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Multistage Capital Budgeting for Shared Investments

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This paper studies the performance of delegated decision-making schemes in a two-stage, multidivision capital budgeting problem for a shared investment with an inherent abandonment option. Applying both robust goal congruence and sequential adverse selection frameworks, we show that the optimal capital budgeting mechanism entails a capital charge rate above the firm's cost of capital in the first stage but below the cost of capital in the second stage. Further, the first-stage asset cost-sharing rule depends only on the relative divisional growth profiles, and equal cost sharing can be optimal even when the divisions receive significantly different benefits from the shared investment project. In the presence of an adverse selection problem, all agency costs are incorporated into the second-stage budgeting mechanism, leaving the first-stage capital charge rate and asset-sharing rule unaffected even though the agency problem induces capital rationing at both stages.

Key words: capital budgeting; cooperative investments; two-stage investment decisions; abandonment options; cost allocation
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1. Introduction

Firms typically coordinate divisional investment decisions via the capital budgeting process. One approach that seems to be prevalent in practice is to make divisions accountable for their funding using capital charge rates or hurdle rates. Empirical and anecdotal evidence suggests substantial variation in capital charge rates, even within the same firm (e.g., Poterba and Summers 1995, Mukherjee and Hingorani 1999). Mukherjee and Hingorani (1999) also find evidence that firms adapt their capital rationing policies over time, leading to within-firm variation in investment decision rules. These empirical findings suggest that the capital budgeting process is more complex than discussed in the existing theoretical literature, particularly if investments involve multiple rounds of funding and investment decisions can be revised over time.

This paper studies the design of a capital budgeting mechanism for a rather simple but instructive two-stage investment problem where multiple divisions can initiate potentially profitable projects if the firm acquires a shared asset at the first stage. Each division can complete its project and realize the associated cash flows if the firm invests further at the second stage. The benefit each division will derive from the shared asset is privately observed by the divisional manager incrementally over the two stages. Our setup is descriptive for firms that act in environments where divisions share substantial resources.

To coordinate the shared investment decisions, the firm's capital budgeting mechanism defines a set of rules that disaggregates the firm's performance into divisional performance measures using an asset cost-sharing rule and capital charge rate. Specifically, the asset-sharing rule assigns each division a share of the joint investment cost, which is allocated across time using a firmwide capital charge rate and depreciation rule. In the first part of the paper, we study robust goal-congruent divisional performance measures (absent an adverse selection problem) that provide each divisional manager with incentives to support the firm's optimal long-term investment strategy regardless of his planning horizon or time preferences. The second part of the paper shows how to adapt the capital budgeting mechanism to a second-best setting with sequential adverse selection.

The management accounting literature has long pointed to potential problems associated with fixed cost allocations.[1] In our analysis, fixed cost allocations are necessary to align the ex ante investment

[1] For example, Sunder (1997, pp. 55–56) points out that in designing a cost-allocation scheme for a shared asset, a decentralized firm will often face a trade-off between motivating truthful reporting

incentives of divisional managers and the owners of the firm, even if the project is ultimately abandoned. However, the interaction between multiple divisions and multiple investment stages leads to different interdivisional asset-sharing rules and capital charge rates at each investment stage even though the assets purchased at each investment stage could be essentially identical.[2] In particular, we find that the firm can only induce robust goal congruence with a single capital charge rate for (i) the static single-stage case, i.e., in the absence of the abandonment option, or (ii) the single-division case.

Consistent with earlier work on cooperative, single-stage investments, which finds that positive externalities lower capital charge rates (Baldenius et al. 2007), the second-stage capital charge rate must be set below the firm's cost of capital to make each division properly internalize the positive externalities created for the other divisions when the investment is carried out. Similar to results in Baldenius et al. (2007), the second-stage asset-sharing rule allocates the second-stage investment cost according to each division's contribution toward making the continuation project break even.

In contrast, we find that the first-stage capital charge rate must be set above the firm's cost of capital. Although the first-stage investment also creates positive expected externalities from any divisional manager's point of view, those externalities are not incorporated into the asset-sharing rule or capital charge rate until the second investment stage. Accounting for positive externalities at both stages would "double count" them, inducing inefficient investment and abandonment decisions. Instead, the first-stage investment cost must be allocated among the divisions in proportion to the present value of each division's intertemporal growth profile with the so-called *relative growth profile* sharing rule (henceforth, the RGP sharing rule). For a given capital charge rate, the RGP sharing rule allocates a smaller share of the initial investment cost to divisions with more "back-loaded" cash flow profiles (i.e., cash flows arrive later). The RGP sharing rule can be interpreted as a multiperiod extension of the equal cost-sharing rule, because it corresponds to equal cost sharing when all divisions have comparable growth profiles or when all cash inflows arrive in a single period. This implies that equal cost sharing can be optimal even when the shared asset provides quite different benefits to the individual divisions. In other words, favoritism in terms of "equal treatment of unequals" can be optimal.

Previous results in the capital budgeting literature have emphasized that agency costs play a key role in determining capital charge rates. The single-divisional capital budgeting literature, for instance, has shown that private managerial information leads to capital rationing (e.g., Antle and Eppen 1985). One common approach to implementing capital rationing is to increase the capital charge rate above the firm's cost of capital. To study how divisional agency conflicts affect the design of capital charge rates and asset-sharing rules in our two-stage setting, we modify our goal-congruence model to a second-best (adverse selection) setting by assuming each manager can increase the profitability of his division via hidden effort.

A sequential agency problem arises because each manager can misreport his project information at both investment stages in order to supply less effort. Consistent with the one-parametric standard adverse selection problem, the firm has to pay each manager informational rents for his precontract information but not for his postcontract information (because it can extract any postcontract informational rents up front).[3] The firm can avoid paying informational rents, however, by either not initiating or abandoning the shared investment project because each manager's effort level can be perfectly inferred in the absence of the cash flows from investment. Accordingly, the second-best solution entails capital rationing in both stages, so that compared to the goal-congruence benchmark case, the shared investment project is initiated less often and abandoned more often.

Interestingly, however, only the second-stage capital charge rate is directly affected by the agency conflicts. Consistent with our previous result, the second-stage cost charge makes the divisional managers internalize the informational rents that lower the firmwide net present value (NPV) when the shared investment project is continued in the second stage. Accordingly, and consistent with previous research (e.g., Antle and Eppen 1985, Baldenius et al. 2007), the second-stage capital charge rate increases in the severity of the agency conflicts.

In contrast, the agency conflicts do not alter the first-stage capital charge rate or the RGP sharing rule, which retains its simple structure. Even though the agency conflicts induce capital rationing in the first stage, increasing the first-stage capital charge rate would indirectly double count the agency costs

about expected utilization at the purchase stage and motivating efficient ex post utilization of the asset. Similarly, Young and O'Byrne (2000) and Zimmerman (1997) provide examples that show how the improper allocation of shared resource costs can derail investment incentives.

[2] For example, if the first-stage investment is a lease of research facilities or computing equipment, the second-stage investment could be a renewal of the same lease for an additional period.

[3] See Pfeiffer and Schneider (2007) for a similar finding in the single-divisional case.

that determine the second-stage capital charge rate. Instead, capital rationing in both stages is induced by the increase in the second-stage capital charge rate. These findings provide an interesting empirical hypothesis in that the first-stage capital charge rate and asset-sharing rule should not be altered by the presence of agency conflicts.

The first part of our analysis complements previous research on the design of robust goal-congruent performance metrics. As previously outlined, our analysis is most closely related to Baldenius et al. (2007), who show how to induce robust goal congruence for a multidivision, single-stage investment problem with a single capital charge rate that is below the firm's cost of capital. Our paper is also related to Dutta and Reichelstein (2005), who show how to construct robust goal-congruent income measures for a single-division, two-stage investment setting with a single capital charge rate that equals the firm's cost of capital. Our paper shows how the presence of multiple divisions and investment stages alters the asset-sharing rules and associated capital charge rates substantially relative to the solutions developed in these papers. Similarly, our work also complements previous research that shows that robust goal-congruent investment can be induced for a single-division, single-stage investment decision with a single capital charge rate equal to the firm's cost of capital (e.g., Rogerson 1997, Reichelstein 1997, Wei 2004, Mohnen and Bareket 2007).

In introducing a multistage adverse selection problem for the individual divisions, we find that our second-stage results are essentially the same as in the multidivision, single-stage investment setting of Baldenius et al. (2007), but our first-stage results differ from theirs significantly. This part of our analysis also complements the single-division, two-stage investment setting of Pfeiffer and Schneider (2007). They show that the firm has to pay informational rents for the manager's private precontract information, but not for his private postcontract information, and as in our model, informational rents are only paid when the project is not abandoned. In extending their work to a multiagent setting, we address how the other divisions' informational rents and the synergy stemming from the cooperative investments affect cost allocations across the individual divisions and across time. In particular, we show how these factors lead to a simple first-stage asset-sharing rule and an associated capital charge rate that is above the firm's cost of capital.

Our paper is also related to Baiman et al. (2013), who study two-stage resource allocation with an abandonment option under adverse selection but in a single-division setting under centralized decision making. In their model a manager creates budgetary slack in the first stage by overreporting his costs. The manager can only consume the slack if the project is not abandoned, but abandoning the project does not allow the firm to recover the slack. Consequently, it is optimal to commit to overinvest in some states ex post in order to reward lower-cost reports and minimize slack creation ex ante. In contrast, the informational rents in our adverse selection model (analogous to the slack in Baiman et al. 2013) can be avoided if the project is abandoned, leading to underinvestment.

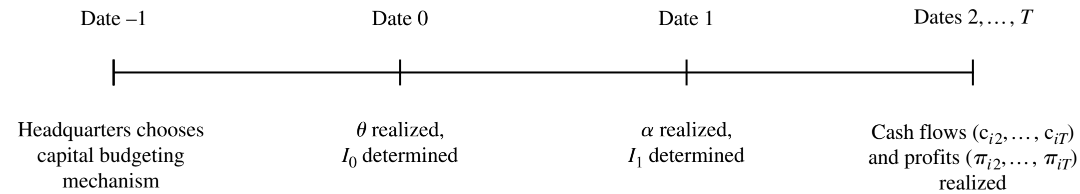
Levitt and Snyder (1997) and Arya and Glover (2003) examine the role of abandonment options in the presence of a moral hazard problem between a principal and a single agent. In contrast to our paper, exercising the abandonment option in these papers can be costly because doing so can reduce the available information about the agent's supplied effort and make it more costly to provide effort incentives. In both papers, the principal's expected payoff and the agent's induced effort levels will be higher if the principal can commit not to abandon some projects that have negative expected payoffs. Arya and Glover (2003) study optimal information system design and show further that coarse information can serve as a commitment device to abandon the project less aggressively.

From a broader perspective, our paper is also related to Arya and Glover (2001) and Antle et al. (2001, 2007), who show in a single-agent setting that the option to delay decision making when faced with mutually exclusive single-parameter investment projects can mitigate adverse selection problems. In general, our findings also supplement recent studies on the design of residual income-based incentive systems in single-stage, single-agent investment settings, which examine factors leading to optimal capital charge rates that vary from the firm's cost of capital. See, for example, Baldenius (2003), Christensen et al. (2002), Dutta (2003), and Dutta and Fan (2009).[4]

Finally, our paper is related to the classical one-parametric public choice literature (e.g., Groves 1973, Green and Laffont 1979) and to the recent extensions of this literature to infinite multistage pivot mechanisms based on the marginal contribution of each agent (Bergemann and Välimäki 2010). Our capital budgeting mechanism is not a multistage version of the pivot mechanism, however, because our mechanism only charges divisions for investments that have

[4] Our paper further adds to the broader literature on single-investment decisions under adverse selection, including Antle and Fellingham (1990), Arya et al. (1993), and Dutta and Reichelstein (2002). It also builds on studies that have examined cost-allocation and budgeting mechanisms for multidivisional firms in one-period settings such as Arya et al. (1996) and Balakrishnan (1995).

Figure 1 **Timeline of Events**



been undertaken, whereas the pivot mechanism can charge divisions even if no investment is carried out.

The remainder of the paper is organized as follows. The formal model is introduced in §2. The multistage budgeting process is analyzed in §3. Section 4 extends the results to a multistage adverse selection problem with a manager who makes unobservable, productive effort decisions. Section 5 concludes. A list of model variables and all proofs are provided in Appendices A and B, respectively.

2. Model

We study a firm's capital budgeting system when investment decisions have to be made incrementally in two stages, and divisional managers have private information about investment profitability at each stage. All parties are risk neutral. At the first stage (date $t=0$), the firm (headquarters) can acquire an asset that will allow N divisions to initiate potentially profitable projects. Purchasing the asset requires a cash outlay of γb_0 at date 0, where $\gamma = 1/(1+r)$ and r is the firm's cost of capital.[5] The indicator variable I_0 denotes the initial purchase decision, where $I_0 = 1$ if the asset is purchased and $I_0 = 0$ otherwise. At the second investment stage, date 1, all divisional projects can continue if the firm invests further in the shared asset at cost b_1. The indicator variable I_1 equals 1 if the second-stage investment is undertaken and 0 otherwise.

If the shared investment receives additional funding at the second stage, each division's project generates verifiable end-of-period cash flows for the remaining periods:

$$c_{it}(\theta_i, \alpha_i, I_1, I_0) = x_{it}(\theta_i + \alpha_i) I_1 I_0 \quad \text{for } t = 2, \ldots, T \text{ and } i = 1, \ldots, N. \quad (1)$$

The intertemporal growth profile of each division, represented by $x_i = (x_{i2}, \ldots, x_{iT}) > 0$, is common knowledge.[6] The productivity parameters θ_i and α_i are observed privately by manager i at the beginnings of dates 0 and 1, respectively. Larger values of θ_i and α_i represent a more favorable investment environment in division i. Common beliefs regarding each manager's private information, θ_i, are represented by the probability distribution $F_i(\theta_i)$ with a strictly positive density $f_i(\theta_i)$ on the interval $[\underline{\theta}_i, \bar{\theta}_i] \subset \mathbb{R}_+$. Similarly, common beliefs regarding α_i are represented by the probability distribution $G_i(\alpha_i)$ with a strictly positive density $g_i(\alpha_i)$ on the interval $[\underline{\alpha}_i, \bar{\alpha}_i] \subset \mathbb{R}_+$. All random variables θ_i and α_i are independently distributed. For simplicity, we use the following vector notation: $\theta = (\theta_1, \ldots, \theta_N)$, $\theta_{-i} = (\theta_1, \ldots, \theta_{i-1}, \theta_{i+1}, \ldots, \theta_N)$, $\alpha = (\alpha_1, \ldots, \alpha_N)$, and $\alpha_{-i} = (\alpha_1, \ldots, \alpha_{i-1}, \alpha_{i+1}, \ldots, \alpha_N)$.

Figure 1 is a timeline showing the sequence of events in the model.

Throughout the analysis all cash inflows and outflows are discounted to period $t=1$. The present value of division i's cash flows is given by

$$PV_i(\theta_i, \alpha_i) \cdot I_1 I_0 = \sum_{t=2}^{T} c_{it} \gamma^{t-1} = \sum_{t=2}^{T} x_{it}(\theta_i + \alpha_i) \gamma^{t-1} \cdot I_1 I_0. \quad (2)$$

Unless stated otherwise, we impose the following assumption. Assumption 1 rules out the trivial case in which the abandonment decision is deterministic and ensures that ex post each division is necessary for the overall investment project to be profitable.[7]

Assumption 1. *For every division $i = 1, \ldots, N$, the following inequalities hold for all θ, α_{-i}: $PV_i(\theta_i, \bar{\alpha}_i) + \sum_{j\neq i}^{N} PV_j(\theta_j, \alpha_j) > b_1 > PV_i(\theta_i, \underline{\alpha}_i) + \sum_{j\neq i}^{N} PV_j(\theta_j, \alpha_j)$.*

As a point of reference, we first derive the firm's optimal multistage investment decisions under full information (i.e., when headquarters observes θ at date 0 and α at date 1). The firm's overall objective is to choose first- and second-stage investment rules, $I_0(\theta)$ and $I_1(\theta, \alpha)$, that maximize the expected firmwide net present value (discounted to date $t=1$):

$$\max_{I_0(\theta), I_1(\theta, \alpha)} E_{\theta, \alpha}\left[\left(\left(\sum_{i=1}^{N} PV_i(\theta_i, \alpha_i) - b_1\right) \cdot I_1(\theta, \alpha) - b_0\right) I_0(\theta)\right]. \quad (3)$$

[5] All cash flows in the paper are discounted to date 1. The initial asset cost is defined as γb_0 at date 0 for ease of notation.

[6] The common-knowledge and separability assumptions are standard (e.g., Reichelstein 1997, Rogerson 1997), despite being somewhat demanding. See, for instance, Pfeiffer and Velthuis (2009) for additional discussion of the implications of these assumptions.

[7] This assumption allows us to avoid case distinctions. Our main results hold if only one division is necessary and the other divisions are assigned zero capital costs.

Solving (3) yields the following solution to the firm's problem:

$$I_1^*(\theta,\alpha)=\begin{cases}1 & \text{if } \sum_{i=1}^{N} PV_i(\theta_i,\alpha_i)\geq b_1,\\ 0 & \text{otherwise,}\end{cases} \tag{4}$$

and (note the value of the initial cash outlay at date 0, γb_0, is b_0 at date 1)

$$I_0^*(\theta)=\begin{cases}1 & \text{if } E_\alpha\left[\left(\sum_{i=1}^{N} PV_i(\theta_i,\alpha_i)-b_1\right)\cdot I_1^*(\theta,\alpha)\right]\geq b_0,\\ 0 & \text{otherwise.}\end{cases} \tag{5}$$

That is, the firm will invest further at date 1 whenever the continuation net present value is positive and will abandon the project otherwise. Taking the optimal abandonment decision into account, the firm initiates the investment if the associated expected net present value of the project is positive.

2.1. Capital Budgeting Mechanism

Now we turn our attention to the design of the capital budgeting mechanism when the divisional managers have private information about their projects' profitability levels and each manager seeks to maximize his own divisional income measure. Initially, we focus on the design of robust performance measures and ignore problems of adverse selection. Subsequently, we show in §4 how our results can be adapted to an optimal second-best capital budgeting mechanism.

To design the capital budgeting mechanism, the firm has to allocate the costs of the shared assets across the individual divisions and across the periods in time. We focus on asset cost-sharing rules that satisfy the usual comprehensive income measurement condition so that the total cost shares allocated across the divisions equal the total investment costs. In particular, the firm chooses the following key items of the capital budgeting mechanism:

(i) asset cost-sharing rules, λ_{0i} and λ_{1i}, assign each division a share of the associated joint asset's investment costs, $\lambda_{0i}b_0$ and $\lambda_{1i}b_1$. Comprehensive income measurement requires that the sum of the shares assigned to the individual divisions equals 1, i.e., $\sum_{i=1}^{N}\lambda_{ki}=1$ for $k=0,1$;

(ii) firmwide capital charge rates $\hat{r}_0$ and $\hat{r}_1$;

(iii) intertemporal cost-allocation rules, $z_{it}(\hat{r}_0)$ and $z_{it}(\hat{r}_1)$, allocate division i's share of the investment costs, $\lambda_{0i}b_0$ and $\lambda_{1i}b_1$, to period t with the associated capital charge rate. The intertemporal cost-allocation rule represents a convenient shortcut for the depreciation schedule plus capital costs per allocated unit calculated with the capital charge rate (e.g., Rogerson 1997, Reichelstein 1997). Formally stated, the intertemporal cost-allocation rule $z_{it}(\hat{r})$ consists of the depreciation schedule d_{it} plus the cost of capital calculated from the capital charge rate $\hat{r}$ and the remaining proportion of division i's asset book value at the end of the preceding period A_{it-1}; i.e., $z_{it}(\hat{r})=d_{it}+\hat{r}A_{it-1}$. The book values (per unit) are presumed to satisfy the clean surplus relationship; i.e., $A_{i1}=1$, $A_{it}=A_{it-1}-d_{it}$ for $t>1$, and $A_{iT}=0$. Consequently, the intertemporal cost-allocation rule is complete with respect to the associated capital charge rate; i.e., $\sum_{t=2}^{T} z_{it}(\hat{r})(1+\hat{r})^{-(t-1)}=1$.

Given the capital budgeting process, division i's performance measure at date t is given as

$$\pi_{it}=c_{it}-(z_{it}(\hat{r}_1)\lambda_{1i}b_1I_{i1}+z_{it}(\hat{r}_0)\lambda_{0i}b_0)I_{i0}\quad \text{for } t=2,\ldots,T, \tag{6}$$

and $\pi_{i0}=\pi_{i1}=0$. The performance measure π_{it} equals division i's current cash flow, c_{it}, less a divisional cost charge that consists of two pieces: one that is allocated to the division if the project is initiated at date 0 and another if the project is continued at date 1. The indicator variables I_{i0} and I_{i1} denote division i's investment decisions, but because we study capital budgeting mechanisms that will always provide dominant incentives for optimal unanimous decision making by all managers, we do not distinguish between I_k and I_{ik}.[8] Each cost charge allocates a share of the investment costs to period t according to the associated intertemporal cost-allocation rule. The class of performance measures in (6) encompasses typically used accounting-based performance measures such as income, residual income, and operating cash flow. Further, it allows us to distinguish between circumstances under which the firm can apply a single capital charge rate to the two investment expenditures and circumstances that require two capital charge rates and asset-sharing rules, supporting observations in practice that some firms use different capital charge rates for different investment decisions.

Following the terminology in earlier literature, we confine attention to performance measures that induce *sequentially robust goal congruence in dominant strategies* (hereafter, *robust goal congruence*). That is, each manager's dominant strategy is to (i) sequentially report his private information truthfully and (ii) undertake, from the firm's perspective, the optimal investment decisions on a period-by-period basis,

[8] For the same reason, our results do not change if the divisions commit ex ante to a report-contingent decision-making rule rather than allowing each division to make its own investment decision. Similarly, it is not necessary to specify rules about the group decision-making process, because procedures such as the order in which they report or the group's decision-making procedures at each stage will not be relevant.

regardless of the weights assigned to his performance measure. Only nonzero performance measures can satisfy this criterion; i.e., $(\pi_{i2}, \ldots, \pi_{iT}) \neq 0$ for all $i = 1, \ldots, N$.

One interpretation for this approach is that the firm does not know the managers' planning horizons or time preferences and, thus, has to ensure nontrivially goal-congruent decisions on a period-by-period basis. Another interpretation is that the accounting rules have to be chosen before the specifics of the managerial contracts become known (e.g., Dutta and Reichelstein 2005). A *capital budgeting mechanism* is called *robust* if for all divisions it induces robust goal-congruent incentives, as defined above, and satisfies the comprehensive income measurement condition.

3. Robust Capital Budgeting Mechanism in the Absence of Adverse Selection

In this section, we characterize the optimal capital budgeting mechanism that induces robust goal-congruent investment decisions absent an adverse selection problem. Each division reports its private information $\hat{\theta}_i$ at date 0 and $\hat{\alpha}_i$ at date 1, with $(\hat{\theta}_i, \hat{\alpha}_i)$ denoting division i's reported profitability levels. The firm can base the components of the capital budgeting mechanism, such as the asset-sharing rules, the capital charges rates, and the intertemporal cost-allocation rules, on the reports.

To characterize the capital budgeting mechanism, it is convenient to define each division's *critical profitability parameter*, $\alpha_i^*(\hat{\theta}, \hat{\alpha}_{-i})$, as the solution to

$$PV_i(\hat{\theta}_i, \alpha_i^*(\hat{\theta}, \hat{\alpha}_{-i})) + \sum_{j\neq i}^{N} PV_j(\hat{\theta}_j, \hat{\alpha}_j) = b_1. \tag{7}$$

That is, $\alpha_i^*(\hat{\theta}, \hat{\alpha}_{-i})$ is the minimum profitability level division i must report if the shared project is to be continued. Assumption 1 ensures that a critical profitability parameter exists for each division. The following result characterizes the capital budgeting mechanism.

Proposition 1. *Given Assumption* 1, *the following multistage capital budgeting mechanism is the only capital budgeting mechanism that induces robust goal-congruent investment incentives for N divisions*, $N > 1$, *while satisfying the comprehensive income requirement*. *In particular, the date* 0 *asset-sharing rule, which we denote the* relative growth profile asset-sharing rule (RGP rule), *is given by*

$$\lambda_{0i} = \frac{\sum_{t=2}^{T} x_{it}(1+\hat{r}_0)^{-(t-1)}}{\sum_{t=2}^{T} x_{it}(1+r)^{-(t-1)}}, \tag{8}$$

the date 1 *asset-sharing rule is given by*

$$\lambda_{1i}(\hat{\theta}, \hat{\alpha}) = \frac{\sum_{t=2}^{T} x_{it}(1+\hat{r}_1(\hat{\theta}, \hat{\alpha}))^{-(t-1)}(\hat{\theta}_i + \alpha_i^*(\hat{\theta}, \hat{\alpha}_{-i}))}{b_1}, \tag{9}$$

the associated capital charge rate $\hat{r}_k(\cdot)$ *satisfies* (*for* $k = 0, 1$)

$$\sum_{i=1}^{N} \lambda_{ki}(\cdot) = 1, \tag{10}$$

and the associated intertemporal cost-allocation rule,

$$z_{it}^{RB}(\hat{r}_k(\cdot)) = \frac{x_{it}}{\sum_{t=2}^{T} x_{it}(1+\hat{r}_k(\cdot))^{-(t-1)}}, \tag{11}$$

is the relative benefit cost-allocation rule (RBCA rule) *calculated with the associated capital charge rate* $\hat{r}_k(\cdot)$.

(All proofs are provided in Appendix B.)

To show how the metric in Proposition 1 works, we first restate the date 0 and date 1 divisional cost charges, respectively, as follows:

$$z_{it}^{RB}(\hat{r}_0)\lambda_{0i}b_0 = z_{it}^{RB}(r)b_0, \tag{12}$$

$$z_{it}^{RB}(\hat{r}_1)\lambda_{1i}b_1 = z_{it}^{RB}(r)\left(b_1 - \sum_{j\neq i}^{N} PV_j(\hat{\theta}_j, \hat{\alpha}_j)\right). \tag{13}$$

That is, the asset-sharing rules, capital charge rates, and intertemporal cost-allocation rules are designed such that the date 0 initial investment cost, b_0, and the date 1 opportunity costs, $b_1 - \sum_{j\neq i}^{N} PV_j(\hat{\theta}_j, \hat{\alpha}_j)$, are allocated to division i at date t according to the RBCA rule calculated with the firm's cost of capital, r.[9] Assumption 1 ensures that the date 1 opportunity costs, which consist of date 1 investment costs less the reported net present value of the other divisions, are positive. We discuss the capital charge rates in more detail in §3.1.

The RBCA rule provides the following relation between division i's current cash flow and the present value of the project: $c_{it}(\theta_i, \alpha_i, I_1, I_0) = z_{it}^{RB}(r) \cdot PV_i(\theta_i, \alpha_i)I_1I_0$ (Rogerson 1997, Reichelstein 1997).[10]

[9] The associated relative benefit depreciation schedule (Rogerson 1997) can be obtained as a one-to-one mapping from the RBCA rule and the capital charge rate (Baldenius et al. 2007, Lemma 1). See Pfeiffer and Velthuis (2009) for a comprehensive summary of previous findings for properties of the relative benefit depreciation schedule.

[10] This follows from $z_{it}(r)I_1I_0 = x_{it}(\theta_i + \alpha_i)I_1I_0/(\sum_{t=2}^{T} x_{it}(1+r)^{-(t-1)} \cdot (\theta_i + \alpha_i)) = c_{it}/PV_i$.

Applying this property, the optimal performance metric for division i can be restated as follows:[11]

$$\pi_{it} = z_{it}^{RB}(r)\left(\left(PV_i(\theta_i, \alpha_i) + \sum_{j\neq i}^{N} PV_j(\hat{\theta}_j, \hat{\alpha}_j) - b_1\right)I_1 - b_0\right)I_0. \quad (14)$$

From division i's perspective, it receives its "true" divisional net present value plus the *reported* net present value of the other divisions less investment costs, allocated over time with the RBCA rule. Because the metric in (14) is not a function of division i's own reports $(\hat{\theta}_i, \hat{\alpha}_i)$, each division i will report its information truthfully, independent of the other divisions' decisions. Given truthful reporting of the other divisions, each period t performance measure π_{it} is a multiple of the firm's objective function shown in (3). Accordingly, each manager undertakes the optimal investment decisions regardless of his time preferences. Hence, the performance metric ensures robust goal congruence.

Although the performance metric has a Groves structure, it is instructive to note that in a strict sense it is not a Groves mechanism because it is not based on realized net present values. A Groves mechanism based on realized net present value would delay performance measurement until all cash flows were realized (back-loading), which violates the goal-congruence criterion requirement $(\pi_{i2}, \ldots, \pi_{iT}) \neq 0$. In this vein, our capital budgeting mechanism is not a multistage version of the so-called pivot mechanism under which a division receives an additional positive transfer payment for a pivotal report that alters the investment decisions. The pivot mechanism can charge the divisions even if no investment is ultimately carried out, whereas our capital budgeting mechanism only allocates costs that have been incurred (see (12) and (13)).[12]

3.1. Properties of the Optimal Robust Capital Budgeting Mechanism

The capital budgeting mechanism outlined in Proposition 1 requires two different asset-sharing rules and capital charge rates. If the abandonment decision is not deterministic, i.e., if Assumption 1 is satisfied, dual capital charge rates will always be required in the multidivision case to make the divisions correctly internalize the expected costs and benefits they impose on each other at each investment stage.[13] Further, the optimal capital budgeting mechanism does not obey a strict "no-play, no-pay" condition that stipulates that costs only be allocated to a division if its project is not abandoned at the second stage. Instead, all divisions will be allocated a portion of any costs incurred at date 0 regardless of the continuation decision at date 1.[14]

We consider first the date 0 divisional cost charge. The date 0 RGP sharing rule λ_{0i}, as defined in (8), does not depend on the divisions' profitability parameters because all opportunity costs are pushed forward to the date 1 cost-sharing rule to induce efficient decision making in the continuation problem. Instead, the RGP rule allocates investment costs in proportion to the present value of each division's intertemporal growth profile (as indicated by its name). Ceteris paribus, divisions with more back-loaded cash flow profiles (i.e., cash flows arrive later) will receive smaller cost allocations. To see this more clearly, consider the geometric cash flow case, $x_{it} = \beta_i^{t-1}$, where the geometric parameter β_i satisfies $\beta_i \in (0, 1+r)$. Then the RGP sharing rule will be

$$\lambda_{0i} = \frac{1 + r - \beta_i}{1 + \hat{r}_0 - \beta_i}. \quad (15)$$

If $\beta_i > \beta_j$, division i receives a relatively larger proportion of its cash flows in later periods (i.e., division i's cash flows are more back-loaded than division j's cash flows). As cash flows in any division

[11] Note that although the metric in (14) is equivalent to the metric in Proposition 1 in its effect on each manager's divisional income and incentives, it does not satisfy comprehensive income accounting. In fact, robust goal congruence can be achieved with a variety of equivalent metrics using different combinations of capital charge rates and asset-sharing rules, but the metric in Proposition 1 is unique in inducing robust goal congruence under comprehensive income accounting. Similarly, only (14) induces robust goal congruence using a capital charge rate that is equal to the firm's cost of capital, but it violates the comprehensive income accounting requirement.

[12] See also Baldenius et al. (2007), who use this line of reasoning to note that their single-stage pay-the-minimum-necessary (PMN) mechanism is not a multiperiod version of the pivot mechanism. They further note that a key property of pivot mechanisms is that they always achieve a "budget surplus," whereas their PMN mechanism runs a deficit in terms of present values. Similarly, in our budgeting mechanism the present value of the divisional cost charges for the date 1 investment decision, $\sum_{i=1}^{N}\sum_{t=2}^{T}\gamma^{t-1}z_{it}^{RB}(\hat{r}_1)\lambda_{1i}b_1 = \sum_{i=1}^{N}\sum_{t=2}^{T}\gamma^{t-1}z_{it}^{RB}(r)(b_1 - \sum_{j\neq i}^{N} PV_i(\theta_i, \alpha_i)) = Nb_1 - (N-1)\sum_{i=1}^{N} PV_i(\theta_i, \alpha_i) < b_1$ (noting that $\sum_{t=2}^{T}\gamma^{t-1}z_{it}^{RB}(r) = 1$), is less than the associated investment outlay b_1 whenever the NPV of the continuation project is positive (i.e., $\sum_{i=1}^{N} PV_i(\theta_i, \alpha_i) > b_1$).

[13] Similarly, dual cost-allocation systems observed in practice use different rules to allocate the fixed and variable portions of shared costs (e.g., Horngren et al. 2009).

[14] Our results are consistent with full cost accounting, which requires the capitalization of all costs on the balance sheet independent of the projects' success. In contrast, successful efforts accounting allows the firm to only capitalize costs associated with successful investment projects. Our finding shows that Dutta and Reichelstein's (2005) insight advocating full cost accounting rather than successful efforts accounting for the single division case carries over to the multiple division case.

become more back-loaded, comprehensive income accounting can be satisfied with a capital charge rate that deviates less from the firm's cost of capital, leading to a lower date 0 capital charge rate for every division. The optimal mechanism recognizes this positive externality by assigning division i a smaller share of the initial investment cost.

Because cost allocations depend only on cash flow patterns, two divisions with equally profitable projects (i.e., $PV_i(\theta_i, \alpha_i) = PV_j(\theta_j, \alpha_j)$) may be allocated different shares of the initial investment cost. Similarly, our capital budgeting mechanism shows that equal cost sharing, which is frequently applied in practice, can be optimal in a multiperiod setting even when divisional projects vary significantly in profitability level. In other words, "equal treatment of unequals" can be optimal.[15] Corollary 1 describes the general circumstances that lead to equal cost sharing under the RGP rule.

Corollary 1. *The RGP sharing rule λ_{0i} corresponds to an equal sharing rule, $\lambda_{0i} = 1/N$, when* (i) *there is only one period of cash inflows, $T = 2$, or* (ii) *the divisional growth parameters exhibit the same pattern across divisions, i.e., $x_{it} = k_{ij} \cdot x_{jt}$ for all i, j, and t, where k_{ij} denotes a positive constant.*

In contrast to the static case, where synergies among divisions lead to a lower capital charge rate (Baldenius et al. 2007), a nondeterministic abandonment option plays an important role in determining the optimal capital budgeting mechanism and pushes the first-stage capital charge rate above the cost of capital. In particular, relation (12), $z_{it}^{RB}(\hat{r}_0)\lambda_{0i}b_0 = z_{it}^{RB}(r)b_0$, implies for $\hat{r}_0 = r$ that each division bears the entire investment cost b_0 (i.e., $\lambda_{0i} = 1$). Since λ_{0i} is decreasing in $\hat{r}_0$, the associated date 0 capital charge rate must exceed the firm's cost of capital to satisfy the comprehensive income measurement requirement (i.e., $\sum_{i=1}^{N} \lambda_{0i} = 1$).

Corollary 2. *In the multiple division case, $N > 1$, the date 0 capital charge rate exceeds the firm's cost of capital, $\hat{r}_0 > r$.*

The investment problem at date 1 can be treated as a single-stage problem because the initial investment cost b_0 is sunk. Consequently, the date 1 capital charge rate and asset-sharing rule are straightforward modifications of the single-stage solution derived by Baldenius et al. (2007). In particular, the date 1 asset-sharing rule is the present value of the division's cash flows at its critical profitability level divided by the date 1 investment cost, and the associated capital charge rate must be set below the firm's cost of capital when the NPV of the continuation project is positive.[16] Because Proposition 1 ensures truth telling, we do not highlight the reports in the subsequent corollary, which is a straightforward modification of the Baldenius et al. (2007, Corollaries 1 and 2) findings for the single-stage case.

Corollary 3 (Baldenius et al. 2007). (i) *The date 1 capital charge rate is below the firm's cost of capital, $\hat{r}_1 \le r$, if the NPV of the continuation project is positive, $\sum_{i=1}^{N} PV_i(\theta_i, \alpha_i) \ge b_1$.*

(ii) *The date 1 asset-sharing rule, $\lambda_{1i}(\theta_i, \alpha_i)$, is increasing in division i's total profitability, $(\theta_i + \alpha_i)$.*

We close this section by exploring the basic properties of the two capital charge rates further. We return to the geometric cash flow setting, letting $x_{it} = \beta_i^{t-1}$ with $\beta_i \in (0, 1+r)$, and setting $\beta_i = \beta$ for all i. Then, the capital charge rates $\hat{r}_0$ and $\hat{r}_1$ can be written as a function of the geometric parameter, β, the number of divisions, N, and the total return rate of the continuation project, $R_1(\hat{\theta}, \hat{\alpha}) = (\sum_{i=1}^{N} PV_i(\hat{\theta}_i, \hat{\alpha}_i)/b_1) - 1$:

$$\begin{aligned} \hat{r}_0 &= r + (N-1)(1+r-\beta) \quad \text{and} \\ \hat{r}_1 &= r - (N-1)(1+r-\beta) \cdot R_1(\hat{\theta}, \hat{\alpha}). \end{aligned} \tag{16}$$

First, the two capital charge rates will only be equal if $N = 1$. In this case, both charge rates will be equal to the firm's cost of capital, r. We show how this insight extends to the general case in the next section. Second, for $R_1 > 0$, the difference between the capital charge rates, $\hat{r}_0 - \hat{r}_1$, is ceteris paribus decreasing in β. The intuition is as described previously—when cash flows are more back-loaded, small changes in either capital charge rate will have a larger impact on the magnitude of the respective asset-sharing rule and smaller capital-charge-rate adjustments will be required to satisfy comprehensive income accounting. Finally, $\hat{r}_0 - \hat{r}_1$ is increasing in the number of divisions, N, and the continuation return rate, R_1, because both asset-sharing rules require larger adjustments to satisfy comprehensive income accounting when N is large, and the date 1 asset-sharing rule requires larger adjustments when R_1 is large.

3.2. Single Capital Charge Rate

The two capital charge rates required to induce robust goal-congruent investment decisions at dates 0 and 1

[15] Consistent with Prendergast and Topel's (1996) positive view of favoritism, the RGP rule can require unequally profitable divisions to be treated equally to ensure robust goal congruence.

[16] If $\hat{r}_1 = r$, the sum of the shares equals $\sum_{i=1}^{N} \lambda_{1i}(\hat{\theta}, \hat{\alpha}) = (Nb_1 - (N-1)\sum_{i=1}^{N} PV_i(\hat{\theta}_i, \hat{\alpha}_i))/b_1$, and the comprehensive income accounting requirement is satisfied only if the (reported) net present value of the continuation project is zero (i.e., $\sum_{i=1}^{N} \lambda_{1i}(\hat{\theta}, \hat{\alpha}) = 1$ only if $\sum_{i=1}^{N} PV_i(\hat{\theta}_i, \hat{\alpha}_i) = b_1$). Since the allocated shares $\lambda_{1i}(\hat{\theta}, \hat{\alpha})$ are decreasing in $\hat{r}_1$, the date 1 capital charge rate must be set below the firm's cost of capital when the NPV of the continuation project is positive.

are quite different, even though the assets purchased at each stage could be identical. In this section, we show that two key ingredients are responsible for this result: (i) the presence of a nondeterministic abandonment option, as required in Assumption 1, and (ii) multiple divisions, $N > 1$.

Suppose that the firm wants to design a capital budgeting mechanism that allows two asset-sharing rules, λ_{0i} and λ_{1i}, but only a single capital charge rate, $\hat{r}$. As mentioned, the associated income measure must be a multiple of the firmwide net present value for all abandonment and investment decisions, I_1 and I_0. That is, the following equation must be satisfied for all $t = 2, \ldots, T$ and $i = 1, \ldots, N$:

$$k_{it} \cdot \left(\left(PV_i(\theta_i, \alpha_i) + \sum_{j \neq i}^{N} PV_j(\theta_j, \alpha_j) - b_1 \right) I_1 - b_0 \right) I_0$$
$$= c_{it}(\theta_i, \alpha_i, I_1, I_0) - z_{it}(\hat{r})(\lambda_{1i}(\theta, \alpha) b_1 I_1 + \lambda_{0i}(\theta) b_0) I_0$$
$$\text{for all } (\theta_i, \alpha_i, I_0, I_1), \quad (17)$$

where k_{it} denotes a positive constant. Condition (17) is a necessary condition that aligns the firm's and division i's investment decisions (and abstracts from problems that the other divisions misreport their information). Because only the zero function satisfies (17) for all $(\theta_i, \alpha_i, I_0, I_1)$, the coefficients must be zero; i.e., $k_{it} = x_{it} / \sum_{t=2}^{T} x_{it} \gamma^{t-1} = z_{it}^{RB}(r)$, $k_{it}(b_1 - \sum_{j \neq i}^{N} PV_j) = z_{it}(\hat{r}) \lambda_{1i} b_1$ and $k_{it} b_0 = z_{it}(\hat{r}) \lambda_{0i} b_0$ for all $t = 2, \ldots, T$ and $i = 1, \ldots, N$.[17] If $N > 1$, a single capital charge rate $\hat{r}$ cannot solve these equations simultaneously while also satisfying the comprehensive income measurement condition, $\sum_{i=1}^{N} \lambda_{ki} = 1$ for $k = 0, 1$. Rather, condition (17) can only be satisfied for the single-division case. In this case, only the relative benefit cost-allocation rule based on the firm's cost of capital, i.e., $z_t(\hat{r}) = z_t^{RB}(r)$, ensures robust goal congruence.[18]

Corollary 4. *Given Assumption* 1, *a single capital charge rate is only optimal in the single-divisional case; i.e.,* $\hat{r}_0 = \hat{r}_1 = r$ *if and only if* $N = 1$.

In previous work, Dutta and Reichelstein (2005, Proposition 4) showed that a residual income measure based on a single capital charge rate can obtain robust goal-congruent investment decisions in the single-division case with multiperiod investments. Corollary 4 shows that this result does not transfer to the multidivisional case.

Similarly, if we relax Assumption 1 and assume that no abandonment option exists, i.e., $I_1 = 1$ for all (θ, α), the overall capital budgeting problem is similar in structure to the continuation problem. Then robust goal congruence is achieved if investment costs for both stages are pooled and allocated with a single asset-sharing rule and capital charge rate that are similar to those in the solution to the date 1 continuation problem.

4. Incentive Contracting Under Adverse Selection

Previous theoretical and empirical research has emphasized the importance of the role of agency costs in influencing the capital budgeting process and determining optimal capital charge rates. Using a simple separable model that allows us to focus on implementation issues, we discuss in this section how agency conflicts between the firm and the individual divisions alter our results. Specifically, we assume manager i provides effort a_{it} from the interval $[0, \bar{a}_{it}]$ in period t. Cash flows in period t are redefined as

$$c_{it}(a_{it}, \theta_i, \alpha_i, I_1, I_0) = a_{it} + x_{it}(\theta_i + \alpha_i) I_1 I_0. \quad (18)$$

The firm can observe cash flows in each period but cannot distinguish between cash flows arising from managerial effort and those arising from investment returns. We make the standard assumption that the inverse hazard rate $H_i(\theta_i) = (1 - F_i(\theta_i)) / f_i(\theta_i)$ is weakly decreasing in θ_i for all i. Manager i is effort averse, with his utility function $U_i(\cdot)$ given by

$$U_i(s_{it}(\cdot), a_{it}) = \sum_{t=2}^{T} \gamma^{t-1} (s_{it}(\cdot) - v_{it} a_{it}), \quad (19)$$

where $s_{it}(\cdot)$ is the compensation payment and v_{it} measures the disutility of effort.[19]

In the following, we consider a direct sequential revelation mechanism that specifies an investment rule $I_0(\hat{\theta}) \in \{0, 1\}$, an abandonment rule $I_1(\hat{\theta}, \hat{\alpha}) \in \{0, 1\}$, target cash flows $c_i(\hat{\theta}, \hat{\alpha}) = (c_{i2}(\hat{\theta}, \hat{\alpha}), \ldots, c_{iT}(\hat{\theta}, \hat{\alpha}))$ to be delivered by division i, and associated compensation payments $s_i(\hat{\theta}, \hat{\alpha}) = (s_{i2}(\hat{\theta}, \hat{\alpha}), \ldots, s_{iT}(\hat{\theta}, \hat{\alpha}))$ contingent on the reports $(\hat{\theta}, \hat{\alpha})$. For any such revelation mechanism, $U_i(\hat{\theta}, \hat{\alpha} \mid \theta_i, \alpha_i)$ denotes manager i's utility contingent on the submitted reports $(\hat{\theta}, \hat{\alpha})$ and the true

[17] We can rearrange (17) as $(x_{it} - k_t \cdot \sum_{t=2}^{T} x_{it} \gamma^{t-1}) \cdot (\theta_i + \alpha_i) I_1 I_0 + (z_{it}(\hat{r}) \lambda_{1i}(\theta, \alpha) b_1 - k_t(b_1 - \sum_{j \neq i}^{N} PV_j(\theta_j, \alpha_j))) I_1 I_0 + (z_{it}(\hat{r}) \lambda_{0i}(\theta) b_0 - k_t b_0) I_0 = 0$ for all $(\theta_i, \alpha_i, I_0, I_1)$. We can interpret this as polynomial $P(Z)$ in variables $Z = (Z_1, Z_2, Z_3) = ((\theta_i + \alpha_i), I_1, I_0)$, i.e., $(x_{it} - k_t \cdot \sum_{t=2}^{T} x_{it} \gamma^{t-1}) \cdot Z_1 Z_2 Z_3 + (z_{it}(\hat{r}) \lambda_{1i}(\theta, \alpha) b_1 - k_t(b_1 - \sum_{j \neq i}^{N} PV_j(\theta_j, \alpha_j))) \cdot Z_2 Z_3 + (z_{it}(\hat{r}) \lambda_{0i}(\theta) b_0 - k_t b_0) \cdot Z_3 = 0$ for all (Z_1, Z_2, Z_3). Then $P(Z) = 0$ can only be the case if $P(Z)$ is the zero function. That is, the coefficients must be zero.

[18] Technically, $z_t(\hat{r}) = z_t^{RB}(r)$ is the only solution that solves the conditions for the single-division case, $N = 1$ (suppressing the index $i = 1$): $k_t = z_t^{RB}(r)$, $k_t b_1 = z_t(\hat{r}) b_1$, and $k_t b_0 = z_t(\hat{r}) b_0$ for $t = 2, \ldots, T$.

[19] The linear cost function is primarily chosen for didactic reasons. Our insights continue to hold if the managers' cost functions are increasing and convex in effort.

profitability parameters (θ_i, α_i). Then manager i's utility is given by

$$U_i(\hat\theta, \hat\alpha \mid \theta_i, \alpha_i) = \sum_{t=2}^{T} \gamma^{t-1}(s_{it}(\hat\theta, \hat\alpha) - v_{it} a_{it}(\hat\theta, \hat\alpha \mid \theta_i, \alpha_i)), \quad (20)$$

where $a_{it}(\hat\theta, \hat\alpha \mid \theta_i, \alpha_i) = \arg\min\{a_{it} \mid a_{it} + x_{it}(\theta_i + \alpha_i) \cdot I_1(\hat\theta, \hat\alpha) I_0(\hat\theta) \geq c_{it}(\hat\theta, \hat\alpha)\}$ is the minimum effort manager i exerts in order to achieve the target cash flow $c_{it}(\hat\theta, \hat\alpha)$. This equation reveals that each manager has an incentive to understate the project's profitabilities θ_i and α_i so that he can deliver the required target cash flows with less effort.

According to the revelation principle, we can restrict our attention to mechanisms that induce the managers to reveal their private information truthfully (e.g., Myerson 1979, 1981). We obtain the following sequential optimization problem:

$$\max_{\substack{(c_i(\theta,\alpha), s_i(\theta,\alpha),\\ I_0(\theta), I_1(\theta,\alpha))_{i=1}^N}} E_{\theta,\alpha}\left[\sum_{i=1}^{N}\sum_{t=2}^{T}\gamma^{t-1}(c_{it}(\theta,\alpha) - s_{it}(\theta,\alpha)) - (b_0 + b_1 I_1(\theta,\alpha)) I_0(\theta)\right]$$

subject to

$$(IC_1)\colon\ U_i(\hat\theta, \alpha_i, \hat\alpha_{-i} \mid \theta_i, \alpha_i) \geq U_i(\hat\theta, \hat\alpha_i, \hat\alpha_{-i} \mid \theta_i, \alpha_i) \quad \forall \hat\theta, \hat\alpha, \theta_i, \alpha_i, i,$$

$$(IC_0)\colon\ E_\alpha[U_i(\theta_i, \hat\theta_{-i}, \alpha \mid \theta_i, \alpha_i)] \geq E_\alpha[U_i(\hat\theta_i, \hat\theta_{-i}, \alpha \mid \theta_i, \alpha_i)] \quad \forall \hat\theta, \theta_i, i,$$

$$(PC)\colon\ E_{\theta_{-i},\alpha}[U_i(\theta, \alpha \mid \theta_i, \alpha_i)] \geq 0 \quad \forall \theta_i, i.$$

The participation constraints (PC) require that each manager break even in expectation over the other managers' types. The incentive compatibility constraints (IC_1) and (IC_0) ensure sequential truthful reporting in dominant strategies at dates 1 and 0, respectively. In our setting, imposing a dominant-strategy equilibrium rather than a sequential Bayesian-Nash equilibrium does not change the equilibrium payoffs of any party.[20] Rather, we get implementation in sequential dominant strategies without cost. We denote the second-best solution by $(c_i^\dagger(\theta,\alpha), s_i^\dagger(\theta,\alpha), I_0^\dagger(\theta), I_1^\dagger(\theta,\alpha))_{i=1}^N$.

Using the standard approach to solving adverse selection problems, we replace the two incentive constraints by their local counterparts and determine each manager's expected information premium. Since manager i's utility is linear in a_{it}, it is optimal to induce the boundary values. To concentrate on the implementation issue, we assume throughout our analysis that it is always optimal to induce the maximum effort level $\bar a_{it}$ for all i, t.[21] The sequential investment problem can then be written as follows (ignoring the constant $\sum_{i=1}^N \sum_{t=2}^T \gamma^{t-1}(1 - v_{it})\bar a_{it}$):

$$\max_{I_0(\theta), I_1(\theta,\alpha)} E_{\theta,\alpha}\left[\sum_{i=1}^{N}((PV_i(\theta_i,\alpha_i) - \kappa_i H_i(\theta_i) - b_1) \cdot I_1(\theta,\alpha) - b_0) I_0(\theta)\right], \quad (21)$$

where $\kappa_i H_i(\theta_i) = \sum_{t=2}^T \gamma^{t-1} v_{it} x_{it} H_i(\theta_i)$ is the present value of division i's virtual costs at date 1. Equation (21) is equivalent to (3) in the goal-congruence section except that the present value of the virtual costs associated with each division, $\kappa_i H_i(\theta_i)$, has to be considered when the project is undertaken ex post, i.e., when $I_1 = I_0 = 1$. The optimal contract requires the firm to pay an information premium to induce truth telling at date 0, but it will only be paid ex post in states in which the project is continued at date 1. If the project is abandoned at date 1, the firm can perfectly infer the managers' effort levels. Further, the firm pays an information premium only for precontract private information because any rents associated with postcontract private information can be extracted by the firm up front.

The optimal abandonment and investment decisions are given below. At date 1, the firm invests further if the firmwide present value of the cash inflows from investment less the associated virtual costs exceeds the additional investment costs:

$$I_1^\dagger(\theta,\alpha) = \begin{cases} 1 & \text{if } \sum_{i=1}^{N}(PV_i(\theta_i,\alpha_i) - \kappa_i H_i(\theta_i)) \geq b_1, \\ 0 & \text{otherwise.}\end{cases} \quad (22)$$

Considering the optimal abandonment decision, the firm initiates the common project if the expected firmwide net present value less the associated virtual costs exceeds the initial investment cost:

$$I_0^\dagger(\theta) = \begin{cases} 1 & \text{if } E_\alpha\left[\left(\sum_{i=1}^{N}(PV_i(\theta_i,\alpha_i) - \kappa_i H_i(\theta_i)) - b_1\right) \cdot I_1^\dagger(\theta,\alpha)\right] \geq b_0, \\ 0 & \text{otherwise.}\end{cases} \quad (23)$$

[20] Similar to Mookherjee and Reichelstein (1992), we calculate the (expected) information premium for each manager under both equilibrium concepts and find they are the same. However, unlike Baldenius et al. (2007), we cannot infer this result from Mookherjee and Reichelstein (1992) directly in our sequential-investment-stage setting.

[21] This assumption is consistent with previous literature (e.g., Baldenius et al. 2007, Baldenius 2003, Dutta 2003). In our setting, it is optimal for the firm to induce the maximum effort level for each division in each period, i.e., $a_{it}(\theta,\alpha) = \bar a_{it}$ for all (θ, α, i, t), if the maximum effort level is sufficiently large, i.e., $\bar a_{it} \geq v_{it} x_{it} H_i(\underline{\theta}_i)/(1 - v_{it})$ for all i, t.

Because the virtual costs that arise from the agency problem increase the cost of investment, the optimal solution calls for investment in a smaller set of states at both stages relative to the goal-congruence case.

Observation 1. In the presence of the agency conflict, rationing occurs at both stages so that the firm initiates the project less often and abandons it more often; i.e., $I_0^\dagger(\theta) \le I_0^*(\theta)$ and $I_1^\dagger(\theta,\alpha) \le I_1^*(\theta,\alpha)$ and there exist some (θ,α) such that $I_0^\dagger(\theta) < I_0^*(\theta)$ and $I_1^\dagger(\theta,\alpha) < I_1^*(\theta,\alpha)$.

In the following analysis we demonstrate how the robust goal-congruent capital budgeting mechanism identified in the previous section provides dominant incentives for each manager to report his private information truthfully and make efficient investment decisions regardless of his incentive weights. A capital budgeting mechanism is said to be *optimal* if there exist linear compensation schemes based on the class of performance measures identified in (6),

$$s_{it} = \phi_{it}(\hat\theta,\hat\alpha) + \beta_{it}(\hat\theta,\hat\alpha)\pi_{it}(\cdot) \quad \text{for all } t = 2,\ldots,T \text{ and } i = 1,\ldots,N, \tag{24}$$

that achieve the same payoff for the firm as the second-best mechanism identified above (e.g., Melumad and Reichelstein 1989). Here, ϕ_{it} denotes the fixed payment and β_{it} is the bonus coefficient.

We adjust our previous assumption to incorporate the virtual costs. Assumption 2 ensures that the abandonment decision is nondeterministic at date 0 and that ex post each division is necessary for the overall investment project to be profitable.

Assumption 2. *For every division $i = 1,\ldots,N$, the following inequalities hold for all θ, α_{-i}: $PV_i(\theta_i,\bar\alpha_i) - \kappa_i H_i(\theta_i) + \sum_{j\ne i}^N (PV_j(\theta_j,\alpha_j) - \kappa_j H_j(\theta_j)) > b_1 > PV_i(\theta_i,\underline{\alpha}_i) - \kappa_i H_i(\theta_i) + \sum_{j\ne i}^N (PV_j(\theta_j,\alpha_j) - \kappa_j H_j(\theta_j))$,*

The firm can induce the optimal effort level by setting the bonus coefficient equal to the manager's disutility parameter; i.e., $\beta_{it} = v_{it}$. To characterize the capital budgeting mechanism, we define each division's critical profitability parameter under adverse selection, $\alpha_i^\dagger(\hat\theta,\hat\alpha_{-i})$, as the solution to the following (noting that Assumption 2 implies that $\alpha_i^\dagger(\hat\theta,\hat\alpha_{-i})$ exists):

$$(PV_i(\hat\theta_i,\alpha_i^\dagger(\hat\theta,\hat\alpha_{-i})) - \kappa_i H_i(\hat\theta_i)) + \sum_{j\ne i}^N (PV_j(\hat\theta_j,\hat\alpha_j) - \kappa_j H_j(\hat\theta_j)) = b_1. \tag{25}$$

Ceteris paribus, the critical profitability parameter of division i, $\alpha_i^\dagger(\hat\theta,\hat\alpha_{-i})$, is increasing in the present value of division i's own virtual costs, $\kappa_i H_i(\hat\theta_i)$, as well as in the other divisions' virtual costs, $\sum_{j\ne i}^N \kappa_j H_j(\hat\theta_j)$. Similar to Proposition 1, we obtain the following result.

Proposition 2. *Given Assumption 2, the following sequential capital budgeting mechanism is optimal. The date 0 asset-sharing rule is the* relative growth profile asset-sharing rule (RGP rule):

$$\lambda_{0i} = \frac{\sum_{t=2}^T x_{it}(1+\hat r_0)^{-(t-1)}}{\sum_{t=2}^T x_{it}(1+r)^{-(t-1)}}, \tag{26}$$

the date 1 asset-sharing rule is given by

$$\lambda_{1i}(\hat\theta,\hat\alpha) = \frac{\sum_{t=2}^T x_{it}(1+\hat r_1(\hat\theta,\hat\alpha))^{-(t-1)}(\hat\theta_i + \alpha_i^\dagger(\hat\theta,\hat\alpha_{-i}))}{b_1}, \tag{27}$$

the associated capital charge rate $\hat r_k(\cdot)$ satisfies (for $k = 0,1$)

$$\sum_{i=1}^N \lambda_{ti}(\cdot) = 1, \tag{28}$$

and the intertemporal cost-allocation rule,

$$z_{it}^{RB}(\hat r_k(\cdot)) = \frac{x_{it}}{\sum_{t=2}^T x_{it}(1+\hat r_k(\cdot))^{-(t-1)}}, \tag{29}$$

is the relative benefit cost-allocation rule (RBCA rule) *calculated with the associated capital charge rate $\hat r_k(\cdot)$.*

As before, the optimal period t performance metric for division i can be restated as follows (recall $z_{it}^{RB}(r)PV_i(\theta_i,\alpha_i) = x_{it}(\theta_i+\alpha_i)$):

$$\pi_{it} = z_{it}^{RB}(r)\Bigg(\bigg(PV_i(\theta_i,\alpha_i) - \kappa_i H_i(\hat\theta_i) + \sum_{j\ne i}^N (PV_j(\hat\theta_j,\hat\alpha_j) - \kappa_j H_j(\hat\theta_j)) - b_1\bigg) I_1 - b_0\Bigg) I_0 + a_{it}, \tag{30}$$

using

$$z_{it}^{RB}(\hat r_1(\cdot))\lambda_{1i}(\cdot)b_1 = z_{it}^{RB}(r)\bigg(\kappa_i H_i(\hat\theta_i) - \sum_{j\ne i}^N (PV_j(\hat\theta_j,\hat\alpha_j) - \kappa_j H_j(\hat\theta_j)) + b_1\bigg)$$

and $z_{it}^{RB}(\hat r_0)\lambda_{0i}b_0 = z_{it}^{RB}(r)b_0$. Given truthful reporting by the divisions, the performance measure π_{it} is a multiple of the firm's objective function (21), providing dominant incentives for each manager to make efficient investment decisions regardless of his incentives weights.

Corollary 5. *The date 0 capital charge rate, $\hat r_0$, and the asset-sharing rule, $\hat\lambda_0$, are not affected by the agency conflict; i.e., they are identical to the date 0 capital charge rate and asset-sharing rule as characterized in Proposition 1.*

Even though the agency conflict does induce capital rationing at date 0 (see Observation 1), the date 0 capital charge rate and the asset-sharing rule are not functions of the agency costs. All agency costs must be incorporated into the date 1 cost charge to ensure efficient decision making in the continuation problem; naively including them also at date 0 would constitute double counting. The date 1 asset-sharing rule and capital charge rate, which incorporate the agency costs through the critical profitability parameter $\alpha_i^\dagger(\hat{\theta}, \hat{\alpha}_{-i})$, are similar to those that arise in the single-stage investment problem with adverse selection described in Baldenius et al. (2007). Consistent with previous results (e.g., Antle and Eppen 1985, Baldenius et al. 2007), more capital rationing as a result of the agency conflict leads to a higher date 1 capital charge rate $\hat{r}_1(\cdot)$, but as highlighted by Corollary 5, the agency conflict does not translate to a higher date 0 capital charge rate $\hat{r}_0(\cdot)$.

5. Conclusion

This paper has studied the optimal design of a capital budgeting mechanism for multistage investments in shared (cooperative) assets. Our model shows that the interaction between multiple divisions and multiple investment stages requires two quite different interdivisional asset cost-sharing rules and associated capital charge rates to arrive at fixed cost allocations that provide appropriate investment incentives. The first-stage capital charge rate must be set above the firm's cost of capital, whereas the second-stage capital charge rate must be set below the firm's cost of capital. This finding supports anecdotal evidence regarding within-firm variation in capital charge rates for different types of projects and at different stages of investment (e.g., Mukherjee and Hingorani 1999).[22]

Empirical studies suggest that firms, on average, apply capital charge rates above the firm's cost of capital. Typically, theorists explain this empirical finding with (i) divisional agency conflicts or (ii) competition between divisions.[23] Our result provides another rationale. In the absence of an agency conflict, interdivisional synergy in combination with a nondeterministic abandonment option leads to a capital charge rate above the cost of capital. This is somewhat surprising because one might conjecture that both factors, synergy and an abandonment option, should lower capital charge rates. As discussed previously, our result arises because the positive externalities generated by each division's investment decision must be incorporated into the first- and second-stage asset-sharing rules and capital charge rates differently, even if the two assets are identical. In the presence of agency conflicts, we find that the second-stage capital charge rate increases in the severity of the divisional agency conflicts, consistent with standard results (e.g., Antle and Eppen 1985). In contrast, the first-stage capital charge rate is not altered when agency conflicts are introduced, demonstrating that agency costs can lead to capital rationing without leading to an increased capital charge rate.

Finally, our mechanism dictates that the individual divisions will always be held responsible for first-stage investment costs, regardless of the abandonment decision at the second stage. The relative growth profile asset-sharing rule (RGP sharing rule), which must be applied in the first stage, allocates the investment cost according to each division's growth profile, regardless of the relative benefits that each division derives from the shared asset. A smaller share of the investment cost is allocated to divisions with relatively more back-loaded cash flow profiles (i.e., cash flows arrive later), and the RGP rule corresponds to equal cost sharing when all cash inflows arrive in a single period. Accordingly, equal cost sharing can be optimal even when the shared asset provides quite different benefits to the individual divisions, highlighting that equal cost sharing can be optimal in a wider variety of circumstances than previously assumed.

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Appendix A

Model Variables

A_{it}	Book value per unit for division i at the end of period t
b_0	Cash outlay required for initial asset purchase at date 0
b_1	Cash outlay required for second asset purchase at date 1
c_{it}	Division i's cash flow at date t
d_{it}	Depreciation rate for division i at date t
$F_i(\theta_i)$	Probability distribution of θ_i
$f_i(\theta_i)$	Density function for θ_i

[22] The analytical finance literature has also identified the use of multiple hurdle rates across divisions within the same firm (see the discussion in Bernardo et al. 2006).

[23] Consistent with agency theory, Baldenius et al. (2007) show that a sufficiently severe agency problem in a single-investment-stage setting can push the capital charge rate for shared investments above the firm's cost of capital.

$G_i(\alpha_i)$ Probability distribution of α_i
$g_i(\alpha_i)$ Density function for α_i
I_0 Indicator variable denoting date 0 investment decision
I_0^* Indicator variable denoting optimal date 0 investment decision
I_1 Indicator variable denoting date 1 investment decision
I_1^* Indicator variable denoting optimal date 1 investment decision
i Index for divisions
N Number of divisions
PV_i Present value of divisions i's cash flows, discounted to period $t=1$
R_1 Return rate of continuation project at date 1
r Firm's cost of capital
$\hat{r}_k$ Firmwide capital charge rate applied to date k investment cost
T Number of time periods
t Index for time periods
x_{it} Commonly observed intertemporal growth profile of division i at date t
$z_{it}(\hat{r})$ Intertemporal cost-allocation rule given a capital charge rate, $\hat{r}$
$z_{it}^{RB}(\hat{r})$ Relative benefit cost-allocation rule given a capital charge rate, $\hat{r}$
α_i Division i's privately observed productivity parameter (realized at date 1)
$\hat{\alpha}_i$ Division i's report about its private information α_i
α_i^* Division i's *critical profitability parameter* (absent adverse selection)
β_i Intertemporal growth parameter for division i under geometric cash flows
β Common intertemporal growth parameter for all divisions under geometric cash flows
γ Firm's discount factor equal to $1/(1+r)$
θ_i Division i's privately observed productivity parameter (realized at date 0)
$\hat{\theta}_i$ Division i's report about its private information θ_i
λ_{ki} Share of date k investment cost allocated to division i (asset-sharing rule)
π_{it} Division i's performance measure at date t

Additional Variables Introduced in §4 (Adverse Selection Setting)

a_{it} Hidden managerial effort in division i at date t
c_i Target cash flows for manager i at date t
$c_i^\dagger$ Target cash flows for manager i at date t under second-best solution
$H_i(\theta_i)$ Inverse hazard rate for distribution of θ_i
$I_0^\dagger$ Indicator variable denoting optimal date 0 investment decision
$I_1^\dagger$ Indicator variable denoting optimal date 1 investment decision
s_{it} Manager i's compensation payment at date t
$s_{it}^\dagger$ Manager i's compensation payment at date t under second-best solution
U_i Manager i's utility function
v_{it} Manager i's disutility of effort at date t
$\alpha_i^\dagger$ Division i's critical profitability parameter under the second-best solution
β_{it} Bonus coefficient in manager i's compensation payment at date t
$\kappa_i H_i(\theta_i)$ Present value of division i's virtual costs, discounted to $t=1$
ϕ_{it} Fixed portion of manager i's compensation payment at date t

Appendix B. Proofs

Proof of Proposition 1. As shown in the text, the capital budgeting mechanism is robust. Now, we prove necessity. We consider all performance measures of the form

$$\pi_{it} = c_{it}(\theta_i, \alpha_i, I_1, I_0) - (z_{it}(\hat{r}_1)\lambda_{1i}(\hat{\theta}, \hat{\alpha})b_1 I_1 + z_{it}(\hat{r}_0)\lambda_{0i}(\hat{\theta})b_0)I_0. \quad \text{(B1)}$$

We fix i and t. Using the relation (recall that $z_{it}^{RB}(r) = x_{it}/\sum_{t=2}^{T} x_{it}\gamma^{t-1}$)

$$PV_i(\theta_i, \alpha_i)I_1 I_0 = \sum_{t=2}^{T} x_{it}(\theta_i+\alpha_i)\gamma^{t-1} I_1 I_0 = c_{it}(\theta_i, \alpha_i, I_1, I_0)/z_{it}^{RB}(r), \quad \text{(B2)}$$

we can restate the residual income measure equivalently as

$$\pi_{it} = z_{it}^{RB}(r)\cdot\Big(PV_i(\theta_i, \alpha_i)I_1 I_0 - z_{it}^{RB}(r)^{-1} \cdot (z_{it}(\hat{r}_1)\lambda_{1i}(\hat{\theta}, \hat{\alpha})b_1 I_1 + z_{it}(\hat{r}_0)\lambda_{0i}(\hat{\theta})b_0)I_0\Big). \quad \text{(B3)}$$

As outlined, the firmwide objective function is given by

$$\left(\left(PV_i(\theta_i, \alpha_i) + \sum_{j\neq i}^{N} PV_j(\theta_j, \alpha_j) - b_1\right)I_1 - b_0\right)I_0. \quad \text{(B4)}$$

To induce the optimal investment decision I_1, (B3) and (B4) must have the same roots for all $(I_1, \theta_i, \alpha_i)$. (See Footnote 17.) Noting that any optimal metrics must induce truth telling, this condition can only be satisfied if

$$z_{it}(\hat{r}_1)\lambda_{1i}(\theta, \alpha)b_1 I_1 = z_{it}^{RB}(r)\left(b_1 - \sum_{j\neq i}^{N} PV_j(\theta_j, \alpha_j)\right)I_1. \quad \text{(B5)}$$

Similarly, to get the optimal investment decision I_0, (B3) and (B4) must have the same roots for all (I_0, θ_i). As before, this condition can only be satisfied if

$$(z_{it}(\hat{r}_1)\lambda_{1i}(\theta, \alpha)b_1 I_1 + z_{it}(\hat{r}_0)\lambda_{0i}(\theta)b_0)I_0 = z_{it}^{RB}(r)\left(\left(b_1 - \sum_{j\neq i}^{N} PV_j(\theta_j, \alpha_j)\right)I_1 + b_0\right)I_0, \quad \text{(B6)}$$

leading to (12): $z_{it}(\hat{r}_0)\lambda_{0i}(\theta)b_0 = z_{it}^{RB}(r)b_0$.

Now we turn our attention to (B5) and (B6), which yields for $t, \tilde{t} = 2, \ldots, T$:

$$\frac{z_{it}(\hat{r}_0)}{z_{i\tilde{t}}(\hat{r}_0)} = \frac{z_{it}^{RB}(r)}{z_{i\tilde{t}}^{RB}(r)} = \frac{x_{it}}{x_{i\tilde{t}}} \quad \text{and} \quad \frac{z_{it}(\hat{r}_1)}{z_{i\tilde{t}}(\hat{r}_1)} = \frac{z_{it}^{RB}(r)}{z_{i\tilde{t}}^{RB}(r)} = \frac{x_{it}}{x_{i\tilde{t}}}. \quad \text{(B7)}$$

Hence, we get $z_{it}(\hat{r}_k) = (x_{it}/x_{i\tilde{t}})z_{i\tilde{t}}(\hat{r}_k)$ for $k=0,1$. According to the clean surplus relationship, the intertemporal cost-allocation rules satisfy the conservation property with respect to the associated capital charge rate, $\sum_{t=2}^{T} z_{it}(\hat{r}_k)\cdot(1+\hat{r}_k)^{-(t-1)}=1$. Hence, we get

$$\sum_{t=2}^{T}\frac{x_{it}z_{i\tilde{t}}(\hat{r}_k)}{x_{i\tilde{t}}}(1+\hat{r}_k)^{-(t-1)}=1\rightarrow z_{i\tilde{t}}(\hat{r}_k)=\frac{x_{i\tilde{t}}}{\sum_{t=2}^{T}x_{it}(1+\hat{r}_k)^{-(t-1)}}=z_{i\tilde{t}}^{RB}(\hat{r}_k),\quad \text{(B8)}$$

and, thus, $z_{it}(\hat{r}_k)=x_{it}/\sum_{t=2}^{T}x_{it}(1+\hat{r}_k)^{-(t-1)}=z_{it}^{RB}(\hat{r}_k)$. Using the comprehensive income requirement, $\sum_{i=1}^{N}\lambda_{0i}=\sum_{i=1}^{N}\lambda_{1i}=1$, shows the result. □

Proof of Corollary 1. (i) For $T=2$, the asset-sharing rule reduces to $\lambda_{0i}=(1+r)/(1+\hat{r}_0)=1/N$ for all i. The latter condition follows from the requirement $\sum_{i=1}^{N}\lambda_{0i}=1$. (ii) Using $\sum_{i=1}^{N}\lambda_{0i}=1$, we get $\lambda_{0j}=\sum_{t=2}^{T}k_{ij}\cdot x_{it}(1+\hat{r}_0)^{-(t-1)}/\sum_{t=2}^{T}k_{ij}x_{it}(1+r)^{-(t-1)}=\lambda_{0i}=1/N$. □

Proof of Corollary 2. The asset-sharing rule λ_{0i} is strictly decreasing in $\hat{r}_0$. Noting that $\lambda_{0i}=1$ for $\hat{r}_0=r$ establishes the result. □

Proof of Corollary 3. See proofs of Corollaries 1 and 2 in Baldenius et al. (2007). □

Proof of Corollary 4. As outlined in §3.2. It remains to show the $N=1$ case. For $N=1$ it is sufficient to set $\lambda_{0i}(\cdot)=1$ and $\lambda_{1i}(\cdot)=1$ and the capital charge rate equal to r to satisfy (17). □

Derivation of the Unconstrained Optimization Problem (21). Throughout this proof, we assume the firm induces the maximum effort level; i.e., $a_{it}(\theta,\alpha)=\bar{a}_{it}$ for all (θ,α,i,t). We first prove the following lemma, which shows how to replace the two incentive constraints, (IC_0) and (IC_1), by their local counterparts.

Lemma 1. *We obtain the following results*:

(i) *The incentive constraints* (IC_1) *can be replaced by the following condition*:

$$U_i(\hat{\theta},\alpha_i,\hat{\alpha}_{-i}\mid\theta_i,\alpha_i)=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}\int_{\underline{\alpha}_i}^{\alpha_i}I_1(\hat{\theta},q_i,\hat{\alpha}_{-i})I_0(\hat{\theta})\,dq_i+U_i(\hat{\theta},\underline{\alpha}_i,\hat{\alpha}_{-i}\mid\theta_i,\underline{\alpha}_i)\quad\text{(B9)}$$

$\forall(\theta_i,\hat{\theta},\alpha_i,\hat{\alpha}_{-i})$, *if the function* $q_i\rightarrow I_1(\hat{\theta},q_i,\hat{\alpha}_{-i})I_0(\hat{\theta})$ *is nondecreasing for all* $(\hat{\theta},\hat{\alpha}_{-i})$.

(ii) *The incentive constraints* (IC_0) *can be replaced by the following condition*:

$$E_\alpha[U_i(\theta_i,\hat{\theta}_{-i},\alpha\mid\theta_i,\alpha_i)]=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}E_\alpha\left[\int_{\underline{\theta}_i}^{\theta_i}I_1(q_i,\hat{\theta}_{-i},\alpha)I_0(q_i,\hat{\theta}_{-i})\,dq_i\right]+E_\alpha[U_i(\underline{\theta}_i,\hat{\theta}_{-i},\alpha\mid\underline{\theta}_i,\alpha_i)]\quad\text{(B10)}$$

$\forall(\theta_i,\hat{\theta}_{-i})$, *if the function* $q_i\rightarrow E_\alpha[I_1(q_i,\hat{\theta}_{-i},\alpha)I_0(q_i,\hat{\theta}_{-i})]$ *is nondecreasing for all* $\hat{\theta}_{-i}$.

Proof of Lemma 1. As is standard, we replace the two incentive constraints (IC_1) and (IC_0) by their local counterparts and determine each manager's expected information premium.

(i) Invoking the envelope theorem yields

$$\frac{d}{d\hat{\alpha}_i}U_i(\hat{\theta},\hat{\alpha}\mid\theta_i,\hat{\alpha}_i)\bigg|_{\hat{\alpha}_i=\alpha_i}=\frac{\partial}{\partial\alpha_i}U_i(\hat{\theta},\hat{\alpha}\mid\theta_i,\alpha_i)\bigg|_{\hat{\alpha}_i=\alpha_i}=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}I_1(\hat{\theta},\alpha_i,\hat{\alpha}_{-i})I_0(\hat{\theta}).\quad\text{(B11)}$$

Integrating the above equation leads to

$$U_i(\hat{\theta},\alpha_i,\hat{\alpha}_{-i}\mid\theta_i,\alpha_i)=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}\int_{\underline{\alpha}_i}^{\alpha_i}I_1(\hat{\theta},q_i,\hat{\alpha}_{-i})I_0(\hat{\theta})\,dq_i+U_i(\hat{\theta},\underline{\alpha}_i,\hat{\alpha}_{-i}\mid\theta_i,\underline{\alpha}_i)\quad\text{(B12)}$$

$\forall(\hat{\theta},\alpha_i,\hat{\alpha}_{-i})$. It is standard to show that the above equation implies the incentive compatibility constraints (IC_1), if the function $q_i\rightarrow I_1(\hat{\theta},q_i,\hat{\alpha}_{-i})I_0(\hat{\theta})$ is nondecreasing for all $(\hat{\theta},\hat{\alpha}_{-i})$.

(ii) Invoking the envelope theorem yields:

$$\frac{d}{d\hat{\theta}_i}E_\alpha[U_i(\hat{\theta},\alpha\mid\hat{\theta}_i,\alpha_i)]\bigg|_{\hat{\theta}_i=\theta_i}=\frac{\partial}{\partial\theta_i}E_\alpha[U_i(\hat{\theta},\alpha\mid\theta_i,\alpha_i)]\bigg|_{\hat{\theta}_i=\theta_i}=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}E_\alpha[I_1(\theta_i,\hat{\theta}_{-i},\alpha)I_0(\theta)].\quad\text{(B13)}$$

Integration leads to

$$E_\alpha[U_i(\theta_i,\hat{\theta}_{-i},\alpha\mid\theta_i,\alpha_i)]=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}E_\alpha\left[\int_{\underline{\theta}_i}^{\theta_i}I_1(q_i,\hat{\theta}_{-i},\alpha)I_0(q_i,\hat{\theta}_{-i})\,dq_i\right]+E_\alpha[U_i(\underline{\theta}_i,\hat{\theta}_{-i},\alpha\mid\underline{\theta}_i,\alpha_i)]\quad\text{(B14)}$$

for all $(\theta_i,\hat{\theta}_{-i})$.

Finally, assuming without loss of generality (w.l.o.g.) $\hat{\theta}_i<\theta_i$ and $E_\alpha[U_i(\hat{\theta},\alpha\mid\cdot)]>E_\alpha[U_i(\theta_i,\hat{\theta}_{-i},\alpha\mid\cdot)]$ implies

$$\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}\int_{\hat{\theta}_i}^{\theta_i}[E_\alpha[I_1(\hat{\theta}_i,\hat{\theta}_{-i},\alpha)I_0(\hat{\theta}_i,\hat{\theta}_{-i})]-E_\alpha[I_1(q_i,\hat{\theta}_{-i},\alpha)I_0(q_i,\hat{\theta}_{-i})]]\,dq_i>0.\quad\text{(B15)}$$

This is a contradiction, if $q_i\longrightarrow E_\alpha[I_1(q_i,\hat{\theta}_{-i},\alpha)I_0(q_i,\hat{\theta}_{-i})]$ is nondecreasing. Thus, (ii) and Lemma 1 is proven.

Next, we show that the sequential adverse selection problem can be restated equivalently as the unconstrained optimization problem (21). Setting $E_{\alpha}[U_i(\underline{\theta}_i,\hat{\theta}_{-i},\alpha\mid\underline{\theta}_i,\alpha_i)]=0$ minimizes manager i's expected information rents while satisfying the participation constraints, (PC). Using Lemma 1(ii) and $U_i(s_{it}(\cdot),\bar{a}_{it})=\sum_{t=2}^{T}\gamma^{t-1}(s_{it}(\cdot)-v_{it}\bar{a}_{it})$ yields

$$E_\alpha\left[\sum_{t=2}^{T}\gamma^{t-1}s_{it}(\cdot)\right]=\sum_{t=2}^{T}\gamma^{t-1}v_{it}x_{it}E_\alpha\left[\int_{\underline{\theta}_i}^{\theta_i}I_1(q_i,\theta_{-i},\alpha)\,I_0(q_i,\theta_{-i})\,dq_i\right]+\sum_{t=2}^{T}\gamma^{t-1}v_{it}\bar{a}_{it}.\quad\text{(B16)}$$

Changing the order of integration and using integration by parts yields

$$E_{\theta_{-i}}\left[\int_{\underline{\theta}_i}^{\bar{\theta}_i} E_\alpha\left[\int_{\underline{\theta}_i}^{\theta_i} I_1(q_i,\theta_{-i},\alpha)I_0(q_i,\theta_{-i})\,dq_i\right]f_i(\theta_i)\,d\theta_i\right] = E_{\theta,\alpha}[H_i(\theta_i)I_1(\theta,\alpha)I_0(\theta)]. \quad \text{(B17)}$$

Using Equations (B16) and (B17) in the principal's objective function yields the unconstrained optimization problem (21).

Finally, for sake of completeness, setting $U_i(\hat{\theta},\underline{\alpha}_i,\hat{\alpha}_{-i}\mid\theta_i,\underline{\alpha}_i) = E_\alpha[U_i(\theta_i,\hat{\theta}_{-i},\alpha\mid\theta_i,\alpha_i)] - E_{\alpha_i}[\sum_{t=2}^T\gamma^{t-1}v_{it}x_{it}\cdot\int_{\underline{\alpha}_i}^{\alpha_i} I_1(\hat{\theta},q_i,\hat{\alpha}_{-i})I_0(\hat{\theta})\,dq_i]$ ensures that Lemmas 1 (i) and (ii) are satisfied (and thus the incentive constraints (IC_0) and (IC_1)). □

Proof of Observation 1. A comparison of (22), (23), (4), and (5) yields Observation 1. □

Proof of Proposition 2. As outlined in the text, the performance measure is given by

$$\pi_{it} = z_{it}^{RB}(r)\left(\left(PV_i(\theta_i,\alpha_i)-\kappa_iH_i(\hat{\theta}_i)+\sum_{j\neq i}^N(PV_j(\hat{\theta}_j,\hat{\alpha}_j) - \kappa_jH_j(\hat{\theta}_j))-b_1\right)I_1-b_0\right)I_0+a_{it}. \quad \text{(B18)}$$

Noting that manager i's decisions, I_0 and I_1, depend on his true productivity and the reports, manager i will choose $I_1(\theta_i,\hat{\theta},\alpha_i,\hat{\alpha})=1$ if and only if

$$PV_i(\theta_i,\alpha_i)-\kappa_iH_i(\hat{\theta}_i)+\sum_{j\neq i}^N(PV_j(\hat{\theta}_j,\hat{\alpha}_j)-\kappa_jH_j(\hat{\theta}_j))\geq b_1 \quad \text{(B19)}$$

and $I_0(\theta_i,\hat{\theta})=1$ if and only if (anticipating truthful reporting at $t=1$)

$$E_\alpha\left[\left(PV_i(\theta_i,\alpha_i)-\kappa_iH_i(\hat{\theta}_i)+\sum_{j\neq i}^N(PV_j(\hat{\theta}_j,\alpha_j)-\kappa_jH_j(\hat{\theta}_j))-b_1\right)\cdot I_1(\theta_i,\hat{\theta},\alpha_i,\alpha)\right]\geq b_0. \quad \text{(B20)}$$

The first equation shows that $I_1(\theta_i,\hat{\theta},\alpha_i,\hat{\alpha})$ is nondecreasing in θ_i and $\hat{\theta}$. The second equation and the monotonicity of $I_1(\theta_i,\hat{\theta},\alpha_i,\alpha)$ reveal that $I_0(\theta_i,\hat{\theta})$ is nondecreasing in θ_i and $\hat{\theta}$. Hence, $\hat{\theta}_i\to I_1(q_i,\hat{\theta}_i,\hat{\theta}_{-i},\alpha_i,\alpha)\cdot I_0(q_i,\hat{\theta}_i,\hat{\theta}_{-i})$ is nondecreasing.

It remains to show that manager i reports $\hat{\theta}_i$ truthfully in dominant strategies. Calculating $E[\pi_{it}(\cdot)]$, we find that manager i's expected utility is an affine function of (omitting the fixed payment):

$$\left(E_\alpha\left[\left(PV_i(\theta_i,\alpha_i)-\kappa_iH_i(\hat{\theta}_i)+\sum_{j\neq i}^N VPV_j(\hat{\theta}_j,\alpha_j)-b_1\right)\cdot I_1(\theta_i,\hat{\theta},\alpha_i,\alpha)\right]-b_0\right)I_0(\theta_i,\hat{\theta}), \quad \text{(B21)}$$

where $VPV_j(\hat{\theta}_j,\alpha_j) = PV_j(\hat{\theta}_j,\alpha_j)-\kappa_jH_j(\hat{\theta}_j)$. The incentive constraints imply (invoking the envelope theorem and Leibniz's rule, noting that $(\partial/\partial\theta_i)I_0(\theta_i,\hat{\theta})|_{\hat{\theta}_i=\theta_i}=0$ almost everywhere (a.e.) and $(\partial/\partial\theta_i)I_0(\theta_i,\hat{\theta})=0$ a.e. $\forall\hat{\theta}$ and setting $E_\alpha[U_i(\underline{\theta}_i,\theta_{-i},\alpha\mid\underline{\theta}_i,\alpha_i)]=0$):

$$E_\alpha[U_i(\theta,\alpha\mid\theta_i,\alpha_i)] = \sum_{t=2}^T\gamma^{t-1}v_{it}x_{it}E_\alpha\left[\int_{\underline{\theta}_i}^{\theta_i} I_1(q_i,q_i,\theta_{-i},\alpha_i,\alpha)\cdot I_0(q_i,q_i,\theta_{-i})\,dq_i\right]\quad\forall\theta. \quad \text{(B22)}$$

Next, we show that the contract induces truthful reporting. This follows by contradiction. Assuming w.l.o.g. $\hat{\theta}_i<\theta_i$ and $E_\alpha[U_i(\hat{\theta}_i,\theta_{-i},\alpha\mid\theta_i,\alpha_i)]>E_\alpha[U_i(\theta,\alpha\mid\theta_i,\alpha_i)]$, we get

$$\int_{\hat{\theta}_i}^{\theta_i} E_\alpha[I_1(q_i,\hat{\theta}_i,\theta_{-i},\alpha_i,\alpha)I_0(q_i,\hat{\theta}_i,\theta_{-i}) - I_1(q_i,q_i,\theta_{-i},\alpha_i,\alpha)I_0(q_i,q_i,\theta_{-i})]\,dq_i>0. \quad \text{(B23)}$$

This contradicts that $\hat{\theta}_i\to I_1(q_i,\hat{\theta}_i,\theta_{-i},\alpha_i,\alpha)I_0(q_i,\hat{\theta}_i,\theta_{-i})$ is nondecreasing. Equation (B22) shows that the manager receives the same information premium as under the optimal centralized mechanism. Hence, the investment decisions $I_0(\cdot)$ and $I_1(\cdot)$ coincide with those of the optimal centralized mechanism. Thus, according to the revenue equivalence theorem, the residual-income-based contract must be optimal. The remainder of the proof follows along the lines of Proposition 1. □

Proof of Corollary 5. Follows directly from (26). □

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