Aggregate Information and Organizational Structures

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ABSTRACT

We study information flows in an organization with a top management (principal) and multiple subunits (agents) with private information that determines the organization's aggregate efficiency. Under centralization, eliciting the agents' private information may induce the principal to manipulate aggregate information, which obstructs an effective use of information for the organization. Under delegation, the principal concedes more information rent, but is able to use the agents' information more effectively. The trade-off between the organizational structures depends on the likelihood that the agents are efficient. Centralizing information flows is optimal when such likelihood is low. Delegation, by contrast, is optimal when it is high.

JEL Classification: D86, L23, L25

Key words: Agency, Aggregate Information, Organization Design

1 Introduction

Organizational structures, as pointed out by Simon (1973), are "authority mechanisms" that are constructed to process and aggregate organizational information. In some organizations, the communication channels are heavily centralized and top management keeps a strong grip on processing information, while in other organizations, such channels are delegated to subunits and information is aggregated through a chain of hierarchies. Given the importance of utilizing an organization's information effectively, understanding the pros and cons of different modes of processing information is crucial for the efficiency of an organization.

Flow of information within an organization is particularly important if the top management cannot process the entire information in detail. As practitioners point out, it is indeed prohibitively costly for the top management to perfectly communicate with all subunits in the organization. For example, in an interview with Harvard Business Review (Taylor 1991), Percy Barnevik, then CEO of ABB Group, reports that one of the largest obstacles he faces is communication with a large number of the organization's subunits.[1] Likewise, Azziz (2013) notes in Huffington Post that it is not possible for the top management of a large and complex organization to base all its operational decisions on too detailed information from all the individual members of the organization. In practice, the top management of an organization often processes only the "aggregate" or "collective" information, as a result of limited resources.

While the top management has limited access to detailed information, it still has an informational advantage over subunits, especially when the organization's information flow is centralized—only the top management has the aggregate information, or the "big picture" of the organization. As noted by Mintzberg (1983), although top managements have less information about operational details, their superior positions often provide them with unique access to all-embracing internal information. As such, an organization can be prone to top management's abuses of its position at the expense of lower levels in the hierarchy. As Bartolome (1989) reports, incentive issues in an organization are not within the boundary of lower level subunits—the top management's manipulation is an issue as well since it has superior access to the organization's bigger picture.

Contrasting centralization of the information flow to its delegation, this paper studies an organization's optimal process of aggregating information in the presence of manipulation

[1] In addition, Chandler (1993) in his interview reports that the top management of General Electric had lost its communicational control of different subunits due to the increasing size of the company by the end of the 1960s.

concerns by the top management. Under centralization, all subunits of the organization directly report only to the top management, who subsequently aggregates the received information. Under delegation, information aggregation is delegated to a subunit, and that particular subunit makes a report on the aggregate information to the top management.

The central trade-off in our paper is as follows. When top management centralizes the organization's communication channels, inducing truthful behavior of the organization's subunits may lead to the top management's own misrepresenting behavior—it may have an incentive to manipulate the aggregate information collected from the subunits. We show that this tension between the top management's and its subunits' incentives stands in the way of screening, leading to a less effective use of the organization's information.

When top management delegates aggregation of information to a subunit, the ability to manipulate aggregate information is transferred to that particular subunit. This has two counter-acting effects. On one hand, the top management has to give more information rent to that particular subunit to prevent it from manipulating the aggregate information. On the other hand, because the top management has now relinquished the power to manipulate, the organization uses information more effectively.

We identify this trade-off by modeling an internal organization with a principal-agent framework—a principal (top management) and two agents (subunits) with private information about their types (efficiencies). The aggregate information of the agents' types in our model indicates the overall efficiency of the organization. We postulate an organization where it is prohibitively costly for the top management to process detailed information in the organization, and thus its decisions depend on the organization's aggregate information, instead of detailed information.[2] In our model, the potential outcome determined by the principal depends only on the agents' aggregate type, instead of individual types.

Under centralization, each agent sends a report about his efficiency to the principal directly, and no direct communication takes place between the agents. As in standard models of screening, each agent can reap information rent by misrepresenting his efficiency and the principal reduces information rents by distorting the project size downward in the optimal contract. When these distortions are large, an incentive for the principal arises to manipulate the aggregate information herself. In particular, when both agents report that they are inefficient so that the organization's aggregate efficiency is low, the principal has an incentive to overstate the aggregate efficiency. In other words, the principal gains ex post by manipulating the aggregate information. We show that reconciling the agents' and

[2] See Weick (1995) for an organization study on this issue.

the principal's incentives hinders an effective use of the agents' private information and may even prevent its use in the sense that optimal contracts exhibit pooling.

Under delegation, one agent, say agent α, becomes the "superior" of the other agent, say agent β. In this structure, agent β first reports his efficiency to agent α, who in turn reports the aggregate efficiency to the principal. Since the authority to process the aggregate information is shifted from the principal to agent α, the principal faces a loss of control. As a result, the principal must concede larger information rent to this agent. In order to reduce this larger information rent, the principal increases the downward distortions in the optimal project size. There is a gain, however, from the loss of control—there is no tension between the principal's and the agents' manipulation incentives. As a result, a fully separating outcome is restored, implying that the principal can utilize the organization's information more effectively under delegation than under centralization.

Comparing the two structures, we show that the principal's optimal choice of organizational structure is determined by the likelihood that an agent is efficient. Our result hinges upon such likelihood because it determines distortions in the project size and thereby the tension between the principal's and the agents' manipulation incentives. When the agents are likely to be inefficient, centralization is the optimal organizational structure. By contrast, when the agents are likely to be efficient, the optimal structure is delegation.

The rest of the paper proceeds as follows. In Section 2, we review the related studies. The model is presented in Section 3. In Section 4, we discuss our benchmark to show that, when the principal cannot manipulate the aggregate information, centralization always dominates delegation. In Section 5, we compare centralization and delegation when the principal can manipulate the aggregate information from the agents. In Section 6, we extend our discussion by endogenizing restrictiveness of communication technology in our model. We conclude in Section 7. All proofs are relegated to Appendix.

2 Review of Related Studies

Optimality of delegation lies at the heart of studies on organizational structures in recent years. While earlier contributions advocate centralized structures by highlighting a loss of control under delegation (e.g. Williamson 1967, McAfee and McMillan 1995), there have been a number of papers identifying situations in which delegation matches or even outperforms centralization. Unlike ours, many of these papers base their analyses of organizational structures on the costs of information processing (e.g. Radner 1992, Bolton and Dewatripont

1994, Qian 1994) or on problems of coordination (e.g. Rosen 1982, Harris and Raviv 2002, Hart and Moore 2005). Our study belongs to the literature that studies organizations in the presence of private information and manipulation incentives.

Distinguishing organizational structures on the basis of differences in monitoring rather than information flows, Baron and Besanko (1992) and Melumad et al. (1995) identify necessary conditions under which the vertical hierarchy achieves the same outcome as the horizontal hierarchy. They demonstrate that if top management can monitor transactions between the subunits, then the optimal outcome is independent of the organizational structure. Melumad et al. (1997) show that, when contracts are complex, delegating a contracting authority to an agent brings the organization more flexibility. Laffont and Martimort (1998) show that contractual delegation enables organizations under limited communication to mitigate collusion among the agents. Similarly, Jansen et al. (2008) study vertical separation versus vertical integration under collusion.

There are a number of studies demonstrating the optimality of delegation under some specific form of incomplete contracting. Beaudry and Poitevin (1995) and Olsen (1996) point out that delegation can make it harder to renegotiate. Aghion and Tirole (1997) demonstrate that delegation induces acquisition of useful information for the organization. Studies such as Dessein (2002) and Alonso et al. (2008) show that organizations can benefit from delegation because it makes better use of private information. Harris and Raviv (2005) study the optimal hierarchical structure in the presence of informational heterogeneity and contract incompleteness. Focusing on a trade-off between coordination and motivation, Choe and Ishiguro (2012) demonstrate that the optimal hierarchy depends on the extent to which externalities among a firm's projects require coordination and effort incentives. Shin and Strausz (2014) show that delegation mitigates dynamic incentives, when the organization cannot use long term contracts. Unlike these studies, we focus on the delegation of information flows rather than delegation of decision rights.

Because the main economic driver behind our delegation result is the agents' fear of receiving a manipulated compensation, our paper is related to studies on private performance evaluation in organization theory (e.g. Demski and Sappington 1993, Sridhar and Balachandran 1997, Strausz 2006, Khalil et al. 2015, Deb et al. 2016, Shin 2017). In these studies, members of the organization receive some information about the performance of others, which they can then distort or manipulate. By contrast, the information manipulation in our framework concerns the manipulation of the agents' own reports rather than information about the agent's performance from others.

In this respect, our type of manipulation is more in line with a recent literature that studies the principal's incentive to manipulate the information flows when executing a contract or mechanism. Closest in spirit is our modeling of manipulation by a public good provider in Celik et al. (2020). A crucial distinction is, however, that due to limitations in intra-organizational communication, the principal in our model here has to base the agents' compensations on aggregated flows of information rather than each agent's individual one. As a result, the oversupply effect that we identify and focus on in Celik et al. (2020) is not present in the current paper. By contrast, the main insight of the current paper is that the principal's manipulation incentive is a driver for delegating the aggregation of information flows to lower hierarchical levels of the organization.

Other studies that consider the principal's manipulation of information flows include papers by Dequiedt and Martimort (2015) and Akbarpour and Li (2020). Dequiedt and Martimort study the incentives of an upstream manufacturer to manipulate the outcome of contracts, when facing privately informed retailers with correlated costs. Akbarpour and Li study the optimal mechanism for an auctioneer who can misrepresent the overall bids of the participants to the auction when the bidders cannot observe each other's bid. While these papers have in common with the current paper that the principal has the ability to manipulate aspects of the information flow within the mechanism, the specific type of manipulation differs according to institutional details of the underlying economic problem, leading to different economic effects. In particular, none of these papers consider the impact of the principal's manipulation incentives on organizational structures.

3 Model of Internal Organization

We model an organization with a principal who needs two agents, α and β, to implement a project. The project of size $q \geq 0$ yields the principal a value $v(q)$, and imposes a cost $\theta^k q$ on agent $k \in \{\alpha, \beta\}$. The value function $v(q)$ is an increasing and concave function that satisfies the Inada conditions: $v(0) = 0$, $v(\infty) = \infty$, $\lim_{q\to 0} v'(q) = \infty$ and $\lim_{q\to\infty} v'(q) = 0$.[3] The project size q is publicly verifiable.

Agent k's cost parameter $\theta^k \in \{\theta_g, \theta_b\}$ is his private information and $\Delta\theta \equiv \theta_b - \theta_g > 0$. We refer to θ^k as agent k's "type." An agent of type θ_g is "efficient," and an agent of type θ_b is "inefficient." The agents' types are drawn independently from identical distributions—an agent is efficient with probability $\varphi \in (0, 1)$, and therefore inefficient with probability $1 - \varphi$.

[3] This ensures an interior solution in our model.

The probability distribution is public knowledge.

Because the project needs both agents, the aggregate marginal cost of the project is $\Theta \equiv \theta^\alpha + \theta^\beta$, which can be one of the three possible values:

$$\Theta_G \equiv 2\theta_g, \quad \Theta_M \equiv \theta_g + \theta_b, \quad \Theta_B \equiv 2\theta_b.$$

Thus, the first-best size of the project, denoted by q^*, satisfies the condition of "marginal value = marginal cost," and is characterized by:

$$v'(q^*_\gamma) = \Theta_\gamma, \ \gamma \in \{G, M, B\}.$$

In order to compensate the agents for their costs, the principal pays each agent a transfer, denoted by t^k, $k \in \{\alpha, \beta\}$. Given transfers, the principal's and agent k's payoffs from the project of size q are respectively:

$$\pi \equiv v(q) - t^\alpha - t^\beta \quad \text{and} \quad u^k \equiv t^k - \theta^k q.$$

In light of the Fair Labor Standards Act that allows the players to walk away from a contract when insufficient compensation for the required effort is expected, we assume the following limited liability of the agents. Each agent can quit and walk away from the organization at any time, if he expects his payoff to be less than his reservation level (normalized to zero).[4] The limited liability of an agent reflects the condition required for employment contracts in practice, also known as "non-slavery condition."

We compare two organizational structures—centralization versus delegation. Under centralization, each agent directly reports his type only to the principal, who subsequently aggregates the information—agents cannot communicate directly with each other.[5] Under delegation, agent β makes a report to agent α, who in turn aggregates the information and reports it to the principal—agent β cannot communicate directly with the principal.

We postulate that the principal processes only the aggregate information, thus centering our analysis on contracts contingent on the aggregate type $\gamma \in \{G, M, B\}$, expressed as:[6]

$$\Phi \equiv \left(q_\gamma, t^\alpha_\gamma, t^\beta_\gamma\right), \ \gamma \in \{G, M, B\}.$$

[4]See Sappington (1983) for an analysis on this issue. We implicitly assume that if one agent quits, the project yields no value but the principal has to pay the non-quitting agent according to the contract. Alternatively, we can assume that if one agent quits the game ends and no payoff is realized for any player, but this assumption may lead to an additional equilibrium where both agents may reject the contracts.

[5]In Section 6, we discuss and motivate these implicit limitations on communication more extensively.

[6]See Laffont and Martimort (1997, 1998) and Jeon (2005) for a similar assumption on contracting.

As mentioned in the introduction, contracting upon aggregate information reflects various reports of practitioners as well as findings in organization studies that top managements tend to work with aggregate, condensed information rather than with the detailed, fine-grained information at the individual level.

Figure 1 illustrates the information flows in the two organizational structures.

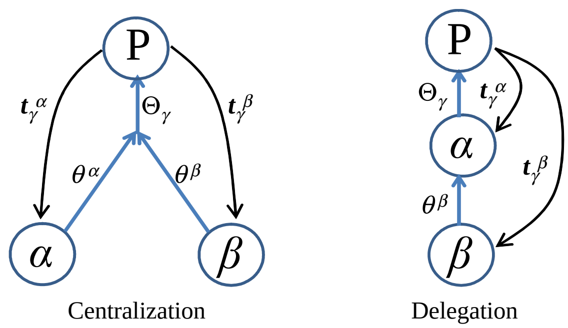

Fig 1. Organizational Structures

The timings under centralization and delegation are summarized below.

Centralization Under centralization, each agent reports his type directly only to the principal. Once the reports are made, the principal makes an announcement on $\gamma \in \{G, M, B\}$.

1. The principal offers the contract $\Phi \equiv \left(q_\gamma, t_\gamma^\alpha, t_\gamma^\beta\right)$, $\gamma \in \{G, M, B\}$.
2. Each agent makes a report on his type, $\theta^k \in \{\theta_g, \theta_b\}$, to the principal.
3. The principal receives aggregation of the reports and makes a public announcement on $\gamma \in \{G, M, B\}$.
4. The project is implemented and transfers are paid according to Φ.

Delegation Under delegation, agent β first reports his information to agent α, who then sends a report on $\gamma \in \{G, M, B\}$ to the principal.

1. The principal offers the contract $\Phi \equiv \left(q_\gamma, t_\gamma^\alpha, t_\gamma^\beta\right)$, $\gamma \in \{G, M, B\}$.
2. Agent β makes a report on his type θ^β to agent α, who in turn, makes a report on $\gamma \in \{G, M, B\}$ to the principal.

3. The principal makes a public announcement on $\gamma \in \{G, M, B\}$.

4. The project is implemented and transfers are paid according to Φ.

In the following two sections, we compare the principal's maximum payoffs under centralization and delegation. We start analyzing a setup in which the principal cannot manipulate the aggregate information. In this case, the principal always prefers centralization over delegation. However, if efficient agents are relatively likely, the optimal contract under centralization provides the principal with an incentive to manipulate aggregate information. Taking the principal's incentive to manipulate aggregate information seriously reveals that delegation dominates centralization when it is more likely that the agents are efficient, because in this case the principal's manipulation incentive is strongest.

4 When the Principal Cannot Manipulate Information

4.1 Centralization

Under centralization, the agents report directly and simultaneously to the principal and are in symmetric positions. As a consequence, an optimal contract exhibits the symmetric structure, $t_\gamma^\alpha = t_\gamma^\beta = t_\gamma$. Thus, under centralization, we can restrict attention to contracts of the form (q_γ, t_γ), $\gamma \in \{G, M, B\}$. This implies that the two agents receive the same level of transfer from the principal, even when they have reported different costs ($\gamma = M$).[7]

In line with the Inada conditions for the value function, the principal wants a strictly positive size of the project regardless of the agents' types. Since an agent can quit anytime, and in particular after the principal announces the project's aggregate type γ, the pair (q_γ, t_γ) must provide a non-negative rent to each agent for each $\gamma \in \{G, M, B\}$. For an efficient agent, the following participation constraints must be satisfied:

$$t_G - \theta_g q_G \geq 0 \text{ and} \tag{PC_G}$$

$$t_M - \theta_g q_M \geq 0, \tag{$\overline{PC}_M$}$$

while the constraints below must be satisfied for an inefficient agent's participation:

$$t_M - \theta_b q_M \geq 0 \text{ and} \tag{$\underline{PC}_M$}$$

[7] In our study, this condition arises as a result of the principal's ability to process only the aggregate information. As we mention in our conclusion, an alternative justification for making the same transfers to the agents would be an obligation to treat the agents anonymously (Laffont and Martimort, 1997, 1998).

$$t_B - \theta_b q_B \geq 0. \tag{PC_B}$$

The left hand side of the participation constraints above are an agent's ex post payoffs when he truthfully reports to the principal.

To induce each agent's truthful report, the following Bayesian incentive compatibility conditions must be satisfied for an efficient and an inefficient agent respectively:

$$\begin{aligned} & \varphi\left[t_G - \theta_g q_G\right] + (1-\varphi)\left[t_M - \theta_g q_M\right] \\ \geq\ & \varphi\left[\max\{t_M - \theta_g q_M, 0\}\right] + (1-\varphi)\left[\max\{t_B - \theta_g q_B, 0\}\right], \end{aligned}$$

$$\begin{aligned} & \varphi\left[t_M - \theta_b q_M\right] + (1-\varphi)\left[t_B - \theta_b q_B\right] \\ \geq\ & \varphi\left[\max\{t_G - \theta_b q_G, 0\}\right] + (1-\varphi)\left[\max\{t_M - \theta_b q_M, 0\}\right]. \end{aligned}$$

When reporting to the principal, each agent does not know the other agent's type under centralization. Therefore, an agent's incentive compatibility constraints are conditional only on his own private information. The left hand sides (LHS) of the constraints express the agent's expected payoff from reporting truthfully, whereas the right hand sides (RHS) represent his expected payoff if he decides to misreport his type. Notice from the constraints that, while the payoff from truthful reporting is always non-negative (implied by the participation constraints), an agent can have a negative payoff by misreporting his type. That is, a misreporting agent may choose to quit depending on the other agent's type—this is captured by the $\max\{\cdot\}$ operators in the RHSs of the constraints. Also, it is implied by the participation constraints ($\overline{PC}_M$) and (PC_B) that an efficient agent will not quit in the case of misrepresenting himself as inefficient, regardless of the other agent's type. Likewise, ($\underline{PC}_M$) implies that a misreporting inefficient agent will remain in the organization if the principal announces that $\gamma = M$. The incentive compatibility constraints, therefore, can be simplified as:

$$\varphi\left[t_G - \theta_g q_G\right] + (1-\varphi)\left[t_M - \theta_g q_M\right] \geq \varphi\left[t_M - \theta_g q_M\right] + (1-\varphi)\left[t_B - \theta_g q_B\right], \tag{IC_g}$$

$$\varphi\left[t_M - \theta_b q_M\right] + (1-\varphi)\left[t_B - \theta_b q_B\right] \geq \varphi\left[\max\{t_G - \theta_b q_G, 0\}\right] + (1-\varphi)\left[t_M - \theta_b q_M\right]. \tag{IC_b}$$

Under centralization, the principal chooses $\Phi = \{q_\gamma,\, t_\gamma\}$, $\gamma \in \{G, M, B\}$, to solve the following problem:

$$\mathcal{P}^c\colon \max_{\Phi}\ \pi(\Phi) = \varphi^2\left[v(q_G) - 2t_G\right] + 2\varphi(1-\varphi)\left[v(q_M) - 2t_M\right] + (1-\varphi)^2\left[v(q_B) - 2t_B\right],$$

subject to the agents' participation and incentive compatibility constraints above.

In the following proposition, we present the optimal outcome in $\mathcal{P}^c$, where the principal cannot manipulate the aggregate information.

Proposition 1 *Suppose the principal cannot manipulate the aggregate information. Under centralization, there exists* $\widetilde{\varphi}^{+} \in (0, 1/2)$ *and* $\widetilde{\varphi}^{-} \in (0, \widetilde{\varphi}^{+}]$ *such that the optimal contract,* Φ^{c}*, entails the following outcome.*[8]

- *For* $\varphi > \widetilde{\varphi}^{+}$,

$$v'(q_G^c) = \Theta_G, \quad v'(q_M^c) = \Theta_M + \frac{\varphi}{1-\varphi}\Delta\theta, \quad v'(q_B^c) = \Theta_B + \frac{2\varphi}{1-\varphi}\Delta\theta.$$

  An efficient agent gets strictly positive rent, and an inefficient agent gets no rent.

- *For* $\varphi \leq \widetilde{\varphi}^{-}$,

$$v'(q_G^c) = \Theta_G, \quad 2\varphi v'(q_M^c) + (1-2\varphi)v'(q_B^c) = \Theta_B, \text{ where } q_B^c = \frac{1-2\varphi}{1-\varphi} q_M^c.$$

  An efficient agent gets strictly positive rent only when $\gamma = M$*, and an inefficient agent gets no rent.*

As in the standard screening problems, with an exception of "no distortion at the top," the optimal project sizes are distorted downward. An efficient agent has an incentive to exaggerate his cost of implementation to reap information rent, and in order to reduce information rent while inducing truthful reports from the agents, the principal distorts the project sizes in the optimal contract except when both agents are efficient.

When φ is large enough ($\varphi > \widetilde{\varphi}^{+}$), an efficient agent receives strictly positive information rent regardless of the other agent's type. When φ is small ($\varphi \leq \widetilde{\varphi}^{-}$), however, an efficient agent receives rent only when he is paired with an inefficient agent. Since the agents of different types receive the same amount of transfer when $\gamma = M$, the efficient agent's rent in that case is guaranteed regardless of φ. Because of this, the principal's rent provision when $\gamma = G$ is relatively smaller, and she decreases the amount of this rent as it becomes less likely that an agent is efficient. As a result, for φ small enough, although an efficient agent's expected rent is strictly positive, he gets no rent when the other agent is also efficient.

4.2 Delegation

Under delegation, agent β reports his type, $\theta^{\beta} \in \{\theta_g, \theta_b\}$, to agent α who, in turn, reports the aggregate type, $\gamma \in \{G, M, B\}$, to the principal. Each agent's participation constraints are:

$$t_G^k - \theta_g q_G \geq 0 \text{ and} \tag{PC_G^k}$$

[8] Whether $\widetilde{\varphi}^{+} = \widetilde{\varphi}^{-}$ depends on the shape of the value function $v(\cdot)$. For a large set of well-behaved functions (e.g., $v(q) = \sqrt{q}$), we have $\widetilde{\varphi}^{+} = \widetilde{\varphi}^{-}$.

$$t_M^k - \theta_g q_M \geq 0,\ k \in \{\alpha, \beta\}, \tag{$\overline{PC}_M^k$}$$

for an efficient agent, and

$$t_M^k - \theta_b q_M \geq 0 \text{ and} \tag{$\underline{PC}_M^k$}$$

$$t_B^k - \theta_b q_B \geq 0,\ k \in \{\alpha, \beta\}, \tag{PC_B^k}$$

for an inefficient agent. Notice that, unlike under centralization, the transfers to the agents cannot be treated symmetrically.

Since agent β does not know agent α's type when reporting his own type, his incentive constraints coincide with the incentive constraints under centralization:

$$\varphi\left[t_G^\beta - \theta_g q_G\right] + (1-\varphi)\left[t_M^\beta - \theta_g q_M\right] \geq \varphi\left[t_M^\beta - \theta_g q_M\right] + (1-\varphi)\left[t_B^\beta - \theta_g q_B\right], \tag{IC_g^β}$$

$$\varphi\left[t_M^\beta - \theta_b q_M\right] + (1-\varphi)\left[t_B^\beta - \theta_b q_B\right] \geq \varphi\left[\max\{t_G^\beta - \theta_b q_G, 0\}\right] + (1-\varphi)\left[t_M^\beta - \theta_b q_M\right]. \tag{IC_b^β}$$

The key difference from centralization is that, under delegation, agent α has more information when reporting to the principal, leading to stricter incentive constraints. More specifically, the Bayesian incentive conditions of agent β above imply that agent α, when he makes a report to the principal, has learned agent β's type. Inducing agent α's truthful report, therefore, requires that the following incentive compatibility conditions be satisfied in the optimal contract:

$$t_G^\alpha - \theta_g q_G \geq t_\gamma^\alpha - \theta_g q_\gamma,\ \gamma \in \{M, B\}, \tag{$IC_{G-\gamma}^\alpha$}$$

$$t_M^\alpha - \theta_g q_M \geq t_\gamma^\alpha - \theta_g q_\gamma,\ \gamma \in \{G, B\}, \tag{$\overline{IC}_{M-\gamma}^\alpha$}$$

$$t_M^\alpha - \theta_b q_M \geq t_\gamma^\alpha - \theta_b q_\gamma,\ \gamma \in \{G, B\}, \tag{$\underline{IC}_{M-\gamma}^\alpha$}$$

$$t_B^\alpha - \theta_b q_B \geq t_\gamma^\alpha - \theta_b q_\gamma,\ \gamma \in \{G, M\}. \tag{$IC_{B-\gamma}^\alpha$}$$

Notice that the incentive constraints for agent α are more restrictive for the principal than the ones for agent β. These stricter incentive constraints reflect that, under delegation, agent α has more flexibility to manipulate information. Because agent α knows agent β's type when making his report to the principal, the incentive constraints for agent α, unlike the constraints for agent β, have to hold state-by-state rather than only in expected terms.

Under delegation, the principal, chooses $\Phi = \{q_\gamma, t_\gamma^\alpha, t_\gamma^\beta\}$ to solve the following problem:

$$\mathcal{P}^d\colon \max_\Phi\ \pi(\Phi) = \varphi^2\left[v(q_G) - \sum_k t_G^k\right] + 2\varphi(1-\varphi)\left[v(q_M) - \sum_k t_M^k\right] + (1-\varphi)^2\left[v(q_B) - \sum_k t_B^k\right],$$

subject to the agents' participation and incentive compatibility constraints above.

The following proposition presents the optimal outcome in $\mathcal{P}^d$.

Proposition 2 *Suppose the principal cannot manipulate the aggregate information. Under delegation, there exists $\widehat{\varphi}^+ \in (0, 1/2)$ and $\widehat{\varphi}^- \in (0, \widehat{\varphi}^+]$ such that the optimal contract, Φ^d, entails the following outcome.*[9]

- *For $\varphi > \widehat{\varphi}^+$,*

$$v'(q_G^d) = \Theta_G, \quad v'(q_M^d) = \Theta_B + \frac{3\varphi - 1}{1-\varphi}\Delta\theta, \quad v'(q_B^d) = \Theta_B + \frac{\varphi}{1-\varphi}\Delta\theta.$$

  An efficient agent gets strictly positive rent, and an inefficient agent gets no rent.

- *For $\varphi \leq \widehat{\varphi}^-$,*

$$v'(q_G^d) = \Theta_G, \quad 2\varphi v'(q_M^d) + (1-2\varphi)v'(q_B^d) = \Theta_B + \frac{\Delta\theta\varphi^2}{1-\varphi}, \quad q_B^d = \frac{1-2\varphi}{1-\varphi}q_M^d.$$

  Agent α, when he is efficient, gets strictly positive rent regardless of agent β's type. Agent β, when he is efficient, gets strictly positive rent only for $\gamma = M$. An inefficient agent gets no rent.

While the reasoning behind the distorted project sizes is similar to the one under centralization, agent α's information rent is larger under delegation due to his stricter incentive constraints. By delegating the aggregation of information, the principal is relinquishing part of her control to agent α. Since agent α ends up possessing more information and makes a report to the principal on behalf of both agents, he has more flexibility to manipulate information, which is the source of larger information rent under delegation. Recall that, for example, when φ is small, an efficient agent under centralization receives rent only when the other agent is inefficient. The same is true for agent β under delegation since he does not know agent α's type when making his report. In contrast, the principal cannot distribute agent α's information rent between different states, because under delegation agent α knows agent β's type when he reports to the principal.

4.3 Comparison

A direct comparison of the two propositions shows that different contracts are optimal under different organizational structures. When the principal cannot manipulate the aggregate information, it is relatively straightforward to see that the principal does better under centralization. The intuition is, as mentioned above, that delegation transfers the principal's

[9] Again, for a large set of well-behaved functions, such as $v(q) = \sqrt{q}$, we have $\widehat{\varphi}^+ = \widehat{\varphi}^-$.

control over agent β to agent α, without bringing her any benefits. A somewhat more technical perspective provides a deeper insight concerning the optimality of centralization, leading to a formal proof. Under delegation, incentive compatibility requires a truthful report from agent α regardless of the other agent's reporting strategy, whereas it asks for a truthful report from him under centralization only under the assumption that the other agent is also truthful. Hence, delegation leads to dominant strategy incentive compatibility constraints for agent α's truth-telling, while centralization demands Bayesian incentive compatibility constraints. Because Bayesian incentive compatibility constraints are weaker than incentive constraints in dominant strategies, the principal's problem is less restricted under centralization. As a result, the allocation which the optimal contract under delegation, Φ^d, implements is also feasible under centralization, whereas the allocation which optimal contract under centralization, Φ^c, implements is not feasible under delegation. This observation leads directly to the following corollary.

Corollary 1 *Suppose the principal cannot manipulate the aggregate information. Then, centralization dominates delegation.*

5 When the Principal Can Manipulate Information

In the previous section, we derived the optimal contracts under the assumption that, after receiving the agents' reports, the principal truthfully announces the aggregate information from the agents. As we now argue, this assumption is not innocuous since the optimal contract under centralization, Φ^c, provides the principal with an incentive to manipulate the aggregate information. In particular, the principal, after learning that both agents are inefficient, may benefit from misreporting aggregate costs as Θ_M rather than Θ_B. Lack of direct information flows between the agents prevents them from cross-checking their reports, and the principal can achieve such manipulation without being caught out by the agents—making each inefficient agent think that the other agent is efficient. In order to clarify this threat of aggregate information manipulation in centralized organizations, we start this section with revisiting the organization under centralization.

5.1 Centralization

The threat of aggregate information manipulation by the principal can be easily seen in the case where both types are equally likely ($\varphi = 1/2$). In this case, Proposition 1 shows that the optimal contract under centralization, Φ^c, provides zero rent to an inefficient agent, i.e., $t_B^c = \theta_b q_B^c$ and $t_M^c = \theta_b q_M^c$. Hence, the principal's *ex post* payoffs from a project size q_B and q_M are, respectively:

$$v(q_B^c) - \Theta_B q_B^c \quad \text{and} \quad v(q_M^c) - \Theta_B q_M^c.$$

Notice that, in Proposition 1, when both types are equally likely ($\varphi = 1/2$), q_M^c coincides with q_B^*, while q_B^c is strictly smaller than q_B^*. Since q_B^* is the unique maximizer of $v(q) - \Theta_B q$, it is implied that:

$$v(q_B^c) - \Theta_B q_B^c < v(q_B^*) - \Theta_B q_B^* = v(q_M^c) - \Theta_B q_M^c.$$

Thus, under the optimal contract Φ^c, the principal is strictly better off when *reported* aggregate types are Θ_M instead of Θ_B for $\varphi = 1/2$. We state this insight as the following lemma.

Lemma 1 *Suppose the principal can manipulate the aggregate information and $\varphi = 1/2$. Under centralization, the optimal contract, Φ^c, provides the principal with an incentive to misreport the aggregate type as $\gamma = M$ when the true type is $\gamma = B$.*

When both agents are inefficient ($\gamma = B$), the principal's announcement of $\gamma = M$ cannot be detected by the agents as a misrepresentation—since it could very well be that the other agent is efficient, without directly cross checking their reports to the principal, each agent cannot tell whether or not the principal's announcement is true.[10] Intuitively, the principal has an incentive to exaggerate the overall efficiency of the organization, because the agents then have to complete the bigger project q_M^c rather than the smaller project q_B^c.

It is worthwhile to remark that the inefficient agents are indifferent to the principal's manipulation of the aggregate type, because they receive a transfer equal to their cost from implementing the project for both $\gamma = B$ and $\gamma = M$. However, the agent's anticipation that the information will be manipulated makes an efficient agent's truth-telling harder to secure—by reporting a high cost, an efficient agent can now guarantee taking part in the implementation of project q_M^c and receiving the associated rent. To rule out an efficient agent's misreporting of the cost, the principal should persuade the agents that she will not manipulate.

[10] In Section 6, we show that if the principal can choose a communication technology before contracting with the agents, she would like to choose a technology that limits communication between the agents to eliminate the possibility of collusion between the agents.

For the principal's truthful behavior, the following incentive constraint must be satisfied in the optimal contract, in addition to the participation and incentive constraints for the agents:[11]

$$v(q_B) - 2t_B \geq v(q_M) - 2t_M. \tag{PIC}$$

When the principal can manipulate the aggregate information, her problem under centralization is:

$$\widetilde{\mathcal{P}}^c\colon \max_{\Phi} \ \pi(\Phi) = \varphi^2 \left[v(q_G) - 2t_G\right] + 2\varphi(1-\varphi) \left[v(q_M) - 2t_M\right] + (1-\varphi)^2 \left[v(q_B) - 2t_B\right],$$

subject to (PIC) and the constraints in $\mathcal{P}^c$.

The next lemma makes precise when the principal's incentive constraint (PIC) matters.

Lemma 2 *Suppose the principal can manipulate the aggregate information. Under centralization, there exist $\varphi^- \in (0, 1/2)$ and $\varphi^+ \in [\varphi^-, 1/2)$ such that:*

- *For $\varphi < \varphi^-$, the principal's manipulation incentive is not an issue, i.e., (PIC) is non-binding.*
- *For $\varphi > \varphi^+$, the principal's manipulation incentive is an issue, i.e., (PIC) is binding.*

The intuition behind Lemma 2 is that the distortion in the project size depends on the likelihood that the agents are efficient. Indeed, when such likelihood is small, the principal expects to provide information rent only with a small probability—for small φ, distortions in the optimal project sizes are also small. More specifically, for φ small enough, $(\varphi < \varphi^-)$, unlike in the case of $\varphi = 1/2$, the project size q_B^c is "closer" to the first best level q_B^* than q_M^c. As a result, the principal has no incentive to manipulate the aggregate information when both agents report that they are inefficient.

By contrast, when the likelihood that the agents are efficient is high, the probability that the principal has to provide information rent is also high. As a result, distortions in the optimal contract to reduce information rent becomes large. For φ large enough $(\varphi > \varphi^+)$, as in the case of $\varphi = 1/2$, the project size q_B^c is further away from the first best level q_B^* than

[11] Notice that the principal cannot misannounce $\gamma = B$ as $\gamma = G$ since the agents will detect the principal's misrepresentation in that case. Likewise, when true $\gamma = M$, the principal cannot misrepresent the aggregate type as $\gamma = B$ or $\gamma = G$—if $\gamma = B$ is announced, then the type-g agent will know the principal's misannouncement, and if $\gamma = G$ is announced, then the type-b agent will know. When $\gamma = G$, the principal can misannounce the aggregate type as $\gamma = M$, but she has no incentive to do so.

q_M^c. When both agents report that they are inefficient, the principal prefers to implement project size q_M^c rather than q_B^c in such cases, which leads to her incentive to misrepresent the aggregate information as $\gamma = M$.

A straightforward way to dispel the principal's manipulation incentive is to set the same project sizes for q_M and q_B. By doing so, she makes herself indifferent to her announcement on the aggregate information (between $\gamma = B$ and $\gamma = M$ when true $\gamma = B$), and her incentive constraint (PIC) is trivially satisfied. The following proposition shows that, when agents are more likely to be efficient, such pooling of project sizes is indeed an optimal response to the principal's manipulation incentive.

Proposition 3 *Suppose the principal can manipulate the aggregate information and $\varphi \geq 1/2$. Under centralization, the optimal outcome, $\Phi^{\widetilde{c}}$, entails:*

$$v'(\widetilde{q}_G^c) = \Theta_G, \quad v'(\widetilde{q}_M^c) = v'(\widetilde{q}_B^c) = \Theta_B + \frac{2\varphi^2}{1-\varphi^2}\Delta\theta.$$

An efficient agent gets strictly positive rent, and an inefficient agent gets no rent.

As shown above, under centralization, the principal's incentive to manipulate the aggregate information arises when it is likely enough that an agent is efficient, and in such a case, the optimal contract must discourage the principal from misrepresentation. In coping with her own manipulation incentive, the principal may pool the project sizes q_B and q_M in the optimal contract. Proposition 3 shows that such pooling is optimal when it is more likely that the agents are efficient. The optimality of pooling is due to the fact that a separating contract requires the principal to concede larger information rent to secure truthful revelation from an efficient agent. That is, when the agents are more likely to be efficient, the principal's own manipulation incentive makes it harder to fine-tune the optimal project sizes according to the available information in the organization.

5.2 Delegation and Comparison

Under delegation, the principal receives the aggregate information directly from agent α. Any manipulation of the information by the principal is therefore directly detectable by agent α, which prevents the principal from misrepresenting the aggregate information. Thus, the same optimal outcome as in $\mathcal{P}^d$ is achieved. Recall from the previous section that, in the absence of the principal's manipulation incentive, delegation is always dominated by centralization—under delegation, the principal simply needs to provide more information rent to agent α, who is granted the authority to aggregate information. In the presence of the principal's manipulation incentive, however, a trade-off between these structures arises.

Proposition 4 *Suppose the principal can manipulate the aggregate information. Then, there exists $\varphi^c > \varphi^-$ and $\varphi^d > \varphi^+$ such that:*

- *For $\varphi < \varphi^c$, centralization dominates delegation.*
- *For $\varphi \geq \varphi^d$, delegation dominates centralization.*

As shown in Lemma 2, the principal's manipulation incentive arises only when the likelihood that the agents are efficient, φ, is large enough. Therefore, for φ small, centralization remains the prevailing structure. As φ becomes larger, the principal's manipulation incentive arises, and a trade-off between the two structures starts to emerge. Under delegation, although the principal must provide more information rent due to a loss of control, the optimality of separating types demonstrates that delegation allows the principal to use the available information within the organization more effectively than centralization.

6 Unlimited Communication and Collusion

In modeling centralization, we postulated that the agents cannot directly communicate with each other. This limitation on direct communication between agents is crucial for our result, because the type of information manipulation that we consider is avoidable when the agents can directly communicate with each other—the agents could then, by simply cross-checking their reports, detect the principal's manipulation of the aggregate information.

Even though these limits on communication seem natural in large organizations, where it is infeasible for an agent to cross-check the reports of all other agents, we provide in this section an endogenous argument for organizations to restrict such unlimited communication. The gist of this argument is that allowing direct communication between agents may invite collusion, and dealing with such collusion is more costly to the principal than dealing with her own manipulation incentive. Indeed, organization studies point out that communication facilitates collusion, stressing that group behaviors are frequently observed in organizations where communication among their members are less restricted.[12] Organization theory also points out the connection of unwanted communication and collusion among agents.[13]

[12] See Mintzberg (1979) for example.

[13] See Laffont and Rochet (1997) among others. Laffont and Martimort (1998) show that delegation can prevent collusion among the agents.

To see the potential of collusion under centralization, recall from Proposition 1 that, without information manipulation, the optimal contract under centralization, Φ^c, yields an efficient agent a strictly larger payoff when the other agent is inefficient than when the other agent is efficient:

$$2t^c_M - \Theta_G q^c_M > 2t^c_G - \Theta_G q^c_G. \tag{$\widetilde{CIC}$}$$

This inequality implies that, when both are efficient, the agents can increase their payoff if they coordinate their reports such that one of them reports to be efficient, while the other misreports his type as inefficient. An implementation of this collusive agreement requires communication between agents for some coordination to learn each other's types—given Φ^c, an efficient agent has no incentive to misreport his type as inefficient to the principal unless he knows that the other agent will report his type as efficient.

To analyze collusion under asymmetric information, we follow Laffont and Martimort (1997) and introduce a third party side-contractor who, given the principal's "grand contract", coordinates collusion between asymmetrically informed agents. The side-contractor's objective is to maximize the expected joint payoff of the agents. Given the principal's contract under centralization, $\Phi = \{q_\gamma,\, t_\gamma\}$, $\gamma \in \{G, M, B\}$, the side-contractor's offer to the agents specifies a collusive reporting function to the principal,

$$\widehat{\gamma} : \{g, b\} \times \{g, b\} \longrightarrow \{G, M, B\},$$

with the interpretation that if agent α reports type $\theta^\alpha \in \{g, b\}$ to the side-contractor and agent β reports type $\theta^\beta \in \{g, b\}$, then the side-contractor reports $\hat{\gamma}(\theta^\alpha, \theta^\beta)$ to the principal. Laffont and Martimort (1997) allows the side contract to specify side transfers, but, in our framework, the threat of collusion has bite without side transfers. Hence, our concept of collusion is weaker than the concept in Laffont and Martimort (1997).[14]

As formally shown in the next proposition, a necessary condition for the principal's contract to be collusion proof is:

$$t_G - \theta_g q_G \geq t_M - \theta_g q_M. \tag{CIC}$$

As a result, an upper bound on the principal's expected payoff is the solution of the following problem:

$$\mathcal{P}^u\colon\ \max_{\Phi}\ \pi(\Phi) = \varphi^2 \left[v(q_G) - 2t_G\right] + 2\varphi(1-\varphi)\left[v(q_M) - 2t_M\right] + (1-\varphi)^2\left[v(q_B) - 2t_B\right],$$

[14] The weaker collusion concept implies weaker collusion-proofness conditions for the principal's optimization problem. Hence, showing that collusion is already problematic in this weaker form emphasizes the problem of collusion. Indeed, in our proof we consider an even weaker form of collusion because we impose the additional restriction that the side-contractor treats the agents equally.

subject to (CIC) and the constraints in $\mathcal{P}^c$. Comparing the optimal outcome in $\mathcal{P}^u$ to those in the previous sections leads to the following result.

Proposition 5 *Suppose the organization's communication technology is the principal's choice and unlimited communication between the agents enables the agents to collude. Then it is suboptimal to allow unlimited communication between them.*

As mentioned above, although unlimited communication between the agents removes the principal's manipulation incentive under centralization, it provides the agents with more flexibility to manipulate their private information through collusion. Our result here shows that although limiting communication among subunits in an organization causes top management's manipulation incentive under centralization, it is less costly to the organization since unlimited communication among subunits opens the door to collusive behavior that lowers the organization's optimal outcome.

7 Conclusion

In this paper, we have analyzed the optimal organizational structure when information can be manipulated, not only by the agents who possess private information, but also by the principal who aggregates the information. Under centralization, a tension between the principal's and the agents' incentives arises, which may lead to pooling in the optimal contract—an organization prone to the top management's aggregate information manipulation cannot use all the available information of its subunits effectively. Under delegation, although the principal must provide more rent to the agent to whom processing the aggregate information is delegated, a separating outcome is restored in the optimal contract—under delegation, an organization can use the information of its subunits more effectively. This trade-off determines the optimal structure of the organization. Its outcome depends on the extent to which the agents' private information leads to distortions, and therefore the likelihood that agents are efficient—centralization is optimal when such likelihood is low, whereas delegation is optimal when it is high. We have also shown that, if the principal has an option, she will choose to impose limits on communication among the agents when communication leads to collusion.

We considered an organization that can base its decisions only on aggregate information due to limits on communication. This assumption in our paper can be interpreted differently. For example, our results also hold if the top management is under an obligation to treat the agents *anonymously* due to "fairness" restriction imposed on the organization as in Laffont and Martimort (1997, 1998). In light of the anecdotal evidence from business practitioners, we believe that our assumption that top management can process only aggregate information reflects a common limitation of organizations.[15] Focusing on this natural limitation organizations face, we identified a drawback—the principal's manipulation incentive—which also arises when organizations are to respect the anonymity of their workers.

Appendix

Proof of Proposition 1

Instead of solving $\mathcal{P}^c$, we first solve the following relaxed problem:

$$\max_{\Phi} \ \pi(\Phi) \text{ s.t. } (IC_g), (\underline{PC}_M), (PC_B).$$

First note that since $\pi(\Phi)$ is strictly decreasing in t_G, the constraint (IC_g) binds for any solution of this relaxed problem—since otherwise one could raise the objective by lowering t_G without affecting (IC_g) and $(\underline{PC}_M)$. Second, note that since $\pi(\Phi)$ is strictly decreasing in t_B, also (PC_B) binds for any solution—since otherwise one could raise the objective by lowering t_B, as this change relaxes (IC_g) and does not affect $(\underline{PC}_M)$. Finally, also $(\underline{PC}_M)$ binds for any solution, since otherwise one could lower t_M by $\delta > 0$ and raise t_G by $(1-2\varphi)/\varphi\delta$. This change does not affect (IC_g) and (PC_B), but raises the objective by $2\varphi\delta$.

A binding $(\underline{PC}_M)$, (PC_B^b) and (IC_g) give the following expressions for the transfers:

$$t_G = \theta_g q_G + \frac{2\varphi - 1}{\varphi}\Delta\theta q_M + \frac{1-\varphi}{\varphi}\Delta\theta q_B, \quad t_M = \theta_b q_M, \quad t_B = \theta_b q_B. \tag{A1}$$

Substituting these transfers in the objective $\pi(\Phi)$ and optimizing with respect to the project sizes gives:

$$v'(q_G^c) = \Theta_G, \quad v'(q_M^c) = \Theta_M + \frac{\varphi}{1-\varphi}\Delta\theta, \quad v'(q_B^c) = \Theta_B + \frac{2\varphi}{1-\varphi}\Delta\theta, \tag{A2}$$

[15] Simon (1962, 2000) notes that the top management's processing of the aggregate information, instead of the detailed raw data, is a consequence of *near decomposability* of the organization into different subunits. Each level of the organizational hierarchy observes the aggregate parameters that summarize the information transmitted by the subunits at a lower level, which allows the top management to avoid facing the full complexity of the organization when making a decision.

implying that $q^c_G > q^c_M > q^c_B$.

We next check whether this solution to the relaxed problem also satisfies the neglected constraints, $(\overline{PC}_M)$, (IC_b), and (PC_G). Notice first that $(\underline{PC}_M)$ implies $(\overline{PC}_M)$. Also, by $(A1)$ the constraint (IC_b) simplifies to:

$$0 \geq \varphi \max\{0,\ t^c_G - \theta_b q^c_G\},$$

which holds because, by $(A1)$ and $q^c_G > q^c_M > q^c_B$, it follows that:

$$t^c_G - \theta_b q^c_G = [(2\varphi - 1)(q^c_M - q^c_G) + (1 - \varphi)(q^c_B - q^c_G)]\, \Delta\theta/\varphi < 0.$$

Finally, to check (PC_G), let $f^c(\varphi) \equiv (2\varphi - 1)q^c_M + (1 - \varphi)q^c_B$, so that the relaxed solution satisfies (PC_G) if and only if $f^c(\varphi) \geq 0$. Because for any $\varphi \in [1/2, 1)$, it holds $f^c(\varphi) > 0$ and since $f^c(0) = q^*_B - q^*_M < 0$, continuity implies that there exists at least one $\widetilde{\varphi} \in (0, 1/2)$ such that $f^c(\widetilde{\varphi}) = 0$. Let $\tilde{\varphi}^+ \in (0, 1/2)$ be the largest (supremum) $\widetilde{\varphi}$ such that $f^c(\widetilde{\varphi}) = 0$, and let $\widetilde{\varphi}^- \in (0, 1/2)$ be the smallest (infimum) $\widetilde{\varphi}$ such that $f^c(\widetilde{\varphi}) = 0$.

Hence, (A1) and (A2) characterize the principal's optimal contract for any $\varphi \geq \widetilde{\varphi}^+$.

Since, for the case $\varphi < \widetilde{\varphi}^-$, the above characterization violates (PC_G), we next consider the (less) relaxed problem

$$\max_{\Phi}\ \pi(\Phi) \text{ s.t. } (IC_g), (\underline{PC}_M), (PC_B), (PC_G),$$

where we know that, given $\varphi < \widetilde{\varphi}^-$, the constraint (PC_G) binds for any solution. Repeating the arguments of the beginning of this proof shows that, again, (PC_B) and $(\underline{PC}_M)$ bind at any solution of this (less) relaxed problem. Given that $(\underline{PC}_M)$, (PC_B), and (PC_G) bind, also (IC_g) binds, since maximizing the relaxed problem when disregarding (IC_g) yields the candidate solution $q_G = q^*_G$; $q_M = q^*_B$, $q_B = q^*_B$, which violates (IC_g). Hence, for any solution (A1) holds. Together with (PC_G) binding, this implies that $(1-\varphi)q_B = (1-2\varphi)q_M$. It follows that, with constraints (IC_g), $(\underline{PC}_M)$, (PC_B), and (PC_G) all binding, we can rewrite the principal's problem as:

$$\max_{q_\gamma}\ \varphi^2 \left[v(q_G) - \Theta_G q_G\right] + 2\varphi(1 - \varphi)\left[v(q_M) - \Theta_B q_M\right] + (1 - \varphi)^2 \left[v(q_B(q_M)) - \Theta_B q_B(q_M)\right],$$

where

$$q_B(q_M) = \frac{1 - 2\varphi}{1 - \varphi} q_M.$$

Substituting out $q_B(q_M)$ in the objective function and optimizing with respect to the project sizes yields:

$$v'(q^c_G) = \Theta_G, \quad 2\varphi v'(q^c_M) + (1 - 2\varphi)v'(q^c_B) = \Theta_B,\ \text{where } q^c_B = \frac{1 - 2\varphi}{1 - \varphi} q^c_M.$$

To check (IC_b), note that it is satisfied if $t_G^c - \theta_b q_G^c \leq 0$. Using (A1) and the relationship $(1-\varphi)q_B^c = (1-2\varphi)q_M^c$, we have:

$$t_G^c - \theta_b q_G^c = -\Delta\theta q_G^c < 0.$$

Thus, as specified in the proposition, for both $\varphi < \widetilde{\varphi}^-$ and $\varphi \geq \widetilde{\varphi}^+$ we have characterized the optimal contract. The agents' rents follow from the binding constraints. ■

Proof of Proposition 2

Similar to the proof of Proposition 1, we make a conjecture about the relevant constraints and optimize the objective function under this subset of constraints. We then verify whether the solution satisfies the other constraints. In particular, we conjecture that incentive constraints, (IC_g^β) and (IC_{G-M}^α), and the participation constraints, $(\underline{PC}_M^\alpha)$, (PC_B^α), $(\underline{PC}_M^\beta)$ and (PC_B^β) are binding. This yields the following expressions for transfers:

$$\begin{array}{ll} t_G^\alpha = \theta_g q_G + \Delta\theta q_M, & t_G^\beta = \theta_g q_G + \frac{2\varphi-1}{\varphi}\Delta\theta q_M + \frac{1-\varphi}{\varphi}\Delta\theta q_B, \\ t_M^\alpha = \theta_b q_M, & t_M^\beta = \theta_b q_M, \\ t_B^\alpha = \theta_b q_B, & t_B^\beta = \theta_b q_B. \end{array} \tag{A3}$$

After substituting these transfers in the objective function, an unconstrained optimization over the remaining variables yields:

$$v'(q_G^d) = \Theta_G, \quad v'(q_M^d) = \Theta_B + \frac{3\varphi - 1}{2(1-\varphi)}\Delta\theta, \quad v'(q_B^d) = \Theta_B + \frac{\varphi}{1-\varphi}\Delta\theta, \tag{A4}$$

implying that $q_G^d > q_M^d > q_B^d$. Since $\theta_g < \theta_b$, (A3) implies that (PC_G^α), $(\overline{PC}_M^\alpha)$ and $(\overline{PC}_M^\beta)$ are satisfied. Also, (A3) together with $q_G^d > q_M^d > q_B^d$ implies that (IC_{G-B}^α), $(\underline{IC}_{M-\gamma}^\alpha)$, $(\overline{IC}_{M-\gamma}^\alpha)$, $(IC_{B-\gamma}^\alpha)$ and (IC_b^β) are satisfied. Hence, it remains to check whether the solution also satisfies (PC_G^β). Using (A3), it holds $t_G^\beta - \theta_g q_G \geq 0$ if and only if $(2\varphi-1)q_M^d + (1-\varphi)q_B^d \geq 0$. Hence, let $f^d(\varphi) \equiv (2\varphi-1)q_M^d + (1-\varphi)q_B^d$, so that this solution satisfies (PC_G^β) only if $f^d(\varphi) \geq 0$. Because for any $\varphi \in [1/2, 1)$, it holds $f^d(\varphi) > 0$ and since $f^d(0) = q_B^d - q_M^d < 0$, continuity implies that there exists at least one $\widehat{\varphi} \in (0, 1/2)$ such that $f^c(\widehat{\varphi}) = 0$. Let $\widehat{\varphi}^+ \in (0, 1/2)$ be the largest (supremum) $\widehat{\varphi}$ such that $f^c(\widehat{\varphi}) = 0$, and let $\widehat{\varphi}^- \in (0, 1/2)$ be the smallest (infimum) $\widehat{\varphi}$ such that $f^c(\widehat{\varphi}) = 0$.

Then, it follows that, for $\varphi \geq \widehat{\varphi}^+$, (A3) together with (A4) fully characterizes the optimal contract as presented in Proposition 2.

For $\varphi < \widehat{\varphi}^-$, the solution characterized above violates (PC_G^β), implying that this participation constraint also binds at the optimum. Under (A3) the constraint (PC_G^β) simplifies to:

$$(1-\varphi)q_B = (1-2\varphi)q_M. \tag{A5}$$

With (IC_g^β), (IC_{G-M}^α), $(\underline{PC}_M^\alpha)$, (PC_B^α), $(\underline{PC}_M^\beta)$, (PC_B^β) and (PC_G^β) binding, the principal's problem rewrites as:

$$\max_{q_M,q_G} \varphi^2 \left[v(q_G) - \Theta_G q_G - \Delta\theta q_M\right] + 2\varphi(1-\varphi)\left[v(q_M) - \Theta_B q_M\right] + (1-\varphi)^2 \left[v(q_B(q_M)) - \Theta_B q_B(q_M)\right],$$

where $q_B(q_M) = (1-2\varphi)q_M/(1-\varphi)$ from (A5). The first order conditions with respect to q_G and q_M imply that the optimal project sizes are characterized by:

$$v'(q_G^d) = \Theta_G, \quad 2\varphi v'(q_M^d) + (1-2\varphi)v'(q_B^d) = \Theta_B + \frac{\varphi^2\Delta\theta}{1-\varphi} \text{ and } (1-\varphi)q_B^d = (1-2\varphi)q_M^d. \tag{A6}$$

To check the ignored constraints are satisfied by this solution, first note that (IC_b^β) is satisfied if $t_G^\beta - \theta_b q_G^d \leq 0$. Using (A3) and $(1-\varphi)q_B^d = (1-2\varphi)q_M^d$, we have:

$$t_G^\beta - \theta_b q_G^d = -\Delta\theta q_G^d < 0.$$

Note that all the remaining ignored constraints are satisfied if the monotonicity, $q_G^d \geq q_M^d \geq q_B^d$, is satisfied. We show the monotonicity by demonstrating that q_M^d in this regime $(\varphi < \widehat{\varphi}^-)$ is smaller than q_M^d in the previous regime $(\varphi > \widehat{\varphi}^+)$. For convenience, we denote q_M^d in the previous regime $(\varphi > \widehat{\varphi}^+)$ by q_M^{d+}. Suppose $q_M^d > q_M^{d+}$. Then it is inconsistent with the second equation in (A6) because:

$$\begin{aligned}
2\varphi v'(q_M^d) + (1-2\varphi)v'(q_B^d) &= \\
2\varphi v'(q_M^d) + (1-2\varphi)v'((1-2\varphi)q_M^d/(1-\varphi)) &< \\
2\varphi v'(q_M^{d+}) + (1-2\varphi)v'((1-2\varphi)q_M^{d+}/(1-\varphi)) &< \\
2\varphi v'(q_M^{d+}) + (1-2\varphi)v'(q_B^{d+}) &= \Theta_B + \frac{\varphi^2\Delta\theta}{1-\varphi},
\end{aligned}$$

where the first equality follows from (A6), the first inequality follows from the assumption that $q_M^d > q_M^{d+}$ and $v''(\cdot) < 0$, the second inequality follows from that q_M^{d+} and q_B^{d+} violate PC_G^β due to $\varphi < \hat{\varphi}^-$, the last equality uses the expressions in (A4). Thus, it must be that $q_M^d < q_M^{d+}$. Since $q_M^d > q_B^d$ from the last equation in (A6) and $q_G^d > q_M^{d+}$, it follows that $q_G^d > q_M^d > q_B^d$. That the remaining ignored constraints are satisfied by the solution is in turn implied. ■

Proof of Corollary 1.

The proof directly follows from comparing $\mathcal{P}^c$ and $\mathcal{P}^d$. The incentive compatibility constraints in $\mathcal{P}^d$ are stronger and therefore the principal's choices are more restricted in $\mathcal{P}^d$ compared to $\mathcal{P}^c$. ■

Proof of Lemma 1.

The proof directly follows from the discussion. ■

Proof of Lemma 2.

In order to show that there exists $\varphi^- \in (0, 1/2)$ such that the constraint (PIC) does not bind, we verify that the optimal contract as identified in Proposition 1 satisfies (PIC) for all φ smaller than some $\varphi^- > 0$. To see this, first recall from Proposition 1 that, for $\varphi \in (0, \widetilde{\varphi}^-)$, the solution is characterized by:

$$2t_B^c = \Theta_B q_B^c;\ 2t_M^c = \Theta_B q_M^c;\ 2\varphi v'(q_M^c) + (1-2\varphi)v'(q_B^c) = \Theta_B;\ \text{and}\ q_B^c = \frac{1-2\varphi}{1-\varphi} q_M^c. \quad \text{(A7)}$$

Hence, for $\varphi \to 0$ we have $q_B^c = q_M^c = q_B^*$, and with these values, (PIC) is satisfied in equality. Using this, we show that (PIC) is non-binding for φ small enough. Defining the function $q_M(x) = (1-\varphi)x/(1-2\varphi)$, (A7) implies that q_B^c is implicitly defined by:

$$2\varphi v'(q_M(q_B^c)) + (1-2\varphi)v'(q_B^c) = \Theta_B.$$

Differentiating the expression with respect to φ yields:

$$2v'(q_M^c) + 2\varphi v''(q_M^c)\left[\frac{1}{(1-2\varphi)^2} q_B^c + \frac{1-\varphi}{1-2\varphi}\frac{\partial q_B^c}{\partial \varphi}\right] - 2v'(q_B^c) + (1-2\varphi)v''(q_B^c)\frac{\partial q_B^c}{\partial \varphi} = 0.$$

Thus, we have:

$$\left.\frac{\partial q_B^c}{\partial \varphi}\right|_{\varphi=0} = \left.\frac{2[v'(q_B^c) - v'(q_M^c)]}{v''(q_B^c)}\right|_{\varphi=0} = \frac{2[v'(q_B^*) - v'(q_B^*)]}{v''(q_B^*)} = 0,$$

where the second equality follows from $q_B^c = q_M^c = q_B^*$ for $\varphi = 0$. Now, differentiating the last equation in (A7), we have:

$$\frac{\partial q_B^c}{\partial \varphi} = \frac{1-2\varphi}{1-\varphi}\frac{\partial q_M^c}{\partial \varphi} - \frac{1}{1-\varphi} q_M^c,$$

and therefore:

$$\left.\frac{\partial q_M^c}{\partial \varphi}\right|_{\varphi=0} = \frac{1}{1-\varphi} q_B^* > 0,$$

since $\partial q_B^c/\partial\varphi = 0$ and $q_M^c = q_B^*$ at $\varphi = 0$. That is, at $\varphi = 0$, (PIC) is satisfied with $q_B^c = q_M^c = q_B^*$ and $\partial q_M^c/\partial\varphi > 0 = \partial q_B^c/\partial\varphi$, which implies that (PIC) is strictly satisfied for $\varphi > 0$ close to zero. Since Φ^c violates (PIC) at $\varphi = 1/2$ from Lemma 1, there exists $\varphi^- \in (0, 1/2)$ such that (PIC) is satisfied for $\varphi < \varphi^-$.

To see that Φ^c violates the constraint for $\varphi \geq 1/2$, consider q_M^c characterized in Proposition 1. Again, at $\varphi = 1/2$, we have $q_M^c = q_B^*$ and by Lemma 1, (PIC) is violated. By the implicit function theorem, it follows for $\varphi > 1/2$ that:

$$\frac{\partial q_M^c}{\partial\varphi} = \frac{\Delta\theta}{v''(q_M^c)(1-\varphi)^2} < 0,$$

where the inequality follows from $v''(\cdot) < 0$. As a result, we have for $\varphi > 1/2$ that $q_B^* > q_M^c$. Also, Proposition 1 implies $q_M^c > q_B^c$, and thus it follows from the concavity of $v(q) - \Theta_b q$ that the ranking $q_B^* > q_M^c > q_B^c$ implies:

$$\max_q v(q) - \Theta_B q = v(q_B^*) - \Theta_B q_B^* > v(q_M^c) - \Theta_B q_M^c > v(q_B^c) - \Theta_B q_B^c.$$

This establishes that (PIC) is violated for all $\varphi \geq 1/2$. By continuity, there exists some $\varphi^+ \in [\varphi^-, 1/2)$ such that (PIC) is violated for all $\varphi > \varphi^+$. ■

Proof of Proposition 3.

For $\varphi \geq 1/2$, Lemma 2 shows that (PIC) is a binding constraint at the optimum. Since (IC_g), $(\underline{PC}_M)$, and (PC_B) are also binding, binding (PIC) can be rewritten as:

$$v(q_B) - \Theta_B q_B = v(q_M) - \Theta_B q_M, \tag{A8}$$

and hence the principal's payoff $\pi(\Phi)$ can be rewritten as:

$$\varphi^2\left[v(q_G) - \Theta_G q_G - 2\left(\frac{2\varphi-1}{\varphi}\Delta\theta q_M + \frac{1-\varphi}{\varphi}\Delta\theta q_B\right)\right] + (1-\varphi^2)\left[v(q_B) - \Theta_B q_B\right], \tag{A9}$$

which is to be maximized subject to (A8). Note that for $\varphi = 1/2$ the objective function simplifies to:

$$\left[v(q_G) - \Theta_G q_G - \Delta\theta q_B\right]/4 + 3\left[v(q_B) - \Theta_B q_B\right]/4,$$

which is independent of q_M. Maximizing this expression with respect to q_G and q_B, and setting $q_M = q_B$ satisfies (A8) and yields a maximizer that coincides with the expression in the proposition.

We next show that, for $\varphi > 1/2$, a solution satisfies $q_M = q_B$. To see this, note first that, for $\varphi > 1/2$, expression (A9) is strictly decreasing in q_M. Moreover note that (A8) is satisfied whenever $q_M = q_B$. These two observations imply that project sizes with $q_M > q_B$ are not optimizing (A9), since it yields less payoff than project sizes with $q_M = q_B$. Likewise, $q_B > q_M$ is not optimal for the following reason. Using (A8), we can express (A9) as:

$$\varphi^2 \left[v(q_G) - \Theta_G q_G - 2\left(\frac{2\varphi - 1}{\varphi} \Delta\theta q_M + \frac{1-\varphi}{\varphi} \Delta\theta q_B \right) \right] + (1-\varphi^2) \left[v(q_M) - \Theta_B q_M \right]. \quad \text{(A10)}$$

Thus, the solution maximizes (A10) subject to (A8). Note however that (A10) is decreasing in q_B. Project sizes with $q_B > q_M$ does not maximize (A10) subject to (A8), since it yields less than project sizes with $q_B = q_M$ which satisfies (A8).

For an optimal solution, we therefore have $q_B = q_M$ so that (A8) is satisfied and (A9) simplifies to:

$$\varphi^2 \left[v(q_G) - \Theta_G q_G + 2\Delta\theta q_M \right] + (1-\varphi^2) \left[v(q_G) - \Theta_B q_M \right].$$

Again, optimizing with respect to q_G and q_M and setting $q_B = q_M$ yields the expression in the proposition. ■

Proof of Proposition 4.

From Lemma 2, $\pi(\Phi^{\widetilde{c}}) = \pi(\Phi^c)$ for $\varphi \leq \varphi^-$, and hence by Corollary 1, $\pi(\Phi^{\widetilde{c}}) > \pi(\Phi^d)$ at $\varphi = \varphi^-$. Continuity then implies the existence of $\varphi^c > \varphi^-$, such that for $\varphi \leq \varphi^c$, $\pi(\Phi^{\widetilde{c}}) \geq \pi(\Phi^d)$. To see the existence of φ^d, recall first from Proposition 3 that, for $\varphi \geq 1/2$, the optimal q_M and q_B are bunched in $\Phi^{\widetilde{c}}$. For $\varphi \geq 1/2$, it can be verified that $\Phi^{\widetilde{c}}$ satisfies all constraints in $\mathcal{P}^d$, and hence can be implemented in $\mathcal{P}^d$. Since $\Phi^{\widetilde{c}} \neq \Phi^d$ and $\Phi^{\widetilde{c}}$ is not a solution to $\mathcal{P}^d$, it follows, for $\varphi \geq 1/2$, that $\pi(\Phi^d) > \pi(\Phi^{\widetilde{c}})$. By continuity there exists a $\varphi^d > \varphi^+$ such that for all $\varphi > \varphi^d$, $\pi(\Phi^d) \geq \pi(\Phi^{\widetilde{c}})$. ■

Proof of Proposition 5.

As noted in footnote 14, imposing more constraints on the side contracting problem relaxes the collusion proofness constraints on the principal. Since our objective is to obtain an upper bound of the principal's expected payoff under collusion (to compare that expected payoff with the principal's expected payoff in $\widetilde{\mathcal{P}}^c$ and $\mathcal{P}^d$), we impose the additional constraint that the side-contractor treats the agents equally—in particular, $\widehat{\gamma}(g, b) = \widehat{\gamma}(b, g) = \widehat{\gamma}(M)$, as well as $\widehat{\gamma}(g, g) = \widehat{\gamma}(G)$ and $\widehat{\gamma}(b, b) = \widehat{\gamma}(B)$. Thus, given the principal's contract Φ, the restricted side contract is $\phi = \widehat{\gamma}(\gamma)$, where $\widehat{\gamma}, \gamma \in \{G, M, B\}$. The side contract is Bayesian incentive compatible if the following conditions hold:

$$\begin{aligned}
& \varphi[t_{\widehat{\gamma}(G)} - \theta_g q_{\widehat{\gamma}(G)}] + (1-\varphi)[t_{\widehat{\gamma}(M)} - \theta_g q_{\widehat{\gamma}(M)}] \\
\geq \;& \varphi[t_{\widehat{\gamma}(M)} - \theta_g q_{\widehat{\gamma}(g,b)}] + (1-\varphi)[t_{\widehat{\gamma}(B)} - \theta_g q_{\widehat{\gamma}(B)}],
\end{aligned} \tag{A11}$$

$$\begin{aligned}
& \varphi[t_{\widehat{\gamma}(M)} - \theta_b q_{\widehat{\gamma}(M)}] + (1-\varphi)[t_{\widehat{\gamma}(B)} - \theta_b q_{\widehat{\gamma}(B)}] \\
\geq \;& \varphi[t_{\widehat{\gamma}(G)} - \theta_b q_{\widehat{\gamma}(G)}] + (1-\varphi)[t_{\widehat{\gamma}(M)} - \theta_b q_{\widehat{\gamma}(M)}].
\end{aligned} \tag{A12}$$

The participation in the side contract requires that:

$$\begin{aligned}
& \varphi\left[t_{\widehat{\gamma}(G)} - \theta_g q_{\widehat{\gamma}(G)}\right] + (1-\varphi)[t_{\widehat{\gamma}(M)} - \theta_g q_{\widehat{\gamma}(M)}] \\
\geq \;& \varphi\left[t_G - \theta_g q_G\right] + (1-\varphi)\left[t_M - \theta_g q_M\right],
\end{aligned} \tag{A13}$$

$$\begin{aligned}
& \varphi\left[t_{\widehat{\gamma}(M)} - \theta_b q_{\widehat{\gamma}(M)}\right] + (1-\varphi)[t_{\widehat{\gamma}(B)} - \theta_b q_{\widehat{\gamma}(B)} \\
\geq \;& \varphi\left[t_M - \theta_b q_M\right] + (1-\varphi)\left[t_B - \theta_b q_B\right].
\end{aligned} \tag{A14}$$

The RHSs of the participation constraints, (A13) and (A14), are an agent's payoffs if he rejects the side contract. In case of a rejection of the side contract, both agents make their reports to the principal non-cooperatively. A reporting function $\widehat{\gamma}(\gamma)$ is feasible if it satisfies the Bayesian incentive compatibility and individual rationality constraints, (A11), (A12), (A13) and (A14). We say that the principal's contract is collusion proof if there does not exist a feasible report function $\widehat{\gamma}(\gamma)$ for which at least one participation constraint is strictly satisfied. As in Laffont and Martimort (1997), the principal considers only the collusion proof contracts when making an offer to the agents.

Next, we show that the principal's contract is not collusion proof if it exhibits $t_G - \theta_g q_G < t_M - \theta_g q_M$. In doing so, we consider the two collectively exhaustive cases: (i) $t_B - \theta_b q_B \geq t_M - \theta_b q_M$ and (ii) $t_B - \theta_b q_B < t_M - \theta_b q_M$. For case (i), consider the side contract $\widehat{\gamma}(G) = \widehat{\gamma}(M) = M$ and $\widehat{\gamma}(B) = B$. With $t_G - \theta_g q_G < t_M - \theta_g q_M$, this side contract satisfies the participation constraint (A13) as a strict inequality and participation constraint (A14) as an equality. In addition, since the principal's contract Φ is Bayesian incentive compatible, the side contract also satisfies (A11). Because $t_B - \theta_b q_B \geq t_M - \theta_b q_M$ for case (i), the side contract satisfies (A12) as well. This establishes that the principal's contract is not collusion proof for case (i) if $t_G - \theta_g q_G < t_M - \theta_g q_M$. For case (ii), consider the side contract $\widehat{\gamma}(G) = \widehat{\gamma}(M) = \widehat{\gamma}(B) = M$. With $t_G - \theta_g q_G < t_M - \theta_g q_M$, this side contract strictly satisfies the participation constraint (A13). Since $t_B - \theta_b q_B < t_M - \theta_b q_M$ for case (ii), it also strictly satisfies (A14). Moreover, Bayesian incentive compatibility of the principal's contract Φ implies that the side contract also satisfies (A11) and (A12). This establishes that the principal's contract is not collusion proof for case (ii) if $t_G - \theta_g q_G < t_M - \theta_g q_M$. Thus, (CIC) is necessary for the principal's contract Φ to be collusion proof.

Since (CIC) is a necessary condition for collusion proofness, we can use it to obtain an upper bound on the principal's payoff from the optimal contract in $\mathcal{P}^u$. The binding constraints in $\mathcal{P}^u$ are (CIC), $(\underline{PC_M})$, (PC_B) and (IC_g). It is straightforward to verify that other constraints are satisfied by the solution without them. From the binding constraints, the transfers are:

$$t_G = \theta_g q_G + \Delta\theta q_M, \quad t_M = \theta_b q_M, \quad t_B = \theta_b q_B,$$

and the binding (IC_g) reduces to $q_M = q_B$. After substituting for the transfers with $q_M = q_B$ in the objective function, optimization gives the following project sizes in $\mathcal{P}^u$:

$$v'(q_G^u) = \Theta_G, \quad v'(q_M^u) = v'(q_B^u) = \Theta_B + \frac{2\varphi^2}{1-\varphi^2}\Delta\theta.$$

The optimal outcome in $\mathcal{P}^u$ satisfies all the constraints in $\widetilde{\mathcal{P}}^c$ and $\mathcal{P}^d$. Thus, the expected payoff from Φ^u can be implemented in $\widetilde{\mathcal{P}}^c$ and $\mathcal{P}^d$. Since $\Phi^u \neq \Phi^{\widetilde{c}}$ and $\Phi^u \neq \Phi^d$, it follows that Φ^u is dominated by $\Phi^{\widetilde{c}}$ and Φ^d. ■

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