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ARTICLE

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Managerial performance evaluation and organizational form

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Abstract

We study the relative efficiency of centralized versus decentralized organizational forms given optimized managerial performance evaluation within an incomplete contracting framework with risk-averse agents under moral hazard. Decentralization and performance evaluation are complementary control choices and the efficiency of an organizational form depends on the design of performance evaluation. Divisions can make relationship-specific investments that not only improve firm performance, but also increase compensation risk. We find that pure divisional performance evaluation is optimal under centralization, whereas under decentralization, optimal compensation contracts include a combination of divisional and firm-wide performance evaluation. When comparing both organizational forms, we find that the optimal form depends on managers' degree of risk-aversion and the uncertainty of the business environment. Contrary to previous literature, we find that centralization dominates in many situations, particularly at high degrees of risk-aversion and high uncertainty.

KEYWORDS
budgeting, hold-up, performance evaluation, transfer pricing

Évaluation de la performance managériale et structure organisationnelle

Résumé

Les auteurs étudient l'efficacité relative des structures organisationnelles centralisées et décentralisées en tenant

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compte d'une évaluation de la performance managériale optimisée dans un cadre contractuel incomplet incluant des agents opposés à la prise de risque faisant face à un aléa moral. La décentralisation et l'évaluation de la performance sont des choix de contrôle complémentaires et l'efficacité d'une structure organisationnelle dépend de la conception de l'évaluation de la performance. Les unités opérationnelles peuvent réaliser des investissements propres à la relation contractuelle qui améliorent la performance de l'entreprise, mais augmentent également le risque lié à la rémunération. Les auteurs constatent que l'évaluation de la performance au sein de l'unité opérationnelle est optimale lorsque la structure est centralisée, tandis que lorsqu'elle est décentralisée, les contrats de rémunération optimaux incluent une combinaison d'évaluations de la performance au sein de l'unité opérationnelle et de l'ensemble de l'entreprise. Lorsque les deux structures organisationnelles sont comparées, les auteurs observent que la structure optimale dépend du degré d'aversion au risque des gestionnaires et de l'incertitude de l'environnement des entreprises. Contrairement aux études réalisées précédemment, les auteurs constatent que la centralisation domine dans de nombreuses situations, en particulier lorsque les degrés d'aversion au risque et l'incertitude sont élevés.

MOTS-CLÉS
budgétisation, établissement de prix de transfert, évaluation de la performance, problème de renonciation

1 | INTRODUCTION

Modern firms are characterized by different degrees of delegation across varying layers of hierarchies (Bloom et al., 2012). The existence of different organizational forms is prompted by complementarities between different control mechanisms (Aghion et al., 2014; Milgrom & Roberts, 1990). In particular, decentralization and performance evaluation are complementary control choices (Abernethy et al., 2004; Hofmann & Indjejikian, 2021; Milgrom & Roberts, 1992) and the design of performance evaluation affects the efficiency of an organizational form. In this paper, we study the influence of performance evaluation on the choice of organizational form.

Decentralized organizations are considered beneficial because divisional managers have access to dispersed decision-relevant information (Alonso et al., 2008; Baiman & Baldenius, 2009; Dessein, 2002). The access to local information results in a flexibility advantage as managers can adapt to local conditions and react timelier to news (Bartlett & Ghoshal, 2002; Zhou, 2015). However, externalities among the divisions require coordination of their activities (Milgrom & Roberts, 1992). Such externalities can result from relationship-specific investments that lead to the well-known hold-up problem (Williamson, 1985). The latter can be mitigated by rewarding managers based on a combination of firm-wide and divisional performance measures (Anctil & Dutta, 1999, AD henceforth) or by centralizing decision-making. It is yet unclear which structure is more efficient. Prior studies have only considered the optimality of either of the two control choices. Although these can be studied in various combinations, the most interesting analysis is one in which both dimensions are varied, as is done in this paper. We endogenize performance evaluation in the analysis of the relative efficiency of different organizational forms.

Related studies of intrafirm trade and relationship-specific investments typically abstract from risk-aversion and moral hazard (Baldenius et al., 1999; Pfeiffer et al., 2011), which is problematic because of compensation risk: under moral hazard, efficiency-enhancing investments also increase the compensation risk borne by managers since investments increase not only the expected value but also the variance of the returns (Baldenius & Michaeli, 2017, BM henceforth). BM (2017, p. 1) label this the "investment/risk-link" (IRL) and find that it "overturns key findings from prior incomplete contracting studies." In particular, they find that the IRL may lead to overinvestment since managers only partly internalize compensation risk under decentralization. Whereas prior literature generally finds that decentralized forms dominate, it is yet unclear how the IRL affects optimal performance evaluation in different organizational forms.

We study an agency model in which a firm with two divisions contracts with two risk- and effort-averse managers to operate its two divisions. An intermediate good is transferred between the divisions. The terms of trade can be determined either by the firm (centralization) or through negotiations between the managers (decentralization). The divisions can make relationship-specific investments to increase the total surplus, for example, by implementing a new production technology to reduce the variable cost of production. Performance evaluation can be based on divisional and firm-wide measures in conjunction with budgeting procedures (centralization) or transfer pricing (decentralization). In our model, the flexibility advantage arises from the fact that divisional managers can make more timely decisions and, hence, can react to realizations of previously uncertain costs and revenues. Under decentralization, decisions about trade quantity are made after this uncertainty has been resolved and investments have been made, whereas trade is determined at the outset in the centralized setting. Consequently, the IRL exists for decentralization only, as investment decisions affect trade quantity and in turn the risk imposed on divisional managers.

We proceed as follows. First, we analyze the centralized setting. Pure divisional performance evaluation proves optimal since the expected performance of each division is unaffected by the other division's effort and investment decisions; compensation based on the other division's profit only adds risk without generating benefits. Moreover, investment decisions are efficient, but underinvestment emerges since the firm faces a trade-off between stimulating investments and operational efforts, similar to BM (2017).

Second, we analyze the decentralized setting. We find that rewarding managers solely based on firm-wide profits does not induce first-best investments, contrary to findings in AD (1999) and consistent with BM (2017). Due to the IRL, additional investments impose additional risk on managers, making investments more costly and muting investment incentives. Optimal compensation contracts under decentralization include both divisional and firm-wide performance measures to mitigate hold-up problems, as in AD (1999). However, the benefits from improved investment incentives are diminished by higher risk compensation paid to the divisional managers. Consequently, the optimal contract under decentralization induces underinvestment.

Third, we examine the relative efficiency of centralized compared to decentralized organizations. That is, we compare the firm's expected surplus for both organizational forms when performance evaluation is optimized. The optimal organizational arrangement trades off the flexibility gain under decentralization against lower risk premia under centralization, depending on the degree of managerial risk-aversion and uncertainty. We find that for different combinations of risk-aversion and uncertainty, centralization outperforms decentralization more often than not: centralization generally dominates irrespective of the degree of risk-aversion for zero uncertainty. Centralization is also optimal irrespective of the degree of uncertainty when managerial risk-aversion is sufficiently high. Decentralization is optimal in an intermediate range of uncertainty, when risk-aversion is not sufficiently high for centralization to dominate regardless of uncertainty. Decentralization may also dominate for low or high uncertainty, provided that risk-aversion is sufficiently low and the effects of risk-aversion approaching zero are more pronounced than those of uncertainty.

Under decentralization, profit-sharing implies that managers only partly benefit from the investment, but are exposed to the other division's operational risk. Under centralization, pure divisional performance evaluation captures the full benefits of the investment without exposure to the other division's risk. For low uncertainty, decentralization is at a clear disadvantage. Yet, when uncertainty increases, this disadvantage is ceteris paribus reduced as the flexibility gain of decentralization increases with increasing uncertainty. However, the flexibility gain comes at the cost of paying risk premia to managers. The risk premia are more sensitive to increasing uncertainty under decentralization since not only contribution margins, but also trade quantities are risky, whereas the latter are fixed under centralization. Decentralization hence suffers more from increasing uncertainty and ultimately gets dominated by centralization: whereas centralization uses quantity budgeting as an additional incentive instrument, decentralization can only employ performance evaluation to provide investment *and* effort incentives. Rising risk premia under decentralization hence have detrimental effects on both investment and effort. The centralized form, however, can react more flexibly to rising risk premia by setting investment and effort incentives separately, adapting incentives more adequately to conditions of high risk-aversion and uncertainty.

Our study differs from the majority of research on transfer pricing, which typically abstracts from risk-aversion and moral hazard and finds that decentralization dominates (Baldenius et al., 1999; Pfeiffer et al., 2011). For example, Pfeiffer et al. (2011) compare transfer prices based on actual costs and centrally determined transfer prices based on standard costs. They find that decentralization dominates when the uncertainty of cost information is high, but do not consider moral hazard and risk-aversion and do not solve for the optimal contract. Under their assumptions, the optimal contract under decentralization would be based on firm-wide profits, which resolves the hold-up problem as demonstrated in AD (1999). However, for risk-averse managers, such compensation is no longer optimal and the hold-up problem persists. We contribute to this literature by establishing that risk-aversion introduces important qualitative differences into the analysis. Our results suggest that the firm's surplus is strongly affected by managerial risk-aversion: whereas the effect of increasing uncertainty is linear under risk-neutrality, it is concave under risk-aversion.

Prior studies that have analyzed specific investments under risk-aversion and moral hazard are AD (1999), BM (2017), and Holmstrom and Tirole (1991). In line with AD (1999) and BM (2017), we assume linear compensation contracts. Although this assumption is restrictive, it ensures comparability with prior literature. AD (1999) study negotiated versus cost-based transfer pricing in a decentralized setting. They demonstrate that first-best investments can be induced by rewarding managers based on firm-wide profits. Since such an incentive system would impose excessive risk on managers, optimal linear compensation contracts contain both divisional and firm-wide components. We extend AD (1999) to include the IRL and find that first-best investments can no longer be attained by rewarding managers solely based on firm-wide profits. The reason is that the IRL increases the risk imposed on managers, making additional investments more costly to managers and muting investment incentives. The optimal incentive contract still includes both firm-wide and divisional profits, but the underinvestment problem persists. Our analysis also extends AD (1999) to the centralized setting.

We extend BM (2017) by studying the role of firm-wide performance measures in optimal organizational forms, whereas BM (2017) examine a decentralized setting with no profit-sharing and do not evaluate the optimality of their organizational design. Whereas BM (2017) find that overinvestment, relative to their benchmark of contractible investment, is induced in cases of high uncertainty, we find that underinvestment relative to the benchmark of first-best investments persists. Our results imply that decentralization is suboptimal in situations of high uncertainty. Hence, overinvestment as predicted in BM (2017) for high uncertainty in decentralized forms may not occur in firms that optimize (within our model assumptions) both performance evaluation and organizational form since they would choose a centralized form in such cases.

Holmstrom and Tirole (1991) were the first to analyze transfer pricing in the context of organizational choice. They find that in most cases, decentralized organizations dominate, but do not allow for different forms of performance evaluation. We extend their analysis by studying the role of firm-wide performance measures and the influence of the IRL. Our findings reveal that centralization dominates in many situations and underinvestment persists for both organizational forms.

In concurrent research, BM (2019, 2020) and Hofmann and Indjejikian (2021) also study aspects of organizational design. BM (2019) compare decentralization to non-integration, where two divisions are run as separate firms and thus cannot implement profit-sharing. They confirm the welfare-improving role of integration. In contrast, our study compares two different organizational forms within one integrated organization and addresses the question how integration can be optimally designed. Whereas BM (2019, 2020), like BM (2017), study the impact of the IRL for given levels of uncertainty, we analyze the consequences of variations in the uncertainty of costs and revenues on the optimality of organizational form. BM (2020) study the optimal allocation of decision rights over non-contractible specific investments in a decentralized organization. They show that decision rights over scalable investments should be bundled in the hands of the manager facing the more volatile environment, that is, one division run as an investment center and the other as a mere profit center. In our study, both divisions are investment centers. In contrast to our study, BM (2020) do not consider centralized organizations and do not allow for firm-wide performance evaluation. Hofmann and Indjejikian (2021) study the endogenous role of incentive systems and monitoring quality on the firm's choice to delegate the authority to hire and evaluate personnel. In contrast to our paper, they are interested in the organization of layers of hierarchy rather than of divisional production processes along the value chain. They do not examine relationship-specific investments, internal trade, and the sensitivity of decentralized versus centralized organizations to variations in uncertainty and risk-aversion.

Our results also speak to the more recent literature in organizational economics (Aghion et al., 2014; Bloom et al., 2012; Dessein et al., 2022; Van Doorn & Volberda, 2009). Dessein (2002), Alonso et al. (2008), and Rantakari (2008) analyze strategic communication between headquarters and risk-neutral managers in decentralized and centralized organizations. Rantakari (2013) endogenizes incentive systems and finds that the optimal level of integration is decreasing in the volatility of the environment and that the use of firm-wide incentives is increasing in the level of integration. Dessein et al. (2022) find empirical evidence for a more widespread use of decentralized organizations in response to more uncertain business environments when coordination needs are small or moderate. The flexibility advantage of decentralization plays a central role in this literature (Bartlett & Ghoshal, 2002; Zhou, 2015). Our findings imply that this advantage is offset by risk premia paid to risk-averse managers.[1]

The paper is organized as follows: Section 2 presents the model, the main assumptions, and benchmark results. Section 3 analyzes performance evaluation in centralized and decentralized organizations. Section 4 compares the efficiency of both organizational forms. We conclude with a summary. All proofs are in the Appendix. Appendix S1 in the Supporting Information contains further analyses.

[1]For good surveys of additional relevant literature, see Hofmann and Indjejikian (2018) and Mookherjee (2006).

2 | MODEL AND BENCHMARK RESULTS

2.1 | The model

A risk-neutral principal (the firm) contracts with the managers of the two firm divisions, a downstream division (Division 1) and an upstream division (Division 2). Both divisional managers are risk- and effort-averse. To ensure comparability of our results with those of AD (1999) and BM (2017), we assume mean-variance preferences: manager i ($i=1,2$) maximizes $\phi_i = \mathrm{E}(w_i) - \alpha_i \mathrm{Var}(w_i)/2 - a_i^2/2$, where w_i denotes compensation, α_i the degree of risk-aversion, and a_i the effort provided by manager i. Without loss of generality, the reservation levels of the two managers are set to zero.

It is assumed that divisional profit π_i is linear in manager i's effort and a random variable ε_i with zero mean and variance σ_i^2. Both divisions trade an intermediate good. We model this transfer by the trade quantity q and the corresponding transfer payment t. In accordance with AD (1999), we do not consider an external market for the good. As long as the transfer is not specified by the firm, divisional managers negotiate to maximize their objective function ϕ_i. So, incentives are needed to induce trade between the divisions. Regarding the transfer payment, we apply the Nash bargaining solution (see, e.g., AD, 1999), which results in equal surplus-splitting.

Regarding the value of interdivisional trade, we assume a linear-quadratic scenario (see, e.g., Lengsfeld et al., 2006; Pfeiffer et al., 2011). The revenue of the downstream division is given by $M_1 = (\vartheta_1 + I_1 - bq/2)q$, where ϑ_1 is a random variable that determines the revenue from selling one unit, while b captures the sensitivity of the price per unit to the quantity of units. We assume $b > 2$ to ensure a non-negative expected outcome of the trade. The production cost for the upstream division is of the form $M_2 = (\vartheta_2 - I_2)q$, where ϑ_2 is a random variable that determines the unit cost. I_1 and I_2 are relationship-specific investments. Note that negative values for M_2 would result if ϑ_2 were less than I_2. In line with BM (2017), we rule out such cases by assuming that the expected value of ϑ_2 is sufficiently high to ensure non-negative costs. The variances $\sigma_{\vartheta_i}^2$ of ϑ_i ($i=1,2$) reflect the ex ante uncertainty of costs and revenues.

Both divisions can make relationship-specific investments I_1, I_2. For example, the upstream division can invest in cost reductions, whereas the downstream division can invest in market research or sales promotion, which translates into higher revenue per unit. These investment decisions are made prior to interdivisional trade and impose immediate additional costs on divisional profits. We assume that these costs are equal to $I_i^2/2$ ($i=1,2$). Under these assumptions, divisional profits are given by $\pi_1 = \beta_1 a_1 + M_1 - t - I_1^2/2 + \varepsilon_1$ and $\pi_2 = \beta_2 a_2 - M_2 + t - I_2^2/2 + \varepsilon_2$, where $\beta_i > 0$ ($i=1,2$) denotes the productivity of divisional effort.

In line with AD (1999), we assume that all random variables are stochastically independent. This assumption allows us to study the effects of interdivisional trade on the optimal incentive contracts without distracting interaction effects such as common errors. Whereas all distributional properties are common knowledge ex ante, the realizations $\widetilde{\vartheta}_i$ of ϑ_i ($i=1,2$) can be observed symmetrically ex post (i.e., after investing) only by the divisional managers. We assume that they cannot share their private information with the firm. This is a standard assumption in the literature on incomplete contracts (Melumad et al., 1992; Prendergast, 2002). According to the Revelation Principle (Myerson, 1982), a centralized organization in which all managers truthfully disclose their private information to the firm that prescribes all actions will perform at least as well as any other organizational form. As Melumad et al. (1997) point out, this precludes a theory that explains the widespread prevalence of decentralized decision-making in organizations.

The resulting firm-wide profit is given by $\pi = \pi_1 + \pi_2 = \beta_1 a_1 + \beta_2 a_2 + M - I_1^2/2 - I_2^2/2 + \varepsilon_1 + \varepsilon_2$, where $M = M_1 - M_2 = (\vartheta_1 - \vartheta_2 + I_1 + I_2 - bq/2)q$ is the joint surplus. In what follows, we use ϑ as an abbreviation for $\vartheta_1 - \vartheta_2$. Ex ante, ϑ is a random variable, so the surplus is stochastic. Let μ denote the expected value and σ^2 the variance of ϑ. To evaluate the variance of ϑ^2, we assume that the distribution of ϑ is symmetric and mesokurtic.

In terms of compensation, we restrict our analysis to linear contracts; that is, $w_i = \underline{w}_i + w_{ii}\pi_i + w_{ij}\pi_j$ for the manager of division i ($i = 1,2$), where $j = 3 - i$ is the other division. This is restrictive, but consistent with AD (1999) and BM (2017).[2] The weight on the agent's own division's profit w_{ii} captures the manager i's pay-performance sensitivity, whereas w_{ij} ($i,j = 1,2, i \neq j$) allows for profit-sharing. Contracts that place some (but not full) weight on the other division's profit ($w_{ij} < w_{ii}$) will be called "partial profit-sharing" and contracts that place equal weights on both divisions' profits ($w_{ij} = w_{ii}$) will be called "full profit-sharing." Whereas BM (2017, 2020) exclude profit-sharing by assumption, we endogenize the corresponding decision. In particular, AD (1999) show that full profit-sharing eliminates the hold-up problem. However, their model does not take the IRL into account. This raises the question whether full profit-sharing still solves the hold-up problem when the IRL is present. To answer this question, in line with BM (2019), we consider the possibility of profit-sharing.

We distinguish between a centralized and a decentralized organizational form. Figures 1 and 2 depict the respective event sequences. For the centralized setting, we assume that the firm determines the trade quantity as well as the incentive contract at Date 1 under incomplete information. At Date 2, the managers decide on effort and investment based on expected costs and revenues. At Date 3, the intermediate good is produced and traded after costs and revenues have been observed. At Date 4, divisional profits are realized and the managers are compensated.

In the centralized setting, consistent with previous literature (Pfeiffer & Wagner, 2007), we assume that the firm determines trade ex ante without knowledge of costs and revenues. This need not be optimal. It could be beneficial for the firm to make the trade quantity contingent on communication with the managers after they have observed their private information. However, for the reasons stated above, we do not permit such communication. Our findings in Section 4 also suggest that centralization is often superior despite this drawback. Mitigating it would reinforce the superiority of centralization. Further note that it is not necessary for the firm to assign a transfer payment under centralization. Since it would be determined ex ante, it has the same effect as a reduction in Manager 1's fixed salary and a corresponding increase in Manager 2's fixed salary.

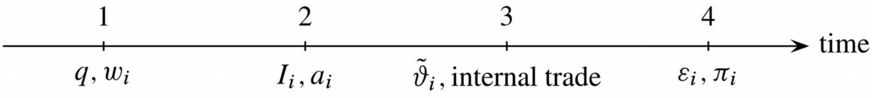
In the decentralized setting, at Date 1, the firm determines the incentive contract but not the trade quantity. At Date 2, the managers decide on effort and investment based on expected costs and revenues. After observing the other manager's investment decision and the costs and revenues at Date 3, the managers decide on interdivisional trade. Finally, at Date 4, divisional profits are realized and the managers are compensated.

Note that under decentralization, trade depends on investments, whereas under centralization, investments depend on the firm's trade decision. We therefore use reaction functions such as $q(\vartheta, I_i, I_j)$ and $I_i(q)$ when discussing such dependencies. Otherwise, especially in the proofs, we refrain from using function-like notation to simplify the presentation.

2.2 | Benchmark results

As benchmarks, we derive the optimal investment and trade decisions given the respective other decision. When the firm determines trade after observing investments, cost, and revenues (as in Figure 2), trade is given by

[2]Holmstrom and Milgrom (1987) show that while linear contracts are not optimal in general, pairing normal distributions with exponential utility leads to the optimality of linear contracts for one-period single-task agencies. Moreover, managers' certainty equivalents then correspond to mean-variance preferences. However, we do not assume normally distributed random variables. Even if this were the case, divisional performance measures under decentralization would not be normally distributed because they depend on the trade quantity in a nonlinear way. Therefore, there is no basis for the optimality of linear contracts.



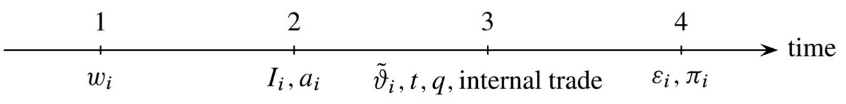
Date 1: The firm determines the trade quantity q and the compensation w_i $(i = 1, 2)$.

Date 2: Divisional managers make investment decisions I_i and supply effort a_i $(i = 1, 2)$.

Date 3: After observing the cost and revenue parameters $\tilde{\vartheta}_i$ $(i = 1, 2)$, the good is produced and sold.

Date 4: Random variables ε_i and thus divisional profits π_i $(i = 1, 2)$ are realized.

FIGURE 1 Timeline of the events in the centralized setting.



Date 1: The firm determines the compensation contracts w_i $(i = 1, 2)$.

Date 2: Divisional managers make investment decisions I_i and supply effort a_i $(i = 1, 2)$.

Date 3: After observing the cost and revenue parameters $\tilde{\vartheta}_i$ $(i = 1, 2)$, managers determine trade quantity q based on the transfer payment t. Then q is produced and sold.

Date 4: Random variables ε_i and thus divisional profits π_i $(i = 1, 2)$ are realized.

FIGURE 2 Timeline of the events in the decentralized setting.

$$\widehat{q}\left(\widetilde{\vartheta}, I_i, I_j\right) = \arg\max_q \{\pi\} = \frac{\widetilde{\vartheta} + I_i + I_j}{b} \tag{1}$$

$(i, j = 1, 2, i \neq j)$. If trade satisfies this condition for given investment levels (but possibly not yet realized costs and revenues), that is, $q(\cdot, I_i, I_j) = \widehat{q}(\cdot, I_i, I_j)$, we refer to trade as "efficient conditional on investments." Note that negative values of $\widehat{q}$ can arise if the realized costs are sufficiently high. Then it would be optimal to refrain from internal trade. As this border case is of minor interest, it will not be discussed further.

When investment decisions are made after trade has been determined (as in Figure 1), but before costs and revenues have been observed, that is, in expectation, investment levels are given by

$$\widehat{I}_i(q) = \arg\max_{I_i} \{\mathrm{E}(\pi)\} = q \tag{2}$$

$(i = 1, 2)$. If investments satisfy this condition for a given trade quantity, that is, $I_i(q) = \widehat{I}_i(q)$, we refer to investments as "efficient conditional on trade."

In the following section, we discuss the conditional efficiency of trade and investments in the second-best situations of centralization and decentralization. Both organizational forms are characterized by the efficiency of only one of these two decisions (trade *or* investments). In contrast, trade *and* investments are simultaneously efficient in the first-best situation, as stated in Lemma 1.

Lemma 1.

(a) Trade is efficient conditional on investments:

$$q^{\text{fb}}\left(\widetilde{\vartheta},I_i^{\text{fb}},I_j^{\text{fb}}\right)=\widehat{q}\left(\widetilde{\vartheta},I_i^{\text{fb}},I_j^{\text{fb}}\right)\;(i,j=1,2,i\neq j).$$

(b) Investments are efficient conditional on trade in expectation:

$$I_i^{\text{fb}}=\text{E}\left[q^{\text{fb}}\left(\vartheta,I_i^{\text{fb}},I_j^{\text{fb}}\right)\right]\;(i,j=1,2,i\neq j).$$

This first-best benchmark determines "underinvestment" as investment falls below the first-best level, that is, if $I_i<I_i^{\text{fb}}$.

3 | CENTRALIZED AND DECENTRALIZED DECISION-MAKING

3.1 | Centralization

Under centralization, trade is determined by the firm in the sense of quantity budgeting. The firm then maximizes its expected profit net of compensation

$$\Phi^c=\left(1-w_{ii}-w_{ji}\right)\text{E}\left(\pi_i^c\right)+\left(1-w_{jj}-w_{ij}\right)\text{E}\left(\pi_j^c\right)-\underline{w}_i-\underline{w}_j \tag{3}$$

$(i,j=1,2,i\neq j)$ with respect to trade and compensation given the incentive compatibility constraints $(a_i,I_i)=\underset{a_i,I_i}{\arg\max}\{\phi_i\}$ and the participation constraints $\phi_i\geq 0$. The latter are binding when the fixed compensation $\underline{w}_1,\underline{w}_2$ is chosen optimally. Proposition 1 summarizes our main findings, where the superscript c denotes optimal values.

Proposition 1 (Centralization).

(a) Purely divisional performance evaluation is optimal: $w_{ii}^c>0, w_{ij}^c=0\;(i,j=1,2,i\neq j)$.
(b) Although investments are efficient conditional on trade, underinvestment is induced in expectation: $I_i^c(q)=\widehat{I}_i(q)$, but $I_i^c(q^c)<\text{E}[q^{fb}(\vartheta,I_i^{fb},I_j^{fb})]\;(i,j=1,2,i\neq j)$.
(c) When costs and revenues are deterministic, both trade and investments are first-best: $q^c(\vartheta,I_i^c,I_j^c)=q^{fb}(\vartheta,I_i^{fb},I_j^{fb})$ and $I_i^c(q^c)=I_j^c(q^c)=q^{fb}(\vartheta,I_i^{fb},I_j^{fb})\;(i,j=1,2,i\neq j)$.

Part (a) characterizes the optimal incentive contract. As zero weight is placed on the other division's profit, it is optimal for the firm to forgo profit-sharing. In particular, the proof in the Appendix yields the following optimal weights on divisional profits:

$$w_{ii}^c=\frac{\beta_i^2}{\beta_i^2+\alpha_i\left(\left[q^c\left(\mu,I_i^c,I_j^c\right)\right]^2\sigma_{\vartheta_i}^2+\sigma_i^2\right)}>0\;\text{ and }\;w_{ij}^c=0 \tag{4}$$

$(i,j=1,2,i\neq j)$. Without trade, the weight on division i's own profit simplifies to the pay-performance sensitivity $\beta_i^2/\left(\beta_i^2+\alpha_i\sigma_i^2\right)$ familiar from standard moral hazard models (Banker & Datar, 1989; Holmstrom & Milgrom, 1991). As trade increases the risk of the surplus, it also affects the risk borne by divisional managers. In order to limit their risk exposure, the firm must balance effort incentives provided by performance evaluation with investment incentives provided by quantity budgeting. Thus, similar to BM (2017), increases in trade require a decrease in pay-performance sensitivity.

It is optimal for the firm to evaluate performance on a purely divisional basis since the effort and investment decisions of one manager do not affect the profit of the other division and divisional profits are uncorrelated. Otherwise, relative performance evaluation would increase the expected net profit of the firm by filtering out systematic risks (see, e.g., Holmstrom, 1982).

Part (b) states that investments are efficient conditional on trade. Note that divisional managers do not participate in the profit of the other division. In addition, investments have no impact on risk under centralization. Thus, maximizing a manager's objective function with respect to investment amounts to maximizing the expected profit of this division. Since the investing division bears the full investment costs, its manager chooses the same level of investment as the firm would, which makes investments conditionally efficient. This resembles the finding in the literature that centralized standard-cost transfer pricing triggers efficient investments because managers receive the full marginal return from their investments (see, e.g., Pfeiffer & Wagner, 2007; Pfeiffer et al., 2011).

However, conditionally efficient investments do not prevent underinvestment. The proof in the Appendix shows that the optimal trade quantity under centralization is given by

$$q^c\left(\mu, I_i^c, I_j^c\right) = \frac{\mu + I_i^c + I_j^c}{b + \alpha_i \left(w_{ii}^c\right)^2 \sigma_{\vartheta_i}^2 + \alpha_j \left(w_{jj}^c\right)^2 \sigma_{\vartheta_j}^2} \tag{5}$$

$(i, j = 1, 2, i \neq j)$. When comparing this to the expected efficient trade quantity $\left(\mu + I_i^c + I_j^c\right)/b$, we see that trade, and hence investments, fall below the first-best level, which implies underinvestment in expectation. Higher pay-performance sensitivities therefore require reductions in trade, in line with BM (2017).

Finally, Part (c) considers the special case where costs and revenues are deterministic $(\sigma_{\vartheta_1}^2 = \sigma_{\vartheta_2}^2 = 0)$. Then, trade and investments are first-best. The intuition is straightforward: if costs and revenues are not risky, the same applies to the joint surplus. Consequently, trade imposes no risk on divisional managers, so there is no need for trade-related risk compensation. As a result, there is no reason to deviate from first-best trade. Furthermore, since the investing division fully internalizes the costs and benefits of its investment and is not affected by the investment decision of the other division, the investment decisions of the divisional managers are identical to the investment decision of the firm in the first-best situation.

3.2 | Decentralization

Under decentralization, the firm delegates the determination of the trade quantity to the divisional managers and maximizes its expected profit net of compensation

$$\Phi^d = \left(1 - w_{ii} - w_{ji}\right) \mathrm{E}\left(\pi_i^d\right) + \left(1 - w_{jj} - w_{ij}\right) \mathrm{E}\left(\pi_j^d\right) - \underline{w}_i - \underline{w}_j \tag{6}$$

$(i, j = 1, 2, i \neq j)$ with respect to compensation only. It takes into account not only the same incentive compatibility and participation constraints as under centralization, but also the fact that divisional managers determine internal trade.

Due to equal surplus-splitting, the transfer payment is given by $t = (M_1 + M_2)/2$. Therefore, divisional profits $\pi_i^d = \beta_i a_i + M^d/2 - I_i^2/2 + \varepsilon_i$ $(i = 1, 2)$, and hence managerial compensation, depend on the joint surplus M^d. Since M^d is stochastic and managers are risk-averse, not only the expectation but also the variance of M^d enters the firm's optimization problem. The proof of Proposition 2 in the Appendix shows that the expected value and variance

$$\mathrm{E}\left(M^d\right) = \frac{\sigma^2}{2b} + \frac{b}{2} \cdot [\mathrm{E}(q)]^2 \quad \text{and} \quad \mathrm{Var}\left(M^d\right) = \frac{\sigma^4}{2b^2} + \sigma^2 \cdot [\mathrm{E}(q)]^2 \tag{7}$$

depend on the uncertainty of costs and revenues σ^2 as well as on the expected trade $\mathrm{E}(q)$. Thus, investments increase not only the expected surplus (via $\mathrm{E}(q)$), but also its variance, and hence the risk premia demanded by divisional managers. BM (2017) refer to this as the "investment/risk-link" (IRL).

Proposition 2 summarizes our main findings regarding decentralization, where superscript d denotes optimal values.

Proposition 2 (Decentralization).

(a) Neither a pure divisional performance evaluation nor full profit-sharing is optimal:

$$0 \neq w_{ij}^d \neq w_{ii}^d \; (i,j = 1,2, i \neq j).$$

(b) Trade is efficient conditional on investments, but underinvestment is induced in expectation:

$$q^d\left(\widetilde{\vartheta}, I_i, I_j\right) = \widehat{q}\left(\widetilde{\vartheta}, I_i, I_j\right), \; but \; I_i^d < \mathrm{E}\left[q^{\mathrm{fb}}\left(\vartheta, I_i^{\mathrm{fb}}, I_j^{\mathrm{fb}}\right)\right] \; (i,j = 1,2, i \neq j).$$

The latter effect is reinforced by the IRL.

(c) Underinvestment relative to the first-best level persists even with full profit-sharing.

Part (a) asserts the optimality of partial profit-sharing. Although we assume that all random variables are stochastically independent, the divisional profits are correlated because both depend on the random joint surplus M^d (as in previous literature that examines the investment/risk-link, e.g., BM 2017, 2019, 2020). Thus, a division's profit provides a means to reduce the other manager's risk premium, which makes pure divisional performance evaluation suboptimal. On the other hand, full profit-sharing would impose excessive risk on divisional managers. The optimal contract lowers the weight on the other division's profit and deviates from full profit-sharing. This finding implies that the result of AD (1999) is robust to the inclusion of the IRL. It is consistent with BM (2019), who, however, do not optimize the weight on the firm-wide bonus coefficient for profit sharing w_{ij} but only examine the effects of varying it on investment decisions.

Part (b) states that trade is efficient conditional on investments. Since trade is determined after the uncertainty of costs and revenues is resolved, it has no impact on risk. Therefore, the divisional managers' trade decision comes down to maximizing their expected compensation. Both compensation and firm-wide profit are affected by trade in the same way. Consequently, both are maximized by the same trade quantity, which makes trade efficient conditional on investments. Accordingly, first-best investments would induce first-best trade. However, decentralized investments are not first-best because divisional managers only partially internalize investment benefits (due to equal surplus-splitting), while they bear all the costs. The IRL exacerbates this problem, as is revealed by the investment incentive compatibility constraints

$$I_i = \frac{w_{ii} + w_{ij}}{2w_{ii}} \cdot \left[1 - \underbrace{\frac{\alpha_i\left(w_{ii} + w_{ij}\right)\sigma^2}{2b}}_{\mathrm{IRL}}\right] \cdot \mathrm{E}(q) \tag{8}$$

($i,j = 1,2, i \neq j$). The term marked "IRL" has a negative impact on investments and results from the investment/risk-link. As investments amplify the variance of the surplus, managers demand higher risk premia. The optimal contract thus mutes investment incentives and intensifies underinvestment in expectation. This observation is similar to Proposition 1 in BM (2017). However, BM (2017) find that overinvestment relative to their benchmark may occur in some situations. The main reason for this difference is that BM (2017) compare delegated investments to contractible investments, whereas our benchmark is first-best investments.

Finally, contrary to AD (1999), Part (c) states that full profit-sharing does not solve underinvestment. Equation (8) reveals that full profit-sharing ($w_{ij} = w_{ii}$) would avoid underinvestment ($I_i = \mathrm{E}(q)$), as in AD (1999), if there were no investment/risk-link (IRL $= 0$). However, as in BM (2017), managers would underinvest due to the IRL even if full profit-sharing were applied. This result is driven by similar forces as Lemma 2 in BM (2017). In their model, a manager who has complete bargaining power (instead of equal surplus-splitting) is not efficiently incentivized due to the IRL and therefore underinvests. BM (2019) also conclude that full profit-sharing fails to deliver benchmark investments. However, as in BM (2017), their benchmark is contractible investments.

Whereas BM (2017, 2019, 2020) study the impact of the IRL for given levels of uncertainty, we analyze the consequences of variations in the uncertainty of costs and revenues in the next section. Such variations affect not only the IRL, but also the expectation and variance of the surplus and thus the objective function of the firm. As their impact is weighted by the degree of managerial risk-aversion, the optimal organizational form depends on the interaction of both uncertainty and risk-aversion.

4 | CHOICE OF ORGANIZATIONAL FORM

4.1 | Results

We now examine the firm's choice between centralization and decentralization in the presence of risk-aversion. This analysis offers new insights compared to risk-neutrality (see, e.g., Baldenius et al., 1999; Pfeiffer et al., 2011), where decentralization generally proves superior because there are no costs (in the form of risk premia) associated with capturing managers' private information. In contrast, risk-averse managers demand compensation for increasing risk, which counteracts the benefits of decentralization.

Exploiting managers' private information becomes more attractive when the uncertainty of costs and revenues $\sigma^2_{\vartheta_i}$ increases, which leads to an increase in the expected surplus $\mathrm{E}(M^d)$. In accordance with previous literature (Pfeiffer et al., 2011), we refer to this effect $\partial \mathrm{E}(M^d)/\partial \sigma^2_{\vartheta_i}$ as the "flexibility gain" (FG). However, increasing uncertainty also translates into a riskier surplus and thus to higher risk premia. We refer to this effect as "variance inflation" (VI), which is $\partial \mathrm{Var}(M^d)/\partial \sigma^2_{\vartheta_i}$ weighted by the risk premium demanded per unit of risk. In addition, increasing uncertainty also affects investment incentives $\partial \phi_i/\partial I_i = 0$. We refer to this effect as "investment/risk-link amplification" (IRLA) since it amounts to exacerbating the IRL. It is given by $\delta_1 \partial \phi_1/\left(\partial I_1 \partial \sigma^2_{\vartheta_i}\right) + \delta_2 \partial \phi_2/\left(\partial I_2 \partial \sigma^2_{\vartheta_i}\right)$, where δ_1, δ_2 denote the Lagrange multipliers on the investment incentive constraints. Both VI and IRLA are new to the literature and capture effects that occur only in the presence of risk-aversion.

These three effects give rise to a trade-off: FG has a positive impact on the firm's objective function, whereas both VI and IRLA make the provision of incentives more costly. The optimal outcome of this trade-off depends on the relative importance of these effects, which is determined by the degrees of uncertainty and managerial risk-aversion. Therefore, studying the optimality of organizational choice requires knowledge of the basic characteristics of FG, VI, and IRLA. Lemma 2 summarizes our main findings in this regard.

Lemma 2 (Marginal effects of increasing uncertainty).

(a) Under centralization, the only effect of increasing uncertainty on the firm's objective function is VI, whereas all three effects FG, VI, and IRLA emerge under decentralization.
(b) VI and IRLA are affected by managers' risk-aversion, whereas FG is not.
(c) VI under decentralization is linear in the uncertainty of costs and revenues, VI under centralization as well as FG and IRLA under decentralization are constant.
(d) FG has a positive impact on the objective function of the firm, whereas VI and IRLA have a negative impact.

Part (a) reveals that VI occurs in both organizational forms. For distinction, we use VI^c and VI^d henceforth. In both cases, the reason for VI is that the surplus depends on the random cost and revenue parameters ϑ_1, ϑ_2. The greater their uncertainty, the riskier the surplus and the higher the risk premia divisional managers demand. FG and IRLA, on the other hand, do not arise under centralization: FG captures the flexibility gain of decentralization and is not present under centralization. Moreover, under centralization, investment incentives do not depend on the uncertainty of costs and revenues such that IRLA does not arise. However, under decentralization, investments increase the variance of the surplus, leading to the IRL. Since the IRL is proportional to the uncertainty of costs and revenues (see, e.g., Equation 8), increasing uncertainty exacerbates the IRL and hence causes IRLA.

The rationale for Part (b) is straightforward: both VI and IRLA capture variance-related effects on the risk premia demanded by divisional managers. Since divisional managers are risk-averse, risk premia in our model are given by the price per unit of risk weighted by the degree of risk-aversion, that is, $\alpha_i \mathrm{Var}(w_i)/2$. More pronounced risk-aversion makes the effects of increasing uncertainty more severe. On the other hand, FG captures the impact of increasing uncertainty on the surplus of the firm. Since the firm is assumed to be risk-neutral, risk-aversion does not affect FG.

Part (c) collects statements about the curvatures of partial effects. Because trade is not risky under centralization, unit costs and revenues are the only sources of risk in the surplus. Thus, their variances are proportional to the variance of the surplus. Consequently, the effect of increasing uncertainty on the variance of the surplus, and hence on VI^c, is constant. Under decentralization, however, trade is risky. Our assumption that the price per unit decreases linearly with the quantity of units makes the surplus dependent on the square of the trade quantity. Therefore, the variance of trade quantity (and hence the uncertainty of costs and revenues) and the expected surplus are proportional, see (7). The proportionality coefficient is FG, which is thus constant. Since the surplus depends on the square of the random trade quantity, its variance is proportional to the square of the variance of the trade quantity, see again (7). Consequently, an increase of the latter leads to a linear increase of VI^d. Furthermore, Equation (24) in the Appendix reveals that the IRL is proportional to the uncertainty of costs and revenues in our model. Consequently, increasing uncertainty results in a constant IRLA.

Finally, Part (d) states that the only positive effect on the firm's objective function is FG because it captures increments in the expected surplus. In contrast, both VI^c and VI^d have negative signs as they capture the negative impact of rising risk premia. The same is true for IRLA, as it exacerbates the negative impact of the IRL on investments.

In summary, the only effect of increasing uncertainty under centralization VI^c is constant, whereas the overall effect under decentralization is $\mathrm{FG} + \mathrm{VI}^d + \mathrm{IRLA}$. The linear part of VI^d is negative and all other parts are constant, making $\mathrm{FG} + \mathrm{VI}^d + \mathrm{IRLA}$ a linear function of variance $c_1 - c_2\sigma^2_{\vartheta_i}$, where c_1 is a constant and $c_2 > 0$ is the proportionality coefficient. Details can be found in the proof of Lemma 2.

Furthermore, the signs of FG, VI, and IRLA create a trade-off: FG is positive, whereas VI and IRLA are negative. Since VI and IRLA are weighted by managerial risk-aversion, whereas

FG is not, we need to examine how both uncertainty and risk-aversion affect this trade-off and hence the choice of organizational form. Proposition 3 summarizes our findings regarding the partial influences of uncertainty and risk-aversion.

Proposition 3 (Organizational choice).

(a) For varying degrees of non-zero managerial risk-aversion and arbitrary but fixed degrees of non-zero uncertainty, decentralization is optimal for sufficiently low degrees of risk-aversion and centralization is optimal for sufficiently high degrees of risk-aversion. For zero risk-aversion, decentralization is optimal regardless of uncertainty.

(b) For varying degrees of non-zero uncertainty and arbitrary but fixed non-zero managerial risk-aversion, centralization is optimal for both sufficiently low and sufficiently high degrees of uncertainty. For zero uncertainty, centralization is optimal regardless of risk-aversion.

In Part (a) of Proposition 3, we establish the optimality of decentralization for sufficiently low degrees of risk-aversion, including risk-neutrality. The driving forces are straightforward: when risk-aversion is very low, VI and IRLA become less important, and FG is the primary effect. Then, the firm can exploit managers' private information at almost no cost (in terms of risk premia) under decentralization, while it cannot benefit from FG under centralization, which renders the latter suboptimal. In the border case of zero risk-aversion, VI and IRLA disappear, and the findings in prior literature under risk-neutrality (see, e.g., Baldenius et al., 1999; Pfeiffer et al., 2011) emerge as a special case.

For sufficiently high risk-aversion, Part (a) states that centralization is superior. As risk-aversion increases, VI and IRLA become more pronounced. These two effects are reflected in higher risk premia demanded by divisional managers. When risk-aversion is high, it is optimal for the firm to avoid risk premia by suppressing the corresponding incentives. Although this is true for both organizational forms, the measures taken differ between the two. Decentralization relies on performance evaluation to incentivize both efforts and investments. Therefore, to avoid risk premia, it is necessary to put zero weight on all divisional profits in all compensation contracts, that is, to suppress all incentives, resulting in zero efforts and investments. This is tantamount to closing the company, so that the firm can no longer benefit from FG. In contrast, centralization offers quantity budgeting as another incentive instrument. High degrees of risk-aversion, and hence prohibitive risk premia, force the firm to avoid VI by not providing incentives for operational effort. Unlike decentralization, this is not accompanied by an abandonment of investment: trade determined by the firm is not risky and can therefore still serve as an investment incentive. This makes centralization superior when the degree of risk-aversion is sufficiently high.

In summary, the findings reported in Proposition 3(a) establish the existence of critical degrees of risk-aversion at which the choice of organizational form changes: for sufficiently low degrees of risk-aversion decentralization is optimal, whereas for sufficiently high degrees of risk-aversion centralization is optimal.

Regarding Part (b), first note that centralization outperforms decentralization when there is no uncertainty of costs and revenues. Since FG, VI, and IRLA capture responses to increasing uncertainty, they do not arise in this border case. The two organizational forms then only differ in terms of investment incentives. Under centralization, divisional profits capture the full benefit of the investment, which renders pure divisional performance evaluation optimal. Consequently, there is no hold-up problem and divisional managers are only exposed to their own operational risks. However, under decentralization, the hold-up problem persists. Profit-sharing mitigates this problem, but imposes greater operational risk on divisional managers and, hence, makes it more expensive to provide incentives. Therefore, centralization outperforms

TABLE 1 Optimal organizational form for combinations of low and high risk-aversion and uncertainty.

	Uncertainty	
Risk-aversion	**Low (excl. 0)**	**High (incl. ∞)**
Low (excl. 0)	*C* or *D**	*C* or *D**
High (incl. ∞)	*C*	*C*

Note: "*C*" stands for centralization, "*D*" for decentralization. Although "low" excludes the limit case 0, "high" includes the limit case ∞. For the combinations marked with *, the optimal form of organization cannot be stated without further assumptions.

decentralization when there is no uncertainty of costs and revenues. By continuity, the same is true for sufficiently low degrees of non-zero uncertainty.

For sufficiently high degrees of uncertainty, Part (b) states that centralization is superior. Similar to the case of high risk-aversion, FG is increasingly offset by VI and IRLA as uncertainty increases. High degrees of uncertainty therefore require muted incentives (thus avoiding VI and IRLA) due to prohibitively high-risk premia. The latter are triggered by internal trade, as increasing uncertainty of costs and revenues affects the variance of the surplus. The firm must therefore refrain from incentivizing investments. Under decentralization, it needs to place zero weight on all divisional profits in all compensation contracts, which implies that effort incentives are absent, and FG disappears. In contrast, centralization provides investment incentives through quantity budgeting. To avoid the associated risk premia (and thus VI), the firm must forgo internal trade, but still provide incentives for operational effort through performance evaluation. This is tantamount to the divisions being run independently. Therefore, centralization outperforms decentralization when the degree of uncertainty of costs and revenues is sufficiently high.

Table 1 presents the joint influence of varying degrees of uncertainty and risk-aversion by considering the four possible combinations of the limit results reported in Proposition 3.

The combinations low risk-aversion/low uncertainty and low risk-aversion/high uncertainty require special attention and are therefore marked with * in Table 1. In these cases, the optimal organizational form cannot be determined without further assumptions since the influences of uncertainty and risk-aversion work in opposite directions, making the optimal organizational form depending on which effect is more pronounced. In the situation considered in the first part of Proposition 3(a), uncertainty is fixed, so the effects of risk-aversion approaching zero predominate. As a result, the firm can benefit from FG at no cost, which makes decentralization optimal. Then, "*D*" would dominate in the two marked cases of Table 1, and comparing the rows of Table 1 corresponds to the first statement in Proposition 3(a).

If, in contrast, risk-aversion is fixed, the impact of uncertainty approaching its limits predominates. Then, non-zero risk-aversion in combination with high uncertainty forces the firm to close its divisions under decentralization but to run them independently under centralization, which makes centralization optimal. Similarly, centralization dominates when uncertainty is so low that decentralization cannot overcome its drawbacks in terms of investment incentives. Then, "*C*" would dominate in the two marked cases of Table 1, and comparing the columns of Table 1 corresponds to the first statement in Proposition 3(b).

If neither uncertainty nor risk-aversion is fixed, the optimal organizational form in the cases marked with * in Table 1 depends on which of the two limits converges faster and thus has more pronounced effects. Decentralization will dominate in these cases if the effects of risk-aversion approaching zero are more pronounced than those of low/high uncertainty. Formal considerations on this issue can be found in Appendix S1. In this supplement, we also discuss the non-limit cases of varying both uncertainty and risk-aversion and demonstrate that decentralization is optimal in an intermediate range of uncertainty, provided risk-aversion is sufficiently low. The following numerical examples illustrate the different combinations.

4.2 | Numerical examples

To illustrate our results, we use numerical examples where we assume that costs and revenues are equally risky ($\sigma_{\vartheta_1}^2 = \sigma_{\vartheta_2}^2 = \sigma_{\vartheta}^2$) and that divisional managers have the same risk-aversion ($\alpha_1 = \alpha_2 = \alpha$). The calculations were performed using Taylor series expansions, since explicit solutions of the contracting problems involve polynomials of the fifth degree and higher.

Figure 3 depicts the organizational choice dependent on the uncertainty of costs and revenues σ_{ϑ}^2 and the degree of risk-aversion α under the assumptions $\beta_1 = \beta_2 = \sigma_1^2 = \sigma_2^2 = \mu = 1, b = 3$. Three different perspectives are taken: Figure 3A,B illustrates the difference in the values of the firm's objective function under decentralization and centralization $\Phi^d - \Phi^c$ for different degrees of uncertainty and risk-aversion, respectively. Here, $\Phi^d - \Phi^c > 0$ indicates the optimality of decentralization and vice versa. In addition, Figure 3C shows the corresponding indifference curve. The points on this curve represent combinations of σ_{ϑ}^2 and α when decentralization and centralization perform equally well ($\Phi^d = \Phi^c$), whereas positions below (above) indicate the optimality of decentralization (centralization).

Figure 3A illustrates the organizational choice depending on managerial risk-aversion for different degrees of uncertainty. Centralization dominates in the lower half of the diagram. All curves for different degrees of non-zero uncertainty start in the region where decentralization dominates and decrease as risk-aversion increases, corresponding to the first sentence in Proposition 3(a). The intersections with the horizontal axis reflect the critical values of risk-aversion at which centralization becomes optimal. The higher the uncertainty, the lower these critical values. Although this is true for all scenarios shown in Figure 3A, Figure 3C reveals that the opposite is true in the few cases where the uncertainty is very low (more precisely, lower than the "peaks" in Figure 3C). In the extreme case of zero uncertainty ($\sigma_{\vartheta}^2 = 0$), the corresponding line starts at the point of origin, where both organizational forms weakly dominate each other and the critical value is $\alpha = 0$. Then, centralization is optimal regardless of risk-aversion, corresponding to the second sentence in Proposition 3(b).

Figure 3B illustrates the organizational choice depending on uncertainty for different degrees of managerial risk-aversion. When risk-aversion is zero ($\alpha = 0$), decentralization is optimal regardless of uncertainty, corresponding to the second sentence in Proposition 3(a). In this case, the only effect is FG > 0. Since FG is constant, $\Phi^d - \Phi^c$ has a constant slope (see the dotted line in Figure 3B). In all other cases, the slope of $\Phi^d - \Phi^c$ is determined by the total effects of VI^c under centralization and $\mathrm{FG} + \mathrm{VI}^d + \mathrm{IRLA}$ under decentralization. Since the latter is linearly decreasing in σ_{ϑ}^2 but the former is constant (see the discussion of Lemma 2), $\Phi^d - \Phi^c$ is concave. All these curves start at negative values of $\Phi^d - \Phi^c$ and, due to their concavity, also reach negative values for sufficiently high uncertainty. Thus, for non-zero risk-aversion centralization is optimal for both sufficiently low and sufficiently high degrees of uncertainty, corresponding to the first sentence in Proposition 3(b). When risk-aversion is sufficiently high, the curves remain below the horizontal axis; that is, centralization dominates at all degrees of uncertainty (see the dashed curve with $\alpha = 0.2$). With sufficiently low risk-aversion, there are thresholds of uncertainty between which decentralization dominates and outside which centralization dominates. These are the cases discussed in Appendix S1. For the curve marked $\alpha = 0.1$ the thresholds are $\sigma_{\vartheta}^2 = 0.2798$ and $\sigma_{\vartheta}^2 = 3.6772$.

Figure 3C depicts the corresponding indifference curve in $\left(\sigma_{\vartheta}^2, \alpha\right)$-space. The thresholds are given by the intersections between this curve and parallels to the horizontal axis (e.g., at $\alpha = 0.1$). When risk-aversion is sufficiently high (higher than 0.1796 in the parametrization used here), no such thresholds exist and centralization dominates regardless of uncertainty.

In Figure 4, we vary the parametrization to analyze the sensitivity of the indifference curves to the specifications of our examples. We vary the parameters one by one, starting with the parametrization used in Figure 3. Figure 4 highlights that increasing the productivity β_1, β_2 of the division-specific efforts (see Figure 4B) and the sensitivity b of the unit price to the trade quantity (see Figure 4C)

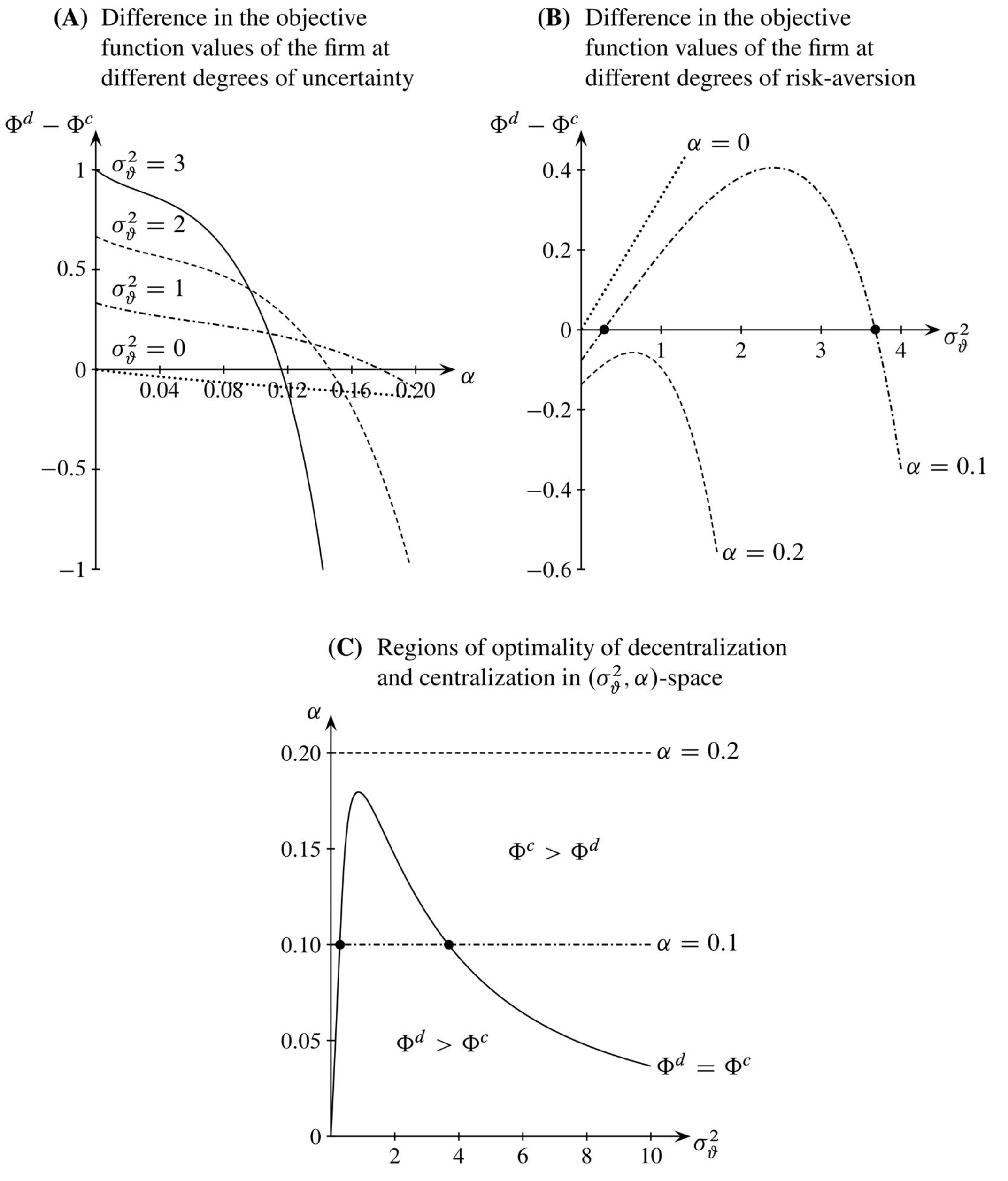


FIGURE 3 Choice of organizational form depending on the uncertainty of costs and revenues σ_ϑ^2 $(=\sigma_{\vartheta_1}^2=\sigma_{\vartheta_2}^2)$ and the degree of risk-aversion α $(=\alpha_1=\alpha_2)$ under the assumption $\beta_1=\beta_2=\sigma_1^2=\sigma_2^2=\mu=1, b=3$.

have a negative effect on the dominance of centralization: with higher productivity and sensitivity, higher degrees of uncertainty and risk-aversion are required for centralization to outperform decentralization. The opposite is true for increasing the expected effect μ in the joint surplus (see Figure 4A) and the variances σ_1^2, σ_2^2 associated with the division-specific efforts (see Figure 4D).

These indifference curves share two common features. First, they are bounded away from the horizontal axis (for non-zero risk-aversion), which implies that the region of optimality of decentralization is not empty. Second, this region has a maximum in terms of α. The maxima are given by the "peaks" of the indifference curves. When managerial risk-aversion exceeds these values, centralization dominates decentralization regardless of uncertainty.

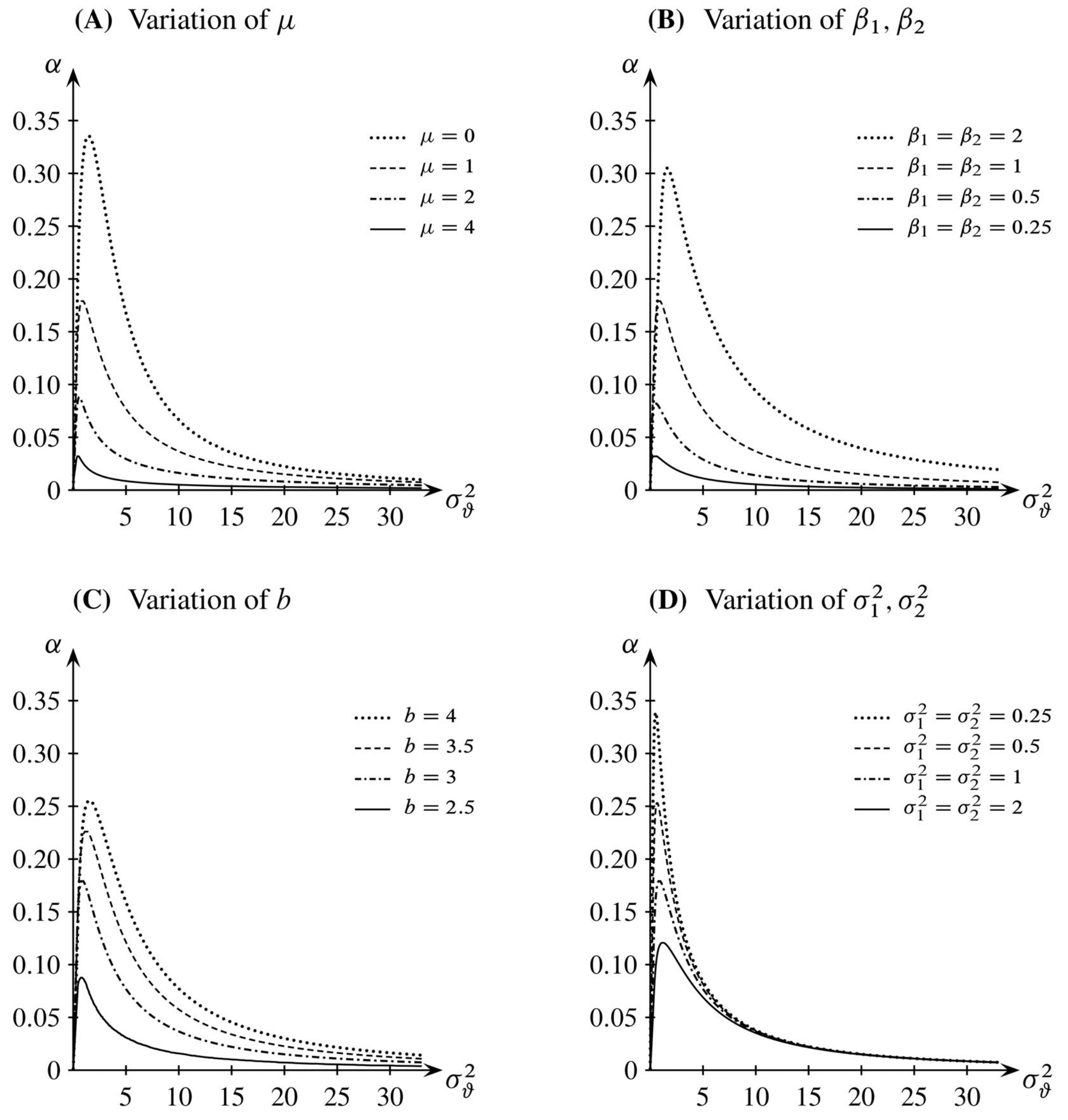


FIGURE 4 Indifference curves in $(\sigma_\vartheta^2, \alpha)$-space where decentralization and centralization perform equally well. (A) The impact of varying the expected effect μ of the unit contribution margin on the joint surplus. (B) The impact of varying the productivity β_1, β_2 of the division-specific efforts. (C) The impact of varying the sensitivity b of the unit price to the trade quantity. (D) The impact of varying the variances σ_i^2 associated with the division-specific efforts. Apart from the parameter varied in each case, the parametrization is the same as in (C) of Figure 3; that is, $\beta_1 = \beta_2 = \sigma_1^2 = \sigma_2^2 = \mu = 1, b = 3$.

Overall, our analyses reveal that centralization is the preferred organizational choice in many cases when divisional managers are risk-averse.

5 | CONCLUSION

The efficiency of different organizational forms has been the subject of many studies. So far, the literature has not considered the link between organizational form and managerial incentive structures. Most studies have found that decentralized designs dominate but have not considered variations of managerial performance evaluation such as profit-sharing. We optimize managerial performance evaluation to mitigate hold-up problems and study the relative efficiency of decentralized versus centralized organizational forms.

In contrast to prior literature (Baldenius et al., 1999; Pfeiffer et al., 2011), we find that centralization is superior in many situations. Decentralization is optimal in an intermediate range of uncertainty, provided that risk-aversion is not high, and it may be optimal for low or high uncertainty, provided that risk-aversion is low and the effects of risk-aversion approaching zero are more pronounced than those of uncertainty.

Whereas only decentralization benefits from the flexibility gain, the risk premia that need to be paid to risk-averse managers are more sensitive to increasing uncertainty under decentralization. Since the centralized form can employ quantity budgeting in addition to performance evaluation, it can react more flexibly to rising risk premia and adapt incentives more adequately to conditions of high risk-aversion and uncertainty.

These results extend recent work of BM (2017) on the link between specific investments and compensation risk by highlighting that this link also influences the choice of organizational form. The flexibility advantage of decentralization plays a key role particularly for the organization of multinational enterprises (Alonso et al., 2008; Bartlett & Ghoshal, 2002; Zhou, 2015). Our results imply that this advantage is increasingly outweighed by risk premia that need to be paid to risk-averse managers, depending on the degree of risk-aversion and the degree of uncertainty. Empirical studies may use these factors to explain the wide variety of organizational forms observable in practice (Bloom et al., 2012; Dessein et al., 2022; Van Doorn & Volberda, 2009).

In this paper, we assume mean-variance preferences and linear contracts. These are, of course, restrictive assumptions. Holmstrom and Milgrom (1987) show the optimality of linear contracts in situations that are closely related to those considered here. Furthermore, divisional managers' certainty equivalents conform with mean-variance preferences in such situations. Nevertheless, linear contracts are not optimal in general. However, nonlinear contracts are difficult to adopt and their implications for the results are not clear (Holmstrom & Milgrom, 1987), therefore extant literature largely focuses on linear contracts.

Furthermore, we assume private information to be symmetric between divisional managers to avoid an additional trade-off between trade and investment decisions. However, the properties of the decentralized arrangement depend on this assumption. In the case of asymmetric information between divisional managers, the bargaining process is subject to incomplete information of divisional managers. The inclusion of incomplete information in the analysis could provide additional insights into the interaction of managerial performance evaluation and organizational form.

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SUPPORTING INFORMATION

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APPENDIX

Proof of Lemma 1. In the first-best situation, the firm maximizes

$$M-\frac{1}{2}I_i-\frac{1}{2}I_j=\left(\vartheta+I_i+I_j-\frac{b}{2}q\right)q-\frac{1}{2}I_i^2-\frac{1}{2}I_j^2$$

with respect to q as well as I_i, I_j $(i,j=1,2, i\neq j)$. Applying backward induction, we first investigate the determination of q^{fb} at Date 3; that is, we consider Part (a). Given investment decisions as well as realized cost and revenue parameters, the firm maximizes $(\widetilde{\vartheta}+I_i+I_j-bq/2)q$ with respect to q. The first-order condition then immediately yields $q^{\mathrm{fb}}(\widetilde{\vartheta},I_i,I_j)=(\widetilde{\vartheta}+I_i+I_j)/b$. In particular, this implies $q^{\mathrm{fb}}(\widetilde{\vartheta},I_i^{\mathrm{fb}},I_j^{\mathrm{fb}})=\widehat{q}(\widetilde{\vartheta},I_i^{\mathrm{fb}},I_j^{\mathrm{fb}})$.

Let us now turn to Part (b). Ex ante, that is, when optimizing investment decisions,

$$q^{\mathrm{fb}}(\vartheta,I_i,I_j)=\frac{\vartheta+I_i+I_j}{b}$$

$(i,j=1,2,i\neq j)$ is a random variable. The same applies to the surplus

$$M^{\mathrm{fb}}=\left(bq^{\mathrm{fb}}-\frac{b}{2}q^{\mathrm{fb}}\right)q^{\mathrm{fb}}=\frac{b}{2}\left(q^{\mathrm{fb}}\right)^2.$$

The expected surplus of the risk-neutral firm is:

$$\begin{aligned}\mathrm{E}\left(M^{\mathrm{fb}}\right)&=\frac{b}{2}\mathrm{E}\left[\left(q^{\mathrm{fb}}\right)^2\right]=\frac{b}{2}\left\{\mathrm{Var}\left(q^{\mathrm{fb}}\right)+\left[\mathrm{E}\left(q^{\mathrm{fb}}\right)\right]^2\right\}\\&=\frac{b}{2}\left[\frac{\sigma^2}{b^2}+\left(\frac{\mu+I_i+I_j}{b}\right)^2\right]=\frac{1}{2b}\left[\sigma^2+\left(\mu+I_i+I_j\right)^2\right].\end{aligned}$$

The firm hence maximizes $\left[\sigma^2+\left(\mu+I_i+I_j\right)^2\right]/(2b)-I_i^2/2-I_j^2/2$ with respect to I_i and I_j $(i,j=1,2,i\neq j)$. The first-order condition

$$\frac{\mu+I_i+I_j}{b}-I_i=0\ ,$$

yields the system of linear equations

$$I_i=\frac{\mu+I_j}{b-1}\quad\text{and}\quad I_j=\frac{\mu+I_i}{b-1}\ .$$

Straightforward algebra reveals that the first-best investment decisions are given by

$$I_i^{\text{fb}}=I_j^{\text{fb}}=\frac{\mu}{b-2}\ .$$

An evaluation of $\mathrm{E}\left[q^{\text{fb}}\left(\vartheta,I_i^{\text{fb}},I_j^{\text{fb}}\right)\right]$ yields:

$$\mathrm{E}\left[q^{\text{fb}}\left(\vartheta,I_i^{\text{fb}},I_j^{\text{fb}}\right)\right]=\frac{\mu+(2\mu/b-2)}{b}=\frac{\mu}{b-2}=I_i^{\text{fb}}=I_j^{\text{fb}}\ . \tag{9}$$

This completes the proof. ■

Proof of Proposition 1. In the centralized setting, the firm's contracting problem is given by the maximization of (3) with respect to the compensation contract as well as trade quantity q, subject to $(a_i,I_i)=\underset{a_i,I_i}{\arg\max}\{\phi_i\}$ and $\phi_i\geq 0\forall i=1,2$. Considering

$$\begin{aligned}\mathrm{Var}(w_i) &= w_{ii}^2\mathrm{Var}(\pi_i)+w_{ij}^2\mathrm{Var}(\pi_j)=w_{ii}^2[\mathrm{Var}(M_i)+\mathrm{Var}(\varepsilon_i)]+w_{ij}^2\left[\mathrm{Var}(M_j)+\mathrm{Var}(\varepsilon_j)\right]\\ &= w_{ii}^2\left(q^2\sigma_{\vartheta_i}^2+\sigma_i^2\right)+w_{ij}^2\left(q^2\sigma_{\vartheta_j}^2+\sigma_j^2\right)\end{aligned}$$

$(i,j=1,2,i\neq j)$ and by applying the first-order conditions

$$\begin{aligned}\frac{\partial\phi_i}{\partial a_i} &= \frac{\partial\left(w_{ii}\beta_i a_i-(1/2)a_i^2\right)}{\partial a_i}=\beta_i w_{ii}-a_i=0\Leftrightarrow a_i=\beta_i w_{ii}\\ \frac{\partial\phi_i}{\partial I_i} &= \frac{\partial w_{ii}\left(I_i q-(1/2)I_i^2\right)}{\partial I_i}=w_{ii}(q-I_i)=0\Leftrightarrow I_i=q\end{aligned}$$

$(i=1,2)$, the firm's contracting problem can be replaced by

$$\begin{aligned}\Phi^c &= \mathrm{E}(\pi)-\frac{1}{2}a_i^2-\frac{1}{2}a_j^2-\frac{1}{2}\alpha_i\mathrm{Var}(w_i)-\frac{1}{2}\alpha_j\mathrm{Var}(w_j)\\ &= \beta_i^2 w_{ii}+\beta_j^2 w_{jj}-\frac{1}{2}\beta_i^2 w_{ii}^2-\frac{1}{2}\beta_j^2 w_{jj}^2+\mathrm{E}(M^c)-\frac{1}{2}I_i^2-\frac{1}{2}I_j^2\\ &\quad -\frac{1}{2}\alpha_i\left\{w_{ii}^2\left[\mathrm{Var}\left(M_i^c\right)+\sigma_i^2\right]+w_{ij}^2\left[\mathrm{Var}\left(M_j^c\right)+\sigma_j^2\right]\right\}\\ &\quad -\frac{1}{2}\alpha_j\left\{w_{jj}^2\left[\mathrm{Var}\left(M_j^c\right)+\sigma_j^2\right]+w_{ji}^2\left[\mathrm{Var}\left(M_i^c\right)+\sigma_i^2\right]\right\}\to\max_{w_i,q}\end{aligned}$$

subject to the investment incentive constraints $I_i-q=0$ $(i,j=1,2,i\neq j)$. M^c,M_i^c denote the joint surplus under centralization and the divisional contributions, respectively. Note that the expected surplus $\mathrm{E}(M^c) = (\mu + I_i + I_j - bq/2)q$ differs from the expected surplus under decentralization $\mathrm{E}(M^d)$ as trade quantity q is deterministic under centralization.

The corresponding Lagrangian

$$\mathscr{L}^c = \Phi^c + \delta_i \cdot (I_i - q) + \delta_j \cdot (I_j - q), \tag{10}$$

where δ_i, δ_j $(i,j = 1,2, i \neq j)$ denote the Lagrange multipliers on the investment incentive constraints, is maximized by pointwise optimization. The first-order conditions are:

$$\frac{\partial \mathscr{L}^c}{\partial w_{ii}} = \beta_i^2 (1 - w_{ii}) - \alpha_i w_{ii} \left(q^2 \sigma_{\vartheta_i}^2 + \sigma_i^2 \right) = 0, \tag{11}$$

$$\frac{\partial \mathscr{L}^c}{\partial w_{ij}} = -\alpha_i w_{ij} \left(q^2 \sigma_{\vartheta_j}^2 + \sigma_j^2 \right) = 0, \tag{12}$$

$$\frac{\partial \mathscr{L}^c}{\partial q} = \mu + I_i + I_j - bq - q\left[\alpha_i \left(w_{ii}^2 \sigma_{\vartheta_i}^2 + w_{ij}^2 \sigma_{\vartheta_j}^2 \right) + \alpha_j \left(w_{jj}^2 \sigma_{\vartheta_j}^2 + w_{ji}^2 \sigma_{\vartheta_i}^2 \right) \right] - \delta_i - \delta_j = 0, \tag{13}$$

$$\frac{\partial \mathscr{L}^c}{\partial I_i} = q - I_i + \delta_i = 0, \tag{14}$$

$$\frac{\partial \mathscr{L}^c}{\partial \delta_i} = I_i - q = 0. \tag{15}$$

We now turn to Part (a). Condition (12) implies $w_{ij}^c = 0$. To analyze the other optimal weight, (11) is solved for w_{ii}:

$$w_{ii}^c = \frac{\beta_i^2}{\beta_i^2 + \alpha_i \left(q^2 \sigma_{\vartheta_i}^2 + \sigma_i^2 \right)}. \tag{16}$$

Regarding trade quantity, (14) and (15) imply $\delta_i = 0$. In conjunction with $w_{ij}^c = 0$ and (13), trade quantity can be expressed as follows:

$$q^c\left(\mu, I_i^c, I_j^c \right) = \frac{\mu + I_i^c(q^c) + I_j^c(q^c)}{b + \alpha_i \left(w_{ii}^c \right)^2 \sigma_{\vartheta_i}^2 + \alpha_j \left(w_{jj}^c \right)^2 \sigma_{\vartheta_j}^2}. \tag{17}$$

An evaluation of (16) for the optimal trade quantity (17) yields that $w_{ii}^c > 0$.

Let us now turn to Part (b). Condition (15) reveals that investment decisions satisfy $I_i^c(q^c) = q^c$. Substituting this into (17), solving for $I_i^c(q^c)$, and taking (9) into account yields

$$I_i^c(q^c) = \frac{\mu}{b - 2 + \alpha_i \left(w_{ii}^c \right)^2 \sigma_{\vartheta_i}^2 + \alpha_j \left(w_{jj}^c \right)^2 \sigma_{\vartheta_j}^2} < \frac{\mu}{b-2} = \mathrm{E}\left[q^{\mathrm{fb}}\left(\vartheta, I_i^{\mathrm{fb}}, I_j^{\mathrm{fb}} \right) \right]$$

as long as costs and revenues are stochastic.

To prove Part (c), we first show that trade is efficient if $\sigma^2_{\vartheta_1} = \sigma^2_{\vartheta_2} = 0$. Given this assumption, $q^c(\vartheta, I_i, I_j) = \widehat{q}(\vartheta, I_i, I_j)$ follows immediately from (17). Furthermore, (15) reveals the conditional efficiency of the investment decisions even in the presence of uncertainty of costs and revenues. Therefore,

$$q^c\left(\vartheta, I_i^c, I_j^c\right) = \frac{\vartheta + I_i^c(q^c) + I_j^c(q^c)}{b} \quad \text{and} \quad I_i^c(q^c) = I_j^c(q^c) = q^c\left(\vartheta, I_i^c, I_j^c\right)$$

$(i,j = 1,2, i \neq j)$ hold true. Combining these equations results in:

$$q^c\left(\vartheta, I_i^c, I_j^c\right) = \frac{\vartheta + 2q^c\left(\vartheta, I_i^c, I_j^c\right)}{b} \Leftrightarrow q^c\left(\vartheta, I_i^c, I_j^c\right) = I_i^c(q^c) = I_j^c(q^c) = \frac{\vartheta}{b-2}. \tag{18}$$

On the other hand, the proof of Lemma 1 yields $q^{\mathrm{fb}}\left(\vartheta, I_i^{\mathrm{fb}}, I_j^{\mathrm{fb}}\right) = \vartheta/(b-2)$ since trade quantity is deterministic when $\sigma^2_{\vartheta_i} = \sigma^2_{\vartheta_j} = 0$. In conjunction with (18), one immediately arrives at:

$$q^c\left(\vartheta, I_i^c, I_j^c\right) = I_i^c(q^c) = I_j^c(q^c) = q^{fb}\left(\vartheta, I_i^{fb}, I_j^{fb}\right)$$

$(i,j = 1,2, i \neq j)$. ■

Proof of Proposition 2. In the decentralized setting, the firm's contracting problem is given by the maximization of (6) with respect to the compensation contract and subject to $q = \arg\max_q \{\phi_i\}$, $(a_i, I_i) = \arg\max_{a_i, I_i} \{\phi_i\}$ and $\phi_i \geq 0 \forall i = 1,2$. Let us first consider the decentralized trade decision $\widetilde{q}$ made at date 3. Note that divisional profits only depend on trade quantity via the realized joint surplus $\widetilde{M} = (\widetilde{\vartheta} + I_i + I_j - b\widetilde{q}/2)\widetilde{q}$ $(i,j = 1,2, i \neq j)$, which is no longer random when managers determine the trade quantity. The first-order condition regarding trade

$$\frac{\partial \phi_i}{\partial \widetilde{q}} = \frac{\partial (1/2)(w_{ii} + w_{ij})\widetilde{M}}{\partial \widetilde{q}} = -\frac{1}{2}(w_{ii} + w_{ij})\left(\widetilde{\vartheta} + I_i + I_j - b\widetilde{q}\right) = 0 \tag{19}$$

yields

$$\widetilde{q} = \frac{\widetilde{\vartheta} + I_i + I_j}{b}$$

$(i,j = 1,2, i \neq j)$ as long as $w_{ii} + w_{ij} \neq 0$. Otherwise, $\widetilde{q} = 0$ by assumption. Ex ante, that is, when the firm optimizes its objective function, q is a random variable. The same applies to the surplus $M^d = (bq - bq/2)q = bq^2/2$.

Under the assumption of risk-averse divisional managers, not only the expected values, but also the variances of q and M^d need to be evaluated. Expectation and variance of q are given by $\mathrm{E}(q) = \left(\mu + I_i + I_j\right)/b$ $(i,j = 1,2, i \neq j)$ and $\mathrm{Var}(q) = \sigma^2/b^2$. This yields:

$$\mathrm{E}\left(M^d\right) = \frac{b}{2}\mathrm{E}\left(q^2\right) = \frac{b}{2}\left\{\mathrm{Var}(q) + [\mathrm{E}(q)]^2\right\} = \frac{\sigma^2}{2b} + \frac{b}{2}[\mathrm{E}(q)]^2 \ . \tag{20}$$

To compute the variance

$$\begin{aligned}\mathrm{Var}\left(M^d\right) &= \frac{b^2}{4}\mathrm{Var}\left(q^2\right) = \frac{b^2}{4}\left\{\mathrm{E}\left(q^4\right) - \left[\mathrm{E}\left(q^2\right)\right]^2\right\} = \frac{b^2}{4}\left[\mathrm{E}\left(q^4\right) - \left\{\mathrm{Var}(q) + [\mathrm{E}(q)]^2\right\}^2\right] \\ &= \frac{b^2}{4}\left\{\mathrm{E}\left(q^4\right) - [\mathrm{E}(q)]^4 - 2[\mathrm{E}(q)]^2\frac{\sigma^2}{b^2} - \frac{\sigma^4}{b^4}\right\},\end{aligned}$$

it is necessary to evaluate

$$\begin{aligned}\mathrm{E}\left(q^4\right) &= \frac{1}{b^4}\mathrm{E}\left[\vartheta^4 + 4\vartheta^3\left(I_i + I_j\right) + 6\vartheta^2\left(I_i + I_j\right)^2 + 4\vartheta\left(I_i + I_j\right)^3 + \left(I_i + I_j\right)^4\right] \\ &= \frac{1}{b^4}\left[\mathrm{E}\left(\vartheta^4\right) + 4\mathrm{E}\left(\vartheta^3\right)\left(I_i + I_j\right) + 6\left(\mu^2 + \sigma^2\right)\left(I_i + I_j\right)^2 + 4\mu\left(I_i + I_j\right)^3 + \left(I_i + I_j\right)^4\right]\end{aligned}$$

$(i,j = 1,2, i \neq j)$ and hence the third and fourth moments of ϑ. Since the distribution of ϑ is assumed to be symmetric and mesokurtic, that is,

$$\frac{\mathrm{E}\left[(\vartheta - \mu)^3\right]}{\sigma^3} = \frac{\mathrm{E}\left[(\vartheta - \mu)^4\right]}{\sigma^4} - 3 = 0 \ ,$$

it follows that

$$\mathrm{E}\left(\vartheta^3\right) = \mu^3 + 3\mu\sigma^2 \text{ and } \mathrm{E}\left(\vartheta^4\right) = \mu^4 + 6\mu^2\sigma^2 + 3\sigma^4 \ .$$

In combination with

$$[\mathrm{E}(q)]^4 = \frac{1}{b^4}\left[\mu^4 + 4\mu^3\left(I_i + I_j\right) + 6\mu^2\left(I_i + I_j\right)^2 + 4\mu\left(I_i + I_j\right)^3 + \left(I_i + I_j\right)^4\right]$$

$(i,j = 1,2, i \neq j)$ one arrives at:

$$\begin{aligned}\mathrm{Var}\left(M^d\right) &= \frac{1}{2b^2}\left\{\sigma^4 + 3\mu^2\sigma^2 + 6\mu\sigma^2\left(I_i + I_j\right) + 3\sigma^2\left(I_i + I_j\right)^2 - [\mathrm{E}(q)]^2 b^2\sigma^2\right\} \\ &= \frac{\sigma^4}{2b^2} + \frac{\sigma^2}{2b^2}\left\{3\left(\mu + I_i + I_j\right)^2 - [\mathrm{E}(q)]^2 b^2\right\} \\ &= \frac{\sigma^4}{2b^2} + \sigma^2[\mathrm{E}(q)]^2 \ .\end{aligned} \tag{21}$$

Regarding the effort decisions of divisional managers, the first-order condition

$$\frac{\partial \phi_i}{\partial a_i} = \frac{\partial\left(w_{ii}\beta_i a_i - (1/2)a_i^2\right)}{\partial a_i} = \beta_i w_{ii} - a_i = 0 \Leftrightarrow a_i = \beta_i w_{ii} \tag{22}$$

$(i = 1, 2)$ holds. Considering

$$\begin{aligned} \mathrm{E}(w_i) &= \underline{w}_i + w_{ii}\mathrm{E}(\pi_i) + w_{ij}\mathrm{E}(\pi_j) \\ &= \underline{w}_i + w_{ii}\left(\beta_i a_i - \frac{1}{2}I_i^2\right) + w_{ij}\left(\beta_j a_j - \frac{1}{2}I_j^2\right) + \frac{1}{2}\left(w_{ii} + w_{ij}\right)\mathrm{E}\left(M^d\right) \text{ and} \\ \mathrm{Var}(w_i) &= w_{ii}^2\mathrm{Var}(\pi_i) + w_{ij}^2\mathrm{Var}(\pi_j) + 2w_{ii}w_{ij}\mathrm{Cov}(\pi_i, \pi_j) \\ &= w_{ii}^2\sigma_i^2 + w_{ij}^2\sigma_j^2 + \frac{1}{4}\left(w_{ii} + w_{ij}\right)^2\mathrm{Var}\left(M^d\right) \end{aligned} \tag{23}$$

$(i, j = 1, 2, i \neq j)$, the first-order condition with respect to the investment decisions requires:

$$\begin{aligned} \frac{\partial \phi_i}{\partial I_i} &= \frac{\partial\left[-\frac{1}{2}w_{ii}I_i^2 + \frac{1}{2}\left(w_{ii} + w_{ij}\right)\mathrm{E}\left(M^d\right) - \frac{\alpha_i}{8}\left(w_{ii} + w_{ij}\right)^2\mathrm{Var}\left(M^d\right)\right]}{\partial I_i} \\ &= \frac{w_{ii} + w_{ij}}{2} \cdot \frac{\partial \mathrm{E}\left(M^d\right)}{\partial I_i} - \frac{\alpha_i\left(w_{ii} + w_{ij}\right)^2}{8} \cdot \frac{\partial \mathrm{Var}\left(M^d\right)}{\partial I_i} - w_{ii}I_i = 0 . \end{aligned}$$

Since

$$\frac{\partial \mathrm{E}\left(M^d\right)}{\partial I_i} = \frac{b}{2} \cdot 2\mathrm{E}(q) \cdot \frac{\partial \mathrm{E}(q)}{\partial I_i} = \mathrm{E}(q)$$

and

$$\frac{\partial \mathrm{Var}\left(M^d\right)}{\partial I_i} = 2\mathrm{E}(q) \cdot \frac{\partial \mathrm{E}(q)}{\partial I_i} \cdot \sigma^2 = \frac{2\sigma^2}{b} \cdot \mathrm{E}(q) , \tag{24}$$

it follows that

$$\frac{\partial \phi_i}{\partial I_i} = \frac{w_{ii} + w_{ij}}{2} \cdot \left[1 - \frac{\alpha_i\left(w_{ii} + w_{ij}\right)\sigma^2}{2b}\right] \cdot \mathrm{E}(q) - w_{ii}I_i = 0 \tag{25}$$

$(i, j = 1, 2, i \neq j)$. Considering (22) and (23), the firm's contracting problem can be replaced by

$$\begin{aligned} \Phi^d &= \mathrm{E}(\pi) - \frac{1}{2}a_i^2 - \frac{1}{2}a_j^2 - \frac{1}{2}\alpha_i\mathrm{Var}(w_i) - \frac{1}{2}\alpha_j\mathrm{Var}(w_j) \\ &= \beta_i^2 w_{ii} + \beta_j^2 w_{jj} - \frac{1}{2}\beta_i^2 w_{ii}^2 - \frac{1}{2}\beta_j^2 w_{jj}^2 + \mathrm{E}\left(M^d\right) - \frac{1}{2}I_i^2 - \frac{1}{2}I_j^2 \\ &\quad - \frac{1}{2}\alpha_i\left(w_{ii}^2\sigma_i^2 + w_{ij}^2\sigma_j^2\right) - \frac{1}{2}\alpha_j\left(w_{jj}^2\sigma_j^2 + w_{ji}^2\sigma_i^2\right) \\ &\quad - \frac{1}{8}\left[\alpha_i\left(w_{ii} + w_{ij}\right)^2 + \alpha_j\left(w_{jj} + w_{ji}\right)^2\right]\mathrm{Var}\left(M^d\right) \rightarrow \max_{w_i} \end{aligned}$$

$(i,j=1,2,i\neq j)$ subject to the investment incentive constraints (25). The corresponding Lagrangian

$$\begin{aligned}\mathscr{L}^d = \Phi^d &+ \delta_i \cdot \left\{\frac{w_{ii}+w_{ij}}{2}\cdot\left[1-\frac{\alpha_i\left(w_{ii}+w_{ij}\right)\sigma^2}{2b}\right]\cdot \mathrm{E}(q) - w_{ii}I_i\right\} \\ &+\delta_j \cdot \left\{\frac{w_{jj}+w_{ji}}{2}\cdot\left[1-\frac{\alpha_j\left(w_{jj}+w_{ji}\right)\sigma^2}{2b}\right]\cdot \mathrm{E}(q) - w_{jj}I_j\right\}\,,\end{aligned} \tag{26}$$

where δ_i, δ_j $(i,j=1,2,i\neq j)$ denote the Lagrange multipliers on the investment incentive constraints, is maximized by pointwise optimization. The first-order conditions are:

$$\begin{aligned}\frac{\partial \mathscr{L}^d}{\partial w_{ii}} &= \beta_i^2(1-w_{ii}) - \alpha_i w_{ii}\sigma_i^2 - \frac{\alpha_i\left(w_{ii}+w_{ij}\right)}{4}\mathrm{Var}\left(M^d\right) + \delta_i\left[\frac{1}{2}-\frac{\alpha_i\left(w_{ii}+w_{ij}\right)\sigma^2}{2b}\right]\cdot \mathrm{E}(q), \\ &-\delta_i I_i = 0,\end{aligned} \tag{27}$$

$$\frac{\partial \mathscr{L}^d}{\partial w_{ij}} = -\alpha_i w_{ij}\sigma_j^2 - \frac{\alpha_i\left(w_{ii}+w_{ij}\right)}{4}\mathrm{Var}\left(M^d\right) + \delta_i\left[\frac{1}{2}-\frac{\alpha_i\left(w_{ii}+w_{ij}\right)\sigma^2}{2b}\right]\cdot \mathrm{E}(q) = 0, \tag{28}$$

$$\begin{aligned}\frac{\partial \mathscr{L}^d}{\partial I_i} &= \mathrm{E}(q) - I_i - \frac{1}{8}\left[\alpha_i\left(w_{ii}+w_{ij}\right)^2 + \alpha_j\left(w_{jj}+w_{ji}\right)^2\right]\cdot\frac{2\sigma^2}{b}\mathrm{E}(q) \\ &+\delta_i\left\{\frac{w_{ii}+w_{ij}}{2b}\cdot\left[1-\frac{\alpha_i\left(w_{ii}+w_{ij}\right)\sigma^2}{2b}\right] - w_{ii}\right\} + \delta_j\left\{\frac{w_{jj}+w_{ji}}{2b}\cdot\left[1-\frac{\alpha_j\left(w_{jj}+w_{ji}\right)\sigma^2}{2b}\right]\right\} = 0,\end{aligned} \tag{29}$$

$$\frac{\partial \mathscr{L}^d}{\partial \delta_i} = \frac{w_{ii}+w_{ij}}{2}\cdot\left[1-\frac{\alpha_i\left(w_{ii}+w_{ij}\right)\sigma^2}{2b}\right]\cdot \mathrm{E}(q) - w_{ii}I_i = 0. \tag{30}$$

We now turn to Proposition 2(a). Conditions (27) and (28) require

$$\beta_i^2(1-w_{ii}) - \alpha_i\left(w_{ii}\sigma_i^2 - w_{ij}\sigma_j^2\right) - \delta_i I_i = 0, \tag{31}$$

which is equivalent to

$$w_{ij} = \frac{\delta_i I_i - \beta_i^2 + \left(\beta_i^2 + \alpha_i\sigma_i^2\right)w_{ii}}{\alpha_i\sigma_j^2}$$

$(i,j=1,2,i\neq j)$. From that it follows that $0\neq w_{ij}^d\neq w_{ii}^d$ in general. Hence, neither pure divisional performance evaluation nor full profit-sharing are optimal under decentralization.

Let us now turn to Part (b). Regarding trade, recall that $q=\left(\vartheta+I_i+I_j\right)/b$ $(i,j=1,2,i\neq j)$ was observed at the outset of this proof. Hence, it follows that $q^d(\widetilde{\vartheta},I_i,I_j)=\widehat{q}(\widetilde{\vartheta},I_i,I_j)$. Regarding investment decisions, solving (30) for I_i yields:

$$I_i = \frac{w_{ii}+w_{ij}}{2w_{ii}}\cdot\left[1-\frac{\alpha_i\left(w_{ii}+w_{ij}\right)\sigma^2}{2b}\right]\cdot \mathrm{E}(q)\,. \tag{32}$$

Decentralized investment decisions are lower than the expected efficient level $\mathrm{E}(q)$ for two reasons. First, $w_{ij} < w_{ii}$ as full profit-sharing is not optimal. Second, the term in square brackets is less than one due to the IRL.

Substituting $\mathrm{E}(q) = (\mu + I_i + I_j)/b$ into (32) and solving for investments yields:

$$I_i^d = \frac{\mu\gamma_i}{b - 2\gamma_i}\ ,\ \text{where } \gamma_i = \frac{(w_{ii})^d + (w_{ij})^d}{2(w_{ii})^d} \cdot \left\{1 - \frac{\alpha_i\left[(w_{ii})^d + (w_{ij})^d\right]\sigma^2}{2b}\right\} < 1 \tag{33}$$

$(i,j = 1,2, i \neq j)$. Note that manager i only invests when $\gamma_i > 0$. Then, comparing (9) and (33) immediately reveals $I_i^d < \mathrm{E}[q^{\mathrm{fb}}(\vartheta, I_i^{\mathrm{fb}}, I_j^{\mathrm{fb}})]$.

To prove Part (c) it suffices to observe that the latter finding persists under full profit-sharing. Assuming $w_{ij}^d = w_{ii}^d$ $(i,j = 1,2, i \neq j)$, one obtains $\gamma_i = 1 - \alpha_i(w_{ii})^d\sigma^2/b < 1$ $(i = 1,2)$ and hence $I_i^{\mathrm{d}} = \mu\gamma_i/(b - 2\gamma_i) < \mu/(b-2) = \mathrm{E}[q^{\mathrm{fb}}(\vartheta, I_i^{\mathrm{fb}}, I_j^{\mathrm{fb}})]$ $(i,j = 1,2, i \neq j)$. ■

Proof of Lemma 2. We evaluate the marginal effects of increasing uncertainty by computing the partial derivatives of the Lagrangians $\mathscr{L}^c$ and $\mathscr{L}^d$ with respect to $\sigma_{\vartheta_i}^2$ $(i = 1,2)$ using the Envelope Theorem (see, e.g., Mas-Colell et al., 1995).

First consider the case of centralization. Taking $w_{ij}^c = 0$ into account, the partial derivative of (10) with respect to $\sigma_{\vartheta_i}^2$ can be determined as follows:

$$\frac{\partial \mathscr{L}^c}{\partial \sigma_{\vartheta_i}^2} = \underbrace{-\frac{\alpha_i\left(w_{ii}^c\right)^2}{2} \cdot \frac{\partial \mathrm{Var}\left(M_i^c\right)}{\partial \sigma_{\vartheta_i}^2}}_{\mathrm{VI}^c}. \tag{34}$$

This effect is VI under centralization.

Next consider the case of decentralization. Note that (26) depends on $\sigma_{\vartheta_i}^2$ $(i = 1,2)$ only via $\sigma^2 = \sigma_{\vartheta_i}^2 + \sigma_{\vartheta_j}^2$. As

$$\frac{\partial \mathscr{L}^d}{\partial \sigma_{\vartheta_i}^2} = \frac{\partial \mathscr{L}^d}{\partial \sigma^2} \cdot \frac{\partial \sigma^2}{\partial \sigma_{\vartheta_i}^2} = \frac{\partial \mathscr{L}^d}{\partial \sigma^2}\ ,$$

the partial derivative of (26) with respect to $\sigma_{\vartheta_i}^2$ is given by:

$$\begin{aligned} \frac{\partial \mathscr{L}^d}{\partial \sigma_{\vartheta_i}^2} &= \underbrace{\frac{\partial \mathrm{E}\left(M^d\right)}{\partial \sigma_{\vartheta_i}^2}}_{\mathrm{FG}} \underbrace{- \frac{\alpha_i\left(w_{ii}^d + w_{ij}^d\right)^2 + \alpha_j\left(w_{jj}^d + w_{ji}^d\right)^2}{8} \cdot \frac{\partial \mathrm{Var}\left(M^d\right)}{\partial \sigma_{\vartheta_i}^2}}_{\mathrm{VI}^d} \\ &= \underbrace{-\frac{\delta_i\alpha_i\left(w_{ii}^d + w_{ij}^d\right)^2 + \delta_j\alpha_j\left(w_{jj}^d + w_{ji}^d\right)^2}{4b} \cdot \mathrm{E}\left(q^d\right)}_{\mathrm{IRLA}} \end{aligned} \tag{35}$$

$(i,j = 1,2, i \neq j)$, where VI^d denotes VI under decentralization.

Let us now turn to Part (a). Equation (34) reveals that the only effect under centralization is VI^c, whereas (35) shows that FG, VI^d, and IRLA emerge under decentralization.

Regarding Part (b), Equations (34) and (35) immediately reveal that VI^c, VI^d, and IRLA are weighted with α_i $(i = 1, 2)$. With respect to FG, (20) implies

$$\frac{\partial \mathrm{E}\left(M^d\right)}{\partial \sigma^2_{\vartheta_i}} = \frac{1}{2b} \ , \tag{36}$$

which is not weighted with α_i.

Part (c) addresses the curvature of the effects. Regarding VI^c, observe that $\mathrm{Var}\left(M_i^c\right)$ is given by $[q^c(\mu, I_i^c, I_j^c)]^2 \sigma^2_{\vartheta_i}$. Together with (34), this implies

$$\frac{\partial \mathscr{L}^c}{\partial \sigma^2_{\vartheta_i}} = -\frac{\alpha_i \left[w_{ii}^c q^c\left(\mu, I_i^c, I_j^c\right)\right]^2}{2} \ , \tag{37}$$

which does not depend on $\sigma^2_{\vartheta_i}$ and, hence, is constant. Regarding decentralization, (36) immediately reveals that FG is constant, too. In contrast to that, (21) implies

$$\frac{\partial \mathrm{Var}\left(M^d\right)}{\partial \sigma^2_{\vartheta_i}} = \frac{\sigma^2_{\vartheta_i} + \sigma^2_{\vartheta_j}}{b^2} + \left[\mathrm{E}\left(q^d\right)\right]^2 \ , \tag{38}$$

indicating that VI^d is linear in $\sigma^2_{\vartheta_i}$. The last term in (35) corresponds to IRLA. It does not depend on $\sigma^2_{\vartheta_i}$ and, hence, is constant.

With respect to Part (d), equation (37) immediately reveals that VI^c is negative and (36) shows that FG has a positive sign. Furthermore, (35) in conjunction with (38) implies that VI^d is negative. Finally, IRLA < 0 immediately follows from (35).

In summary, the only effect under centralization VI^c is a negative constant, such that $\mathscr{L}^c$ is linearly decreasing in $\sigma^2_{\vartheta_i}$. On the other hand, the three effects under decentralization together make (35) linearly decreasing in $\sigma^2_{\vartheta_i}$. Thus, $\mathscr{L}^d$ is concave in $\sigma^2_{\vartheta_i}$. Its slope is a function of the type

$$\frac{\partial \mathscr{L}^d}{\partial \sigma^2_{\vartheta_i}} = c_1 - c_2 \sigma^2_{\vartheta_i} \ ,$$

where

$$c_1 = \frac{1}{2b} - \frac{\alpha_i \left(w_{ii}^d + w_{ij}^d\right)^2 + \alpha_j \left(w_{jj}^d + w_{ji}^d\right)^2}{8} \cdot \left\{ \frac{\sigma^2_{\vartheta_j}}{b^2} + \left[\mathrm{E}\left(q^d\right)\right]^2 \right\}$$
$$- \frac{\delta_i \alpha_i \left(w_{ii}^d + w_{ij}^d\right)^2 + \delta_j \alpha_j \left(w_{jj}^d + w_{ji}^d\right)^2}{4b} \cdot \mathrm{E}\left(q^d\right)$$

and

$$c_2 = \frac{\alpha_i \left(w_{ii}^d + w_{ij}^d\right)^2 + \alpha_j \left(w_{jj}^d + w_{ji}^d\right)^2}{8b^2}$$

$(i,j=1,2,i\neq j)$. Although c_2 is unambiguously positive, the sign of c_1 depends on the interplay of the various parameters. However, $c_1>0$ proves true provided sufficiently low degrees of managerial risk-aversion. The proof of Proposition 3(a) reveals that $\delta_i,\delta_j\to 0, w_{ii}^d, w_{ij}^d\to 1$ and $\mathrm{E}(q^d)\to\mu/(b-2)$ in the limit case $\alpha_i\to 0\forall i=1,2$. Then,

$$\lim_{\substack{\alpha_i\to 0\\ \alpha_j\to 0}} c_1=\frac{1}{2b}>0$$

$(i,j=1,2,i\neq j)$. By continuity, the same applies for sufficiently low degrees of risk-aversion.

If, in addition to that, uncertainty is sufficiently low, $c_2\sigma_{\vartheta_i}^2$ will be lower than c_1, making $\mathscr{L}^d$ increasing in $\sigma_{\vartheta_i}^2$. However, sufficiently high levels of $\sigma_{\vartheta_i}^2$ (namely $\sigma_{\vartheta_i}^2>c_1/c_2$) make the slope negative and hence $\mathscr{L}^d$ decreasing in $\sigma_{\vartheta_i}^2$. ■

Proof of Proposition 3. First, we simplify the Lagrangian under centralization $\mathscr{L}^c$ taking the properties $w_{ij}^c=w_{ji}^c=0$ and $I_i^c=I_j^c=q^c$ $(i,j=1,2,i\neq j)$ of the optimal contract into account. These properties together with $\mathrm{E}(M^c)=(\mu+I_i^c+I_j^c-bq^c/2)q^c$ and $\mathrm{Var}(M_i^c)=(q^c)^2\sigma_{\vartheta_i}^2$ imply

$$\begin{aligned}\mathscr{L}^c=\beta_i^2w_{ii}^c+\beta_j^2w_{jj}^c-\frac{1}{2}\beta_i^2\left(w_{ii}^c\right)^2-\frac{1}{2}\beta_j^2\left(w_{jj}^c\right)^2+\mu q^c-\frac{1}{2}(b-2)(q^c)^2\\ -\frac{1}{2}\alpha_i\left(w_{ii}^c\right)^2\left(q^2\sigma_{\vartheta_i}^2+\sigma_i^2\right)-\frac{1}{2}\alpha_j\left(w_{jj}^c\right)^2\left(q^2\sigma_{\vartheta_j}^2+\sigma_j^2\right)\end{aligned}$$

$(i,j=1,2,i\neq j)$ in the optimum. Furthermore, substituting (16) yields

$$\begin{aligned}\beta_i^2w_{ii}^c-\frac{1}{2}\beta_i^2\left(w_{ii}^c\right)^2-\frac{1}{2}\alpha_i\left(w_{ii}^c\right)^2\left(q^2\sigma_{\vartheta_i}^2+\sigma_i^2\right)&=\beta_i^2w_{ii}^c-\frac{1}{2}\left[\beta_i^2+\alpha_i\left(q^2\sigma_{\vartheta_i}^2+\sigma_i^2\right)\right]\left(w_{ii}^c\right)^2\\ &=\beta_i^2w_{ii}^c-\frac{1}{2}\beta_i^2w_{ii}^c=\frac{1}{2}\beta_i^2w_{ii}^c,\end{aligned}$$

$(i=1,2)$ and hence

$$\mathscr{L}^c=\frac{1}{2}\beta_i^2w_{ii}^c+\frac{1}{2}\beta_j^2w_{jj}^c+\mu q^c-\frac{1}{2}(b-2)(q^c)^2 \tag{39}$$

$(i,j=1,2,i\neq j)$. Regarding trade, note that (17) and $I_i^c=q^c$ $(i=1,2)$ imply

$$q^c=\frac{\mu}{b-2+\alpha_i\left(w_{ii}^c\right)^2\sigma_{\vartheta_i}^2+\alpha_j\left(w_{jj}^c\right)^2\sigma_{\vartheta_j}^2} \tag{40}$$

$(i,j=1,2,i\neq j)$. We now prove Part (a). Regarding the case of low degrees of risk-aversion (including risk-neutrality and hence the second sentence in this part), we evaluate the limits when risk-aversion approaches zero; that is $\alpha_i\to 0$ $\forall i=1,2$, for given degrees of uncertainty. Under centralization, (11) yields $w_{ii}^c\to 1$ $\forall i=1,2$ and (40) reveals $q^c\to\mu/(b-2)$. Using these results, (39) yields:

$$\lim_{\substack{\alpha_i \to 0 \\ \alpha_j \to 0}} \mathscr{L}^c = \frac{1}{2}\left(\beta_i^2 + \beta_j^2 + \frac{\mu^2}{b-2}\right) \tag{41}$$

$(i,j = 1,2, i \neq j)$. Since VI^c is weighted with α_i, see (34), $\alpha_i \to 0$ implies $\mathrm{VI}^c \to 0$. That is why VI^c does not appear in (41).

Regarding decentralization, the corresponding Lagrangian (26) approaches

$$\begin{aligned} &\beta_i^2 w_{ii} + \beta_j^2 w_{jj} - \frac{1}{2}\beta_i^2 w_{ii}^2 - \frac{1}{2}\beta_j^2 w_{jj}^2 + \mathrm{E}\left(M^d\right) - \frac{1}{2}I_i^2 - \frac{1}{2}I_j^2 \\ &\quad + \delta_i \cdot \left(\frac{w_{ii}+w_{ij}}{2} \cdot \mathrm{E}(q) - w_{ii}I_i\right) + \delta_j \cdot \left(\frac{w_{jj}+w_{ji}}{2} \cdot \mathrm{E}(q) - w_{jj}I_j\right) \end{aligned} \tag{42}$$

$(i,j = 1,2, i \neq j)$. Furthermore, $\alpha_i \to 0 \ \forall i = 1,2$ in conjunction with condition (28) requires $\delta_i, \delta_j \to 0$. Then, (27) yields $w_{ii}^d \to 1 \ \forall i = 1,2$. Additionally, (29) reveals $I_i^d, I_j^d \to \mathrm{E}[\widehat{q}(\vartheta, I_i^d, I_j^d)]$ $(i,j = 1,2, i \neq j)$, which in turn implies full profit-sharing $(w_{ij}^d \to 1, i,j = 1,2, i \neq j)$, see (30). Finally, $I_i^d, I_j^d \to \mathrm{E}[\widehat{q}(\vartheta, I_i^d, I_j^d)]$ implies $I_i^d, I_j^d, \mathrm{E}[\widehat{q}(\vartheta, I_i^d, I_j^d)] \to \mu/(b-2)$. Substituting these findings and $\mathrm{E}(M^d) = \sigma^2/(2b) + \{\mathrm{E}[\widehat{q}(\vartheta, I_i^d, I_j^d)]\}^2 b/2 \to \sigma^2/(2b) + b\mu^2/[2(b-2)^2]$ $(i,j = 1,2, i \neq j)$ into (42) yields:

$$\lim_{\substack{\alpha_i \to 0 \\ \alpha_j \to 0}} \mathscr{L}^d = \frac{1}{2}\left(\beta_i^2 + \beta_j^2 + \frac{\mu^2}{b-2} + \frac{\sigma^2}{b}\right) \tag{43}$$

$(i,j = 1,2, i \neq j)$. Note that the derivative of the last term in (43) with respect to $\sigma_{\vartheta_i}^2$ is given by $1/(2b)$. This is the FG of decentralization, see (36). In contrast to that, VI^d and IRLA do not appear in (43) as both effects are weighted with α_i, see (35), and hence disappear in the limit case $\alpha_i \to 0 \ \forall i = 1,2$.

Comparing the limits (41) and (43) immediately results in

$$\lim_{\substack{\alpha_i \to 0 \\ \alpha_j \to 0}} \left(\mathscr{L}^d - \mathscr{L}^c\right) = \frac{\sigma^2}{2b} > 0 \tag{44}$$

$(i,j = 1,2, i \neq j)$ and, hence, the optimality of decentralization (regardless of the level at which uncertainty is fixed) when risk-aversion approaches zero. By continuity, the same applies for sufficiently low degrees of risk-aversion given any arbitrary but fixed degree of uncertainty.

Proposition 3(a) also deals with the case of high degrees of risk-aversion. For this case, we evaluate the limits when risk-aversion approaches infinity, that is $\alpha_i \to \infty$ $\forall i = 1,2$, for given degrees of uncertainty. Regarding centralization, note that (16) then implies $w_{ii}^c \to 0 \forall i = 1,2$. Since VI^c is weighted with $\left(w_{ii}^c\right)^2$, see (34), $w_{ii}^c \to 0$ prevents VI under decentralization; that is, $\mathrm{VI}^c \to 0$. Furthermore, $w_{ii}^c \to 0 \forall i = 1,2$ in combination with (39) implies $\mathscr{L}^c \to \mu q^c - (b-2)(q^c)^2/2$. To evaluate the limit value of q^c, we examine the limit value of $\alpha_i\left(w_{ii}^c\right)^2$. L'Hôspital's rule yields

$$\lim_{\alpha_i \to \infty} \alpha_i \left(w_{ii}^c\right)^2 = \lim_{\alpha_i \to \infty} \frac{\alpha_i \beta_i^4}{\left[\beta_i^2 + \alpha_i \left(q^2 \sigma_{\vartheta_i}^2 + \sigma_i^2\right)\right]^2}$$
$$= \lim_{\alpha_i \to \infty} \frac{\beta_i^4}{2\left[\beta_i^2 + \alpha_i \left(q^2 \sigma_{\vartheta_i}^2 + \sigma_i^2\right)\right]\left(q^2 \sigma_{\vartheta_i}^2 + \sigma_i^2\right)} = 0$$

$(i = 1, 2)$. Thus, (40) reveals $q^c \to \mu/(b-2)$ and (39) approaches the limit value

$$\lim_{\substack{\alpha_i \to \infty \\ \alpha_j \to \infty}} \mathscr{L}^c = \frac{\mu^2}{2(b-2)} \tag{45}$$

$(i,j = 1, 2, i \neq j)$.

Regarding decentralization, note that condition (31) requires $w_{ii}^d, w_{ij}^d \to 0$ when $\alpha_i \to \infty$ $(i,j = 1, 2, i \neq j)$. This, in turn, ensures $\text{VI}^d \to 0$ as well as IRLA $\to 0$ since both effects are weighted with w_{ii}^d and w_{ij}^d, see (35). The Lagrangian (26) now approaches $\text{E}\left(M^d\right) - \left(I_i^d\right)^2/2 - \left(I_j^d\right)^2/2$. Further note that condition (29) requires $I_i^d \to \text{E}\left(q^d\right)$ $(i = 1, 2)$, whereby trade approaches zero since no incentives are provided in this limit case. This in turn implies $\text{E}\left(M^d\right) \to 0$, which causes FG $\to 0$. Put together, it follows that

$$\lim_{\substack{\alpha_i \to \infty \\ \alpha_j \to \infty}} \mathscr{L}^d = 0 \tag{46}$$

$(i,j = 1, 2, i \neq j)$.

Combining (45) and (46) results in

$$\lim_{\substack{\alpha_i \to \infty \\ \alpha_j \to \infty}} \left(\mathscr{L}^d - \mathscr{L}^c\right) = -\frac{\mu^2}{2(b-2)} < 0 \tag{47}$$

$(i,j = 1, 2, i \neq j)$ and, hence, the optimality of centralization when risk-aversion approaches infinity. By continuity, the same applies for sufficiently high degrees of risk-aversion.

To prove Part (b), we verify the superiority of centralization for low and high degrees of uncertainty assuming non-zero risk-aversion, that is $\alpha_i > 0\ \forall i = 1, 2$. First consider the limit case when the uncertainty of costs and revenues approaches zero (corresponding to the second sentence in Part (b)), that is $\sigma_{\vartheta_i}^2 \to 0 \forall i = 1, 2$, for given degrees of risk-aversion. Under centralization, (16) yields $w_{ii}^c \to \beta_i^2/\left(\beta_i^2 + \alpha_i \sigma_i^2\right)\ \forall i = 1, 2$ and (40) reveals $q^c \to \mu/(b-2)$. Due to

$$\mu q^c - \frac{1}{2}(b-2)(q^c)^2 \to \frac{1}{2} \cdot \frac{\mu^2}{b-2},$$

(39) approaches the limit value

$$\lim_{\substack{\sigma_{\vartheta_i}^2 \to 0 \\ \sigma_{\vartheta_j}^2 \to 0}} \mathscr{L}^c = \frac{1}{2}\left(\frac{\beta_i^4}{\beta_i^2 + \alpha_i\sigma_i^2} + \frac{\beta_j^4}{\beta_j^2 + \alpha_j\sigma_j^2} + \frac{\mu^2}{b-2}\right) \tag{48}$$

$(i,j = 1,2, i \neq j)$. Since $\mathrm{Var}\left(M_i^c\right)$ is given by $\left[q^c\left(\mu, I_i^c, I_j^c\right)\right]^2 \sigma_{\vartheta_i}^2$, $\mathrm{Var}\left(M_i^c\right) \to 0$ also applies. This, in turn, ensures $\mathrm{VI}^c \to 0$, see (34).

Under decentralization, (27) and (28) in conjunction with $\sigma_{\vartheta_1}^2, \sigma_{\vartheta_2}^2 \to 0 \Rightarrow \sigma^2 \to 0 \Rightarrow \mathrm{Var}\left(M^d\right) \to 0$ yield

$$w_{ii}^d \to \frac{\beta_i^2 + \delta_i\left(\frac{1}{2}\widehat{q} - I_i^d\right)}{\beta_i^2 + \alpha_i\sigma_i^2} \text{ and } w_{ij}^d \to \frac{\delta_i \widehat{q}}{2\alpha_i\sigma_j^2} \tag{49}$$

$(i,j = 1,2, i \neq j)$, where $\widehat{q}$ is a shortcut for $\widehat{q}\left(\vartheta, I_i^d, I_j^d\right)$, that is, the trade quantity that is not only efficient, but also deterministic in the case considered here. Furthermore, $\mathrm{Var}\left(M^d\right) \to 0$ ensures $\mathrm{VI}^d \to 0$. In addition to that, $\mathrm{Var}\left(M^d\right) \to 0$ prevents the IRL and, hence, causes IRLA $\to 0$.

The limit weights (49) on the performance measures imply

$$\beta_i^2 w_{ii}^d - \frac{1}{2}\beta_i^2\left(w_{ii}^d\right)^2 - \frac{1}{2}\alpha_i\left(w_{ii}^d\right)^2\sigma_i^2 = \left[\beta_i^2 - \frac{1}{2}\left(\beta_i^2 + \alpha_i\sigma_i^2\right)w_{ii}^d\right]w_{ii}^d$$
$$\to \frac{\left[\beta_i^2 - \delta_i\left(\frac{1}{2}\widehat{q} - I_i^d\right)\right] \cdot \left[\beta_i^2 + \delta_i\left(\frac{1}{2}\widehat{q} - I_i^d\right)\right]}{2\left(\beta_i^2 + \alpha_i\sigma_i^2\right)} = \frac{\beta_i^4 - \delta_i^2\left(\frac{1}{2}\widehat{q} - I_i^d\right)^2}{2\left(\beta_i^2 + \alpha_i\sigma_i^2\right)}$$

and

$$-\frac{1}{2}\alpha_i\left(w_{ij}^d\right)^2\sigma_j^2 \to -\frac{\delta_i^2\widehat{q}^2}{8\alpha_i\sigma_j^2}$$

$(i,j = 1,2, i \neq j)$. As the expected surplus net of investment costs cannot exceed the respective first-best value, the upper bound

$$\mathrm{E}\left(M^d\right) - \frac{1}{2}\left(I_i^d\right)^2 - \frac{1}{2}\left(I_j^d\right)^2 \leq \mathrm{E}\left(M^{\mathrm{fb}}\right) - \frac{1}{2}\left(I_i^{\mathrm{fb}}\right)^2 - \frac{1}{2}\left(I_j^{\mathrm{fb}}\right)^2$$
$$= \frac{\left(\mu + I_i^{\mathrm{fb}} + I_j^{\mathrm{fb}}\right)^2}{2b} - \frac{1}{2}\left(I_i^{\mathrm{fb}}\right)^2 - \frac{1}{2}\left(I_j^{\mathrm{fb}}\right)^2$$
$$= \frac{[\mu + 2\mu/(b-2)]^2}{2b} - \left(\frac{\mu}{b-2}\right)^2 = \frac{\mu^2}{2(b-2)}$$

$(i,j = 1,2, i \neq j)$ applies. Put together, the following upper bound regarding the optimal value of (26) results:

$$1 \lim_{\substack{\sigma^2_{\vartheta_i}\to 0\\ \sigma^2_{\vartheta_j}\to 0}} \mathscr{L}^d \leq \frac{1}{2}\left[\frac{\beta_i^4-\delta_i^2\left(\frac{1}{2}\widehat{q}-I_i^d\right)^2}{\beta_i^2+\alpha_i\sigma_i^2}+\frac{\beta_j^4-\delta_j^2\left(\frac{1}{2}\widehat{q}-I_j^d\right)^2}{\beta_j^2+\alpha_j\sigma_j^2}+\frac{\mu^2}{b-2}-\frac{\delta_i^2\widehat{q}^2}{4\alpha_i\sigma_j^2}-\frac{\delta_j^2\widehat{q}^2}{4\alpha_j\sigma_i^2}\right] \tag{50}$$

$(i,j=1,2,i\neq j)$. In contrast to (43), no term $\sigma^2/(2b)$ and, hence, no FG is present in (50). This is because $\sigma^2_{\vartheta_1},\sigma^2_{\vartheta_2}\to 0$ implies $\sigma^2\to 0$.

Combining (48) and (50) yields:

$$\lim_{\substack{\sigma^2_{\vartheta_i}\to 0\\ \sigma^2_{\vartheta_j}\to 0}}\left(\mathscr{L}^d-\mathscr{L}^c\right)\leq -\frac{1}{2}\left[\frac{\delta_i^2\left(\frac{1}{2}\widehat{q}-I_i^d\right)^2}{\beta_i^2+\alpha_i\sigma_i^2}+\frac{\delta_j^2\left(\frac{1}{2}\widehat{q}-I_j^d\right)^2}{\beta_j^2+\alpha_j\sigma_j^2}+\frac{\delta_i^2\widehat{q}^2}{4\alpha_i\sigma_j^2}+\frac{\delta_j^2\widehat{q}^2}{4\alpha_j\sigma_i^2}\right]\leq 0 \tag{51}$$

$(i,j=1,2,i\neq j)$. Note that the limit value in (51) is less than or equal to zero, with strict inequality as long as $I_i^d=I_j^d=\widehat{q}=0$ does not apply. This special case is of minor interest as both organizational forms do not differ then. Otherwise, centralization outperforms decentralization (regardless of the level at which risk-aversion is fixed) when the variances of costs and revenues approach zero. By continuity, the same applies when these variances are sufficiently low, given any arbitrary but fixed degree of risk-aversion.

Proposition 3(b) also deals with the case of high degrees of uncertainty. For this case, we evaluate the limits when the uncertainty of costs and revenues approaches infinity, that is $\sigma^2_{\vartheta_i}\to\infty\,\forall i=1,2$, for given degrees of risk-aversion. Regarding centralization, L'Hôspital's rule yields:

$$\begin{aligned}\lim_{\sigma^2_{\vartheta_i}\to\infty}(q^c)^2\sigma^2_{\vartheta_i} &= \lim_{\sigma^2_{\vartheta_i}\to\infty}\frac{\mu^2\sigma^2_{\vartheta_i}}{\left[b-2+\alpha_i\left(w_{ii}^c\right)^2\sigma^2_{\vartheta_i}+\alpha_j\left(w_{jj}^c\right)^2\sigma^2_{\vartheta_j}\right]^2}\\ &= \lim_{\sigma^2_{\vartheta_i}\to\infty}\frac{\mu^2}{2\left[b-2+\alpha_i\left(w_{ii}^c\right)^2\sigma^2_{\vartheta_i}+\alpha_j\left(w_{jj}^c\right)^2\sigma^2_{\vartheta_j}\right]\alpha_i\left(w_{ii}^c\right)^2}=0\end{aligned}$$

$(i,j=1,2,i\neq j)$. Then, (16) yields $w_{ii}^c\to\beta_i^2/\left(\beta_i^2+\alpha_i\sigma_i^2\right)$ $(i=1,2)$, which is constant and together with (40) implies $q^c\to 0$. This, in turn, ensures $\mathrm{VI}^c\to 0$, see (37). Put together, (39) yields:

$$\lim_{\substack{\sigma^2_{\vartheta_i}\to\infty\\ \sigma^2_{\vartheta_j}\to\infty}}\mathscr{L}^c=\frac{1}{2}\left(\frac{\beta_i^4}{\beta_i^2+\alpha_i\sigma_i^2}+\frac{\beta_j^4}{\beta_j^2+\alpha_j\sigma_j^2}\right) \tag{52}$$

$(i,j=1,2,i\neq j)$.

Regarding decentralization, note that $\sigma^2_{\vartheta_1},\sigma^2_{\vartheta_2}\to\infty\Rightarrow\sigma^2\to\infty\Rightarrow\mathrm{Var}\left(M^d\right)\to\infty$ in conjunction with the maximization of (26) requires $w_{ii}^d,w_{ij}^d\to 0$ $(i,j=1,2,i\neq j)$. This, in turn, ensures $\mathrm{VI}^d\to 0$ as well as $\mathrm{IRLA}\to 0$ since both effects are weighted with w_{ii}^d and w_{ij}^d, see (35). Similar to the case $\alpha_i\to\infty$ $\forall i=1,2$, the Lagrangian (26) approaches $\mathrm{E}(M^d)-(I_i^d)^2/2-(I_j^d)^2/2$. Condition (29) again requires $I_i^d\to\mathrm{E}\left(q^d\right)$

$(i=1,2)$, whereby trade approaches zero since no incentives are provided in this limit case. This in turn implies $\mathrm{E}\left(M^d\right) \to 0$, which causes $\mathrm{FG} \to 0$. Put together, it follows that

$$\lim_{\substack{\sigma^2_{\vartheta_i} \to \infty \\ \sigma^2_{\vartheta_j} \to \infty}} \mathscr{L}^d = 0 \tag{53}$$

$(i,j=1,2, i \neq j)$.

Combining (52) and (53) results in

$$\lim_{\substack{\sigma^2_{\vartheta_i} \to \infty \\ \sigma^2_{\vartheta_j} \to \infty}} \left(\mathscr{L}^d - \mathscr{L}^c\right) = -\frac{1}{2}\left(\frac{\beta_i^4}{\beta_i^2 + \alpha_i \sigma_i^2} + \frac{\beta_j^4}{\beta_j^2 + \alpha_j \sigma_j^2}\right) < 0 \tag{54}$$

$(i,j=1,2, i \neq j)$ and, hence, the optimality of centralization when the variances of costs and revenues approach infinity. By continuity, the same applies when these variances are sufficiently high. ■