $Eu_1(1,1;w_1) \geq Eu_1(1,0;w_1)$ for $w_1 \geq \frac{2c}{\Delta_1}$. We find that $Eu_1(1,1;w_1) > Eu_1(1,0;w_1)$ at $w_1 = \frac{2c}{\Delta_1}$. Thus, the optimal wage is:

$$w_1^{D_1} = \frac{2c}{\Delta_1}.$$

Taken together, the results of both subcases yield proposition 4.

Proof of Proposition 5.
Define $E_{e_1 e_2} = \{w_1, w_2\}$ the set of wage-tuples that allow the implementation of (e_1, e_2) as a SPE of Γ_3. Then we have:

$E_{11} = \{w_1, w_2\}$ such that: (1) $w_2 - w_1 \geq c/\Delta_1$ and (2) $w_1 \geq c/\Delta_1$ if $w_2 - w_1 \geq c/\Delta_0$ and (3) $w_1 \geq c/(\Delta_1 + \Delta_0)$ if $w_2 - w_1 < c/\Delta_0$.

$E_{10} = \{w_1, w_2\}$ such that: (1) $w_2 - w_1 < c/\Delta_1$ and (2) $w_1 \geq c/\Delta_0$ and (3) $w_2 - w_1 < c/\Delta_0$.

$E_{01} = \{w_1, w_2\}$ such that: (1) $w_2 - w_1 \geq c/\Delta_0$ and (2) $w_1 < c/\Delta_1$ and (3) $w_2 - w_1 \geq c/\Delta_1$.

$E_{00} = \{w_1, w_2\}$ such that: (1) $w_2 - w_1 < c/\Delta_0$ and (2) $w_1 < c/(\Delta_1 + \Delta_0)$ if $w_2 - w_1 \geq c/\Delta_1$ and (3) $w_1 < c/\Delta_0$ if $w_2 - w_1 < c/\Delta_1$.

Furthermore, in all cases the limited liability constraint $w_2 \geq w_1$ must be satisfied. Again, define $\alpha = \frac{c}{\Delta_1} + \frac{c}{\Delta_1 + \Delta_0}$, $\beta = \frac{c}{\Delta_0} + \frac{c}{\Delta_1 + \Delta_0}$, $\gamma = \frac{c}{\Delta_0} + \frac{c}{\Delta_1}$ and $\theta = \frac{c}{\Delta_0}$, where $\theta < \beta < \gamma$. In Figures A3 and A4 we display the sets which allow the implementation of the different equilibria.

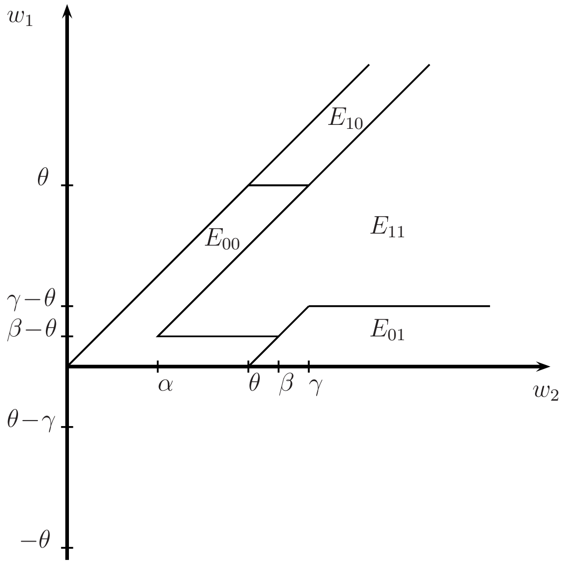

Figure A3. Implementable equilibria for $\triangle_1 > \triangle_0$ which implies that $\beta > \alpha$. In the Figure $\theta > \alpha$, which is not necessarily the case.

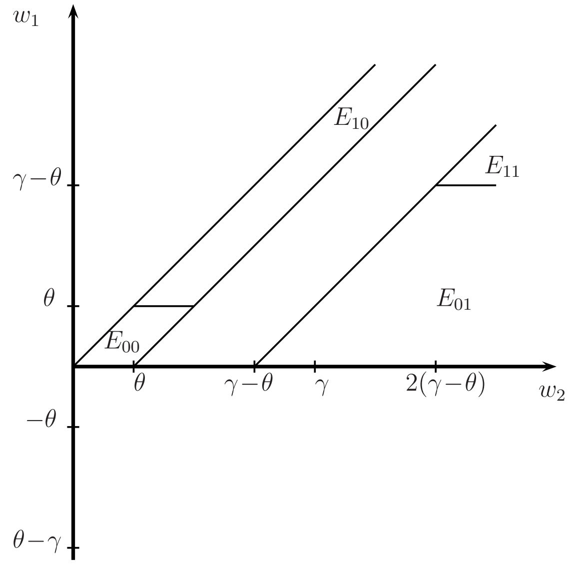

Figure A4. Implementable equilibria for $\triangle_1 \leq \triangle_0$

Consider first the case $\Delta_1 > \Delta_0$. Then, from Figure A3 we see that agent 2 chooses the following wages to maximize his expected utility:

$$\begin{aligned}
w_1(1,1) &= \begin{cases} \beta-\theta & \text{for} \quad \alpha \leq w_2 < \beta \\ w_2-\theta & \text{for} \quad \beta \leq w_2 < \gamma \\ \gamma-\theta & \text{for} \quad \gamma \leq w_2 \end{cases} \\
w_1(1,0) &= \begin{cases} \theta & \text{for} \quad \theta \leq w_2 < \gamma \\ w_2-\theta & \text{for} \quad \gamma \leq w_2 \end{cases} \\
w_1(0,1) &= 0 \qquad\qquad \text{for} \quad \theta \leq w_2 \\
w_1(0,0) &= \begin{cases} 0 & \text{for} \quad 0 \leq w_2 < \theta \\ w_2-\theta & \text{for} \quad \theta \leq w_2 < \beta \end{cases}
\end{aligned}$$

Denoting $Eu_2(e_1, e_2; w_2) = Eu_2(e_1, e_2; w_2 - w_1(e_1, e_2))$, the maximal expected utility of agent 2 is:

$$\begin{aligned}
Eu_2(1,1;w_2) &= \begin{cases} p_{11}(w_2-\beta+\theta)-c & \text{for} \quad \alpha \leq w_2 < \beta \\ p_{11}\theta - c & \text{for} \quad \beta \leq w_2 < \gamma \\ p_{11}(w_2-\gamma+\theta)-c & \text{for} \quad \gamma \leq w_2 \end{cases} \\
Eu_2(1,0;w_2) &= \begin{cases} \bar{p}(w_2-\theta) & \text{for} \quad \theta \leq w_2 < \gamma \\ \bar{p}\theta & \text{for} \quad \gamma \leq w_2 \end{cases} \\
Eu_2(0,1;w_2) &= \bar{p}w_2 - c \qquad\qquad \text{for} \quad \theta \leq w_2 \\
Eu_2(0,0;w_2) &= \begin{cases} p_{00}w_2 & \text{for} \quad 0 \leq w_2 < \theta \\ p_{00}\theta & \text{for} \quad \theta \leq w_2 < \beta \end{cases}
\end{aligned}$$

To find the minimum wage $w_2^{D_2}$ that induces agent 2 to implement $e = (1,1)$ as a SPE of Γ_3 we must guarantee that $Eu_2(1,1;w_2^{D_2}) \geq Eu_2(e_1,e_2;w_2^{D_2})$ where $w_2^{D_2} \in E_{11}$. First, we show that $Eu_2(0,1;w_2) > Eu_2(1,0;w_2)$, $\forall w_2 \in E_{10}$.

$$Eu_2(0,1;w_2) - Eu_2(1,0;w_2) = \begin{cases} \frac{p_{00}}{\Delta_0}c > 0 & \text{for} \quad \theta \leq w_2 < \gamma \\ \bar{p}(w_2-\gamma) + \frac{1-\bar{p}}{\Delta_0}c + \frac{\bar{p}}{\Delta_1}c > 0 & \text{for} \quad \gamma \leq w_2 \end{cases}$$

Thus, agent 2 will never implement an equilibrium in which only agent 1 works. Next, define $Eu_2(0,.;w_2) = sup\{Eu_2(0,0;w_2), Eu_2(0,1;w_2)\}$ the highest expected utility agent 2 can obtain if he decides to implement an equilibrium where he shirks. Then, we have:

$$Eu_2(0,.;w_2) = \begin{cases} p_{00}w_2 & \text{for} \quad 0 \le w_2 < \theta \\ \bar{p}w_2 - c & \text{for} \quad \theta \le w_2 \end{cases}$$

Finally, the principal chooses $w_2^{D_2}$ the lowest w_2 such that $Eu_2(1,1;w_2) = Eu_2(0,.;w_2)$. We get:

$$\begin{array}{rcll} w_2^{D_2} & = & \alpha & \text{for} \quad Eu_2(1,1;\alpha) \ge p_{00}\alpha \quad \text{and} \quad \alpha < \theta \\ p_{11}(w_2^{D_2} - \frac{c}{\Delta_1+\Delta_0}) - c & = & p_{00}w_2^{D_2} & \text{for} \quad Eu_2(1,1;\alpha) < p_{00}\alpha \quad \text{and} \quad \alpha < \theta \\ & & & \quad \text{and} \quad Eu_2(1,1;\theta) \ge \frac{p_{00}}{\Delta_0}c \\ p_{11}(w_2^{D_2} - \frac{c}{\Delta_1+\Delta_0}) - c & = & \bar{p}w_2^{D_2} - c & \text{for} \quad Eu_2(1,1;\theta) < \frac{p_{00}}{\Delta_0}c \quad \text{and} \quad \alpha < \theta \\ & & & \quad \text{and} \quad Eu_2(1,1;\beta) \ge \bar{p}\beta - c \\ p_{11}(w_2^{D_2} - \frac{c}{\Delta_1}) - c & = & \bar{p}w_2^{D_2} - c & \text{for} \quad Eu_2(1,1;\beta) < \bar{p}\beta - c \quad \text{and} \quad \alpha < \theta \\ w_2^{D_2} & = & \alpha & \text{for} \quad Eu_2(1,1;\alpha) > \bar{p}\alpha - c \quad \text{and} \quad \alpha \ge \theta \\ p_{11}(w_2^{D_2} - \frac{c}{\Delta_1+\Delta_0}) - c & = & \bar{p}w_2^{D_2} - c & \text{for} \quad Eu_2(1,1;\alpha) \le \bar{p}\alpha - c \quad \text{and} \quad \alpha \ge \theta \\ & & & \quad \text{and} \quad Eu_2(1,1;\beta) \ge \bar{p}\beta - c \\ p_{11}(w_2^{D_2} - \frac{c}{\Delta_1}) - c & = & \bar{p}w_2^{D_2} - c & \text{for} \quad Eu_2(1,1;\beta) < \bar{p}\beta - c \quad \text{and} \quad \alpha \ge \theta \end{array}$$

Solving for $w_2^{D_2}$ and using $\alpha < \theta \Leftrightarrow \triangle_1 > \frac{1+\sqrt{5}}{2}\triangle_0$ we can rewrite the conditions as:

$$w_2^{D_2} = \begin{cases} \left.\begin{array}{ll} \frac{c}{\Delta_1} + \frac{c}{\Delta_1+\Delta_0} & \text{for} \quad \Delta_1(\overline{p} - 2\Delta_0) \le \Delta_0^2 \\ \frac{2p_{11}-p_{00}}{(\Delta_1+\Delta_0)^2}c & \text{for} \quad \sqrt{\overline{p}\Delta_0} \le \Delta_1 \text{ and } \Delta_1(\overline{p} - 2\Delta_0) > \Delta_0^2 \\ \frac{p_{11}}{(\Delta_1+\Delta_0)\Delta_1}c & \text{for} \quad \frac{1}{2}\Delta_0(\mu - 1) \le \Delta_1 < \sqrt{\overline{p}\Delta_0} \\ \frac{p_{11}}{\Delta_1^2}c & \text{for} \quad \triangle_0 < \Delta_1 < \frac{1}{2}\Delta_0(\mu - 1) \end{array}\right\} \text{and } \frac{1+\sqrt{5}}{2}\triangle_0 < \triangle_1 \\ \left.\begin{array}{ll} \frac{c}{\Delta_1} + \frac{c}{\Delta_1+\Delta_0} & \text{for} \quad \overline{p} - \Delta_0 \le \Delta_1 \\ \frac{p_{11}}{(\Delta_1+\Delta_0)\Delta_1}c & \text{for} \quad \frac{1}{2}\Delta_0(\mu - 1) \le \Delta_1 < \overline{p} - \Delta_0 \\ \frac{p_{11}}{\Delta_1^2}c & \text{for} \quad \triangle_0 < \Delta_1 < \frac{1}{2}\Delta_0(\mu - 1) \end{array}\right\} \text{and } \triangle_0 < \triangle_1 \le \frac{1+\sqrt{5}}{2}\triangle_0 \end{cases}$$

Notice, that for $\overline{p} \le 2\Delta_0$ the first condition in line one is fulfilled trivially, and the second condition in line five implies that the first condition is fulfilled. The conditions in the remaining lines yield contradictions. Therefore, $w_2^{D_2} = \frac{c}{\Delta_1} + \frac{c}{\Delta_1+\Delta_0}$ for $\overline{p} \le 2\Delta_0$. For $\frac{3+\sqrt{5}}{2}\Delta_0 > \overline{p} > 2\Delta_0$ we have:

$$\Delta_0 < \frac{1}{2}\Delta_0(\mu - 1) < \overline{p} - \Delta_0 < \sqrt{\overline{p}\Delta_0} < \frac{1+\sqrt{5}}{2}\triangle_0 < \frac{\Delta_0^2}{\overline{p} - 2\Delta_0}$$

and for $\overline{p} \ge \frac{3+\sqrt{5}}{2}\Delta_0$ we have:

$$\Delta_0 < \frac{1}{2}\Delta_0(\mu - 1) \text{ and } \frac{\Delta_0^2}{\overline{p} - 2\Delta_0} \le \frac{1+\sqrt{5}}{2}\triangle_0 \le \sqrt{\overline{p}\Delta_0} \le \overline{p} - \Delta_0$$

Therefore, for $\overline{p} > 2\Delta_0$ we have:

$$w_2^{D_2} = \begin{cases} \frac{2p_{11}-p_{00}}{(\Delta_1+\Delta_0)^2}c & \text{for} \quad \max\left\{\sqrt{p\Delta_0}, \frac{\Delta_0^2}{\overline{p}-2\Delta_0}\right\} \le \Delta_1 \\ \frac{c}{\Delta_1+\Delta_0} + \frac{c}{\Delta_1} & \text{for} \quad \overline{p} - \Delta_0 \le \Delta_1 < \frac{\Delta_0^2}{\overline{p}-2\Delta_0} \\ \frac{p_{11}}{(\Delta_1+\Delta_0)\Delta_1}c & \text{for} \quad \frac{1}{2}\Delta_0(\mu - 1) \le \Delta_1 < \min\left\{\overline{p} - \Delta_0, \sqrt{\overline{p}\Delta_0}\right\} \\ \frac{p_{11}}{\Delta_1^2}c & \text{for} \quad \triangle_0 < \Delta_1 < \frac{1}{2}\Delta_0(\mu - 1) \end{cases}$$

Now, consider the case $\Delta_1 \leq \triangle_0$. Then, from Figure A4 we see that agent 2 chooses the following wages to maximize his expected utility:

$$\begin{array}{rcll} w_1(1,1) & = & \frac{c}{\Delta_1} & \text{for} \quad \frac{2c}{\Delta_1} \leq w_2 \\ w_1(1,0) & = & \begin{cases} \frac{c}{\triangle_0} & \text{for} \quad 0 \leq w_2 < \frac{2c}{\triangle_0} \\ w_2 - \frac{c}{\triangle_0} & \text{for} \quad \frac{2c}{\triangle_0} \leq w_2 \end{cases} \\ w_1(0,1) & = & 0 & \text{for} \quad \frac{c}{\triangle_0} \leq w_2 \\ w_1(0,0) & = & \begin{cases} 0 & \text{for} \quad 0 \leq w_2 < \frac{c}{\triangle_0} \\ w_2 - \frac{c}{\triangle_0} & \text{for} \quad \frac{c}{\triangle_0} \leq w_2 \leq \frac{2c}{\triangle_0} \end{cases} \end{array}$$

The maximal expected utility of agent 2 is:

$$\begin{array}{rcll} Eu_2(1,1) & = & p_{11}\left(w_2 - \frac{c}{\Delta_1}\right) - c & \text{for} \quad \frac{2c}{\Delta_1} \leq w_2 \\ Eu_2(1,0) & = & \begin{cases} \bar{p}\left(w_2 - \frac{c}{\triangle_0}\right) & \text{for} \quad 0 \leq w_2 < \frac{2c}{\triangle_0} \\ \frac{\bar{p}}{\triangle_0}c & \text{for} \quad \frac{2c}{\triangle_0} \leq w_2 \end{cases} \\ Eu_2(0,1) & = & \bar{p}w_2 - c & \text{for} \quad \frac{c}{\triangle_0} \leq w_2 \\ Eu_2(0,0) & = & \begin{cases} p_{00}w_2 & \text{for} \quad 0 \leq w_2 < \frac{c}{\triangle_0} \\ \frac{p_{00}}{\triangle_0}c & \text{for} \quad \frac{c}{\triangle_0} \leq w_2 \leq \frac{2c}{\triangle_0} \end{cases} \end{array}$$

First, notice that $E_{11} \cap E_{00} = \emptyset$. Second, $\forall w_2 \in E_{11}$:

$$Eu_2(1,1;w_2) - Eu_2(1,0;w_2) = p_{11}\left(w_2 - \frac{2c}{\Delta_1}\right) + \frac{\bar{p}(\triangle_0 - \Delta_1)c}{\Delta_1\triangle_0} > 0.$$

Thus, the wage $w_2^{D_2}$ which allows the implementation of $e = (1,1)$ with lowest cost is the lowest w_2 such that $Eu_2(1,1;w_2) \geq Eu_2(0,1;w_2)$ for $w_2 \geq \frac{2c}{\Delta_1}$. Again, when the last condition holds with equality $Eu_2(1,1;w_2) > Eu_2(0,1;w_2)$. Thus, the optimal wage is:

$$w_2^{D_2} = \frac{2c}{\Delta_1}.$$

Taken together, the results of the two subcases yield proposition 5.

Proof of Proposition 6.
Notice, that $\frac{\Delta_0^2}{2\bar{p}}\lambda < \frac{\Delta_0}{2}(1+\mu)$. Therefore, from propositions 3 and 4 we get:

$$w^{CP} - w_1^{D_1} = \begin{cases} 0 & \textit{for} \quad \Delta_1 \leq \Delta_0 \\ \frac{-p_{00}}{\Delta_0\Delta_1}c < 0 & \textit{for} \quad \Delta_0 < \Delta_1 < \frac{\Delta_0^2}{2\bar{p}}\lambda \\ \frac{c}{\Delta_1+\Delta_0} - \frac{\bar{p}}{\Delta_1^2}c < 0 & \textit{for} \quad \frac{\Delta_0^2}{2p}\lambda \leq \Delta_1 \leq \frac{\Delta_0}{2}(1+\mu) \\ \frac{-p_{00}}{(\Delta_1+\Delta_0)\Delta_1}c < 0 & \textit{for} \quad \frac{\Delta_0}{2}(1+\mu) < \Delta_1. \end{cases}$$

The final statement follows directly from differentiation of $w^{CP} - w_1^{D_1}$ with respect to p_{00} and from $\lim\limits_{p_{00}\to 0} \frac{\Delta_0}{2}(1+\mu) - \frac{\Delta_0^2}{2\bar{p}}\lambda = 0$

Proof of Proposition 7.
Three cases must be considered:

a) $\triangle_1 \leq \triangle_0$.

Then from propositions 3 and 5 we get: $w_2^{D_2} - w^{CP} = 0$.

b) $\Delta_0 < \Delta_1 < \frac{\Delta_0^2}{2\overline{p}}\lambda$.

Notice that $\sqrt{\overline{p}\Delta_0} \leq \Delta_1$ and $\Delta_1 < \frac{\Delta_0^2}{2\overline{p}}\lambda$ yield a contradiction for $p > 2\Delta_0$. Therefore, from propositions 3 and 5 we get:

$$w_2^{D_2} - w^{CP} = \begin{cases} \frac{p_{00}}{\Delta_0\Delta_1}c > 0 & \text{for} \quad \Delta_0 < \Delta_1 < \frac{\Delta_0}{2}(\mu-1) \text{ and } \overline{p} > 2\Delta_0 \\ \frac{\left(\Delta_1\Delta_0+\Delta_1^2-\Delta_0^2\right)(\overline{p}-3\Delta_0)}{(\Delta_1+\Delta_0)\Delta_1^2\Delta_0}c + \frac{\Delta_0(3\Delta_0+2\Delta_1)(\Delta_1-\Delta_0)}{(\Delta_1+\Delta_0)\Delta_1^2\Delta_0}c > 0 & \text{for} \quad \frac{\Delta_0}{2}(\mu-1) \leq \Delta_1 < \min\left\{\overline{p}-\Delta_0, \sqrt{p\Delta_0}\right\} \text{ and } \overline{p} > 2\Delta_0 \\ \frac{\Delta_1^2 p - \Delta_1\Delta_0^2 - \overline{p}\Delta_0^2}{(\Delta_1+\Delta_0)\Delta_1^2\Delta_0}c < 0 & \text{for} \quad \overline{p}-\Delta_0 \leq \Delta_1 < \frac{\Delta_0^2}{p-2\Delta_0} \text{ and } \overline{p} > 2\Delta_0 \text{ or } \overline{p} \leq 2\Delta_0 \end{cases}$$

The sign in line two follows because existence requires that $\frac{\Delta_0}{2}(\mu-1) < \frac{\Delta_0^2}{2\overline{p}}\lambda$, which is true for $\overline{p} > 3.411139\Delta_0$.

c) $\frac{\Delta_0^2}{2\overline{p}}\lambda \leq \Delta_1$.

Then, we get:

$$w_2^{D_2} - w^{CP} = \begin{cases} \frac{-\Delta_1^2+\Delta_1\overline{p}+\overline{p}\Delta_0}{\Delta_1^2(\Delta_1+\Delta_0)}c > 0 & \text{for} \quad \triangle_0 < \Delta_1 < \frac{\Delta_0}{2}(\mu-1) \text{ and } \overline{p} > 2\Delta_0 \\ \frac{\overline{p}-\Delta_0-\Delta_1}{(\Delta_1+\Delta_0)\Delta_1}c > 0 & \text{for} \quad \frac{\Delta_0}{2}(\mu-1) \leq \Delta_1 < \min\left\{\overline{p}-\Delta_0, \sqrt{p\Delta_0}\right\} \text{ and } \overline{p} > 2\Delta_0 \\ \frac{\Delta_1(\overline{p}-2\Delta_0)-\Delta_0^2}{(\Delta_1+\Delta_0)^2\Delta_1}c > 0 & \text{for} \quad \max\left\{\sqrt{\overline{p}\Delta_0}, \frac{\Delta_0^2}{\overline{p}-2\Delta_0}\right\} \leq \Delta_1 \text{ and } \overline{p} > 2\Delta_0 \\ 0 & \text{for} \quad \overline{p}-\Delta_0 \leq \Delta_1 < \frac{\Delta_0^2}{\overline{p}-2\Delta_0} \text{ and } \overline{p} > 2\Delta_0 \text{ or } \triangle_0 < \Delta_1 \text{ and } \overline{p} \leq 2\Delta_0 \end{cases}$$

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