Three Essays on New Product Development: Creating Value from Internal and External Innovation

Inaugural Dissertation
to Obtain the Academic Degree of
a Doctor in Business Administration
at the University of Mannheim

submitted by

Hossein Nikpayam

Mannheim

Dean: *Joachim Lutz*
Referent: *Prof. Dr. Moritz Fleischmann*
Correferent: *Prof. Dr. Jochen Schlapp*

Day of oral examination: 11 November 2022 to my parents, Soheila and Amir

Acknowledgements

This dissertation would not have been possible without the inspiration, encouragement, and support of many people that have accompanied me during the last five years.

First and foremost, I would like to thank Moritz Fleischmann, and Jochen Schlapp, my doctoral advisors. I am very grateful for their ongoing support and their clear guidance. I always appreciated Moritz's approach to research, particularly his attention to keeping the "big picture" in mind throughout a project and the importance of the practical relevance of research questions to him. As a boss, he was always supportive and accommodating and created a family-like atmosphere at the chair full of trust and mutual respect between members. I believe this created a productive and pleasant working environment for everyone. I am also indebted to Jochen for his patience with me during our research discussions, and for teaching me how to take every step in research. I had no idea how to pursue relevant and rigorous research in the beginning and I learned a lot from him. His intelligence and his ability to understand the most complex ideas in the shortest time and to immediately suggest the brightest solutions for the difficult problems that I faced throughout the past five years, never failed to amaze me.

I was very fortunate to meet and work with many bright and supportive people during the last few years, especially my fellow doctoral students at the chair, Luca Biscaro, Maryam Nouri Roozbahani, Sebastian Müller, Kilian Seifried, Gerrit Schumacher, Jonas Schwamberger, Hilal Müge Çakan, Pardis Sahraei, Katrin Waßmuth, Sebastian Szilvas, junior professor Danja Sonntag, and secretaries Julia Peemöller, Helke Naujok, and Ruth Pfitzmann. I was also very lucky to meet many lovely and inspiring people during my first year of studies at CDSB, especially my good friends, Hamed Davari, Amir Foroughi, Mohammad Zenouzzadeh, Marius Krömer, Santanu Kundu, Clemens Müller, Alison Schultz, Hala Jada, Theresa Bührle, Chia-Yi Yen, Mengnan Wu, and Matthew Liew. It was you who made the long train ride worth it.

Finally, I am greatly indebted to my family. The unconditional support of my parents throughout my life has enabled me to achieve my goals and to write this dissertation. Most importantly, I thank my parents, Soheila and Amir, for their love, support, and encouragement through the past five years. Without them, this dissertation would not have been possible.

Summary

Innovation is the cornerstone of business success in this day and age. The concept of innovation, at the firm level, is usually realized through the process of *new product development* (NPD). This dissertation examines specific challenges that a firm experiences during the generation of innovative ideas for NPD initiatives and the selection of the best ones. It then provides explicit guidance on how to efficiently use incentives and communication to manage the tradeoffs involved. The first essay is concerned with the allocation of scarce resources to competing internal and external NPD projects. We investigate the tradeoff between (i) the collection of relevant information about the projects under consideration and (ii) the allocation of resources to the most promising projects. In short, increasing resource allocation flexibility is not always a prudent strategy, and maintaining a combination of dedicated and flexible resource buckets may be an effective way for firms to limit their cost of information acquisition without compromising the scope and composition of their NPD portfolios. The second essay examines how the choice of a communication strategy, by a firm's senior management, in combination with financial incentives affects the process of resource allocation to NPD projects. In an environment where senior management has more refined information about the value of external projects, we ask: Should she reveal this information to the internal project managers, or not? The optimal strategy depends on two key factors: the types of projects the firm pursues and the severity of agency issues in internal R&D. Lastly, the third essay is concerned with innovation contests, in which contestants compete at their own expense for prizes offered by a contest holder. We investigate the role of in-contest performance feedback and characterize the optimal feedback policy in a very wide class of feedback policies. We find that, in many settings where informative feedback is useful, feedback is optimal when it is both truthful and fully informative.

Table of Contents

List of Figures

List of Tables

Chapter I

Introduction

Innovation is the cornerstone of business success in this day and age; as Christopher Freeman puts it, "not to innovate is to die" (Freeman 1982). The concept of innovation, at the firm level, is usually realized through the process of *new product development* (NPD). That is, to survive and prosper, corporations must be able to successfully develop new products and launch them in the market. To successfully manage new product development processes has been a daunting challenge for even the most successful organizations. This is true because NPD initiatives often suffer from strong uncertainties regarding their prospects and consume a lot of resources, thus making project failure expensive. Any development process comprises three different stages: (i) an *ideation* stage, searching for new ideas; (ii) the *selection* stage, deciding which ideas are worthy of further development; and (iii) an *execution* stage, turning the selected ideas into final marketable products. Only firms that excel in all three dimensions can profit from the fruits of their innovation, as failure in any of them is enough for the product, and eventually, the company, to fail in the market.

Another important aspect of innovation through NPD, which has gained much attention and relevance in recent years, is the *source* of innovation. Traditionally, a company carried out all the three stages above purely internally. That is, the company would pursue the discovery and commercial development of new products within the organizational boundaries of the firm, and especially within the internal R&D department. However, this fundamentally inwardly focused approach is increasingly at odds with the innovation landscape of our time. We see, for instance, that a large portion of novel innovative ideas for the development of new treatments in the pharmaceutical industry does not emerge from the well-established large firms, instead from university departments, public research institutes, and small start-up-like *biotechnology* companies. This trend is well exemplified by the discovery of CRISPR technology, a gene editing tool, by various university research teams led by, among many others, Emmanuelle Charpentier and Jennifer Doudna in the 2010s. And the discovery of mRNA vaccines for preventing COVID-19 infections by BioNTech and Moderna, two biotechnology companies based in Germany and the USA respectively, in 2020. This developing environment has led to the adaptation of a new innovation paradigm in most industries, namely Open Innovation, which asserts that "valuable ideas can come from inside or outside the company and can go to market from inside or outside the company as well" (Chesbrough 2003).

To effectively generate or search for ideas inside and outside of the firm, select the most promising ones, and finally execute those selected few, a firm must overcome many challenges. Importantly, these challenges evolve dynamically over time and there are mutual interdependencies between these fundamental decisions. One prominent challenge in this process, arises from the fact that NPD is, by its nature, a decentralized process. That is, NPD activities are distributed over multiple self-interested parties, both within and outside of a firm's organizational hierarchy. The successful implementation of NPD processes, therefore, requires the senior management of an organization to adequately persuade all these parties to take actions that are in the best interests of the organization. In doing so, the senior management can employ mainly two mechanisms: financial incentives, and strategic communication (Hutchison-Krupat 2018). This dissertation examines specific challenges that a firm experiences during the first two stages, *i.e.* ideation and selection, and provides explicit guidance on how to efficiently use incentives and communication to manage the tradeoffs involved.

The first essay, presented in Chapter II, is concerned with the problem of how a firm should allocate resources across candidate NPD initiatives, originating both inside and outside the firm to maximize its R&D output. Given the high level of uncertainty inherent to most NPD projects, selecting the *right* projects has always been an unsettling challenge for the senior management of even the most innovative companies. It is hence vital for firms to engage in two crucial activities that help them attenuate the adverse effects of project uncertainty and hence promote better resource allocation: (i) collecting as much information as possible about the market potential of their NPD projects; and (ii) implementing a resource allocation policy that, based on the acquired information, allows resources to be directed to the most promising projects. However, it is an empirical reality that those two measures are oftentimes conflicting: Installing more allocation flexibility in the second phase intensifies the competition for resources among the different NPD projects, which implies that a project's chances of receiving necessary resources deteriorates; this increased funding uncertainty, in turn, undermines the incentives to exert information acquisition efforts during the first phase because those efforts might be futile. To address this issue, we develop a stylized principal–multiagent model that enables us to study the features of different resource allocation policies—defined by varying degrees of resource commitment and different incentive structures—and to analyze their impact on a firm's information acquisition processes. We identify a contingency plan for how best to (i) acquire information about and (ii) then allocate scarce resources to different internal and external NPD projects, and thus for how to construct optimal NPD portfolios. We complement this contingency plan by detailing recommendations for implementing the optimal resource allocation policy.

The second essay, presented in Chapter III continues the discussion by looking at the problem of resource allocation to internal and external NPD initiatives, from a different angle. From Chapter II, we learn that the internal R&D teams' understanding of the external candidate projects' relative worth has great implications for their incentives to exert information acquisition efforts, and hence the agency costs that the firm incurs. At the same time, the senior management of the company has often a more refined understanding of these projects' value than the project managers inside the firm. In this environment, a natural question arises: Should the senior management reveal their private knowledge, or not? We investigated this question and find that there is no one-size-fits-all solution and that both 'revealing' and 'not revealing' the information can be optimal. In particular, we identify an important trade-off: Revealing—as compared to a not revealing policy—results in a smaller number of funded projects, *i.e.*, it leads to a reduced portfolio scope. Yet, it also allows the senior management to contain agency costs more efficiently, and thus it may (or may not) offset the negative effects of a reduced portfolio scope. Therefore, if the R&D environment of the firm is prone to high agency costs, *i.e.*, it is an environment of low information precision and costly information extraction, senior management should share their private knowledge about the external projects with the project managers; in all other cases, it is best to withhold that information.

The third essay, presented in Chapter IV, looks at the process of innovation management from yet a different perspective. This work is concerned with the issues of external idea generation and how to acquire innovative products, *e.g.* NPD projects, from external partners. Due to high performance uncertainty of such products at the time of acquisition, standard procurement processes such as auctions can not be employed. Instead, the academic literature has for long advocated the use of *innovation contests* as an alternative sourcing mechanism. In a contest, contestants compete—at their own expense (of effort)—for a limited number of prizes; the prizes are awarded to those contestants whose efforts produce the best solution to the contest challenge. Extant work has yielded extensive insight into designing optimal contests, so many aspects of contest design are by now well studied. These aspects include the optimal number of contestants, the optimal award structure, mechanisms for limiting access to contests, and the contest's temporal structure. However, past literature has largely focused on designing actions that the contest holder must take before the contest begins. In contrast, more attention is now being paid to how the contest holder can influence contestants during the contest. Thereby, we investigate when firms should provide suppliers with interim performance feedback during the contest, and when they should refrain from doing so in an innovation contest setting. In particular, we consider a very general setting, allowing for deterministic and stochastic ability differences among contestants and examine a wide span of stochastic feedback policies ranging from providing no information to fully informative policies. In doing so, we characterize how contestants would strategically respond to feedback and we determine the optimal choice of a feedback policy for different contest environments.

Chapter II

How to Compose New Product Development Portfolios: Optimal Resource Commitment

with Moritz Fleischmann, and Jochen Schlapp

Abstract

The process of allocating scarce resources to competing internal and external new product development (NPD) projects comprises two key phases: (i) the collection of relevant information about the projects under consideration and (ii) the allocation of resources to the most promising projects. What makes the management of resource allocation processes challenging is that firms must carefully control the tensions that arise between these two phases. Most notably, a higher level of allocation flexibility in the second phase allows firms to better allocate their resources based on the information they obtain to the most promising projects; however, greater allocation flexibility also induces fiercer competition for resources among the projects, which can severely undermine the reliability of a firm's information acquisition efforts in the first phase and thus deteriorate its overall allocation decisions. Hence, we ask the following question: Which resource allocation policies can best support a firm in coor-

dinating its (ex ante) information acquisition efforts with an optimal degree of resource commitment when the firm contemplates investing in internal and external NPD projects? We study this question by developing a principal-multiagent model, and we identify different contingencies that strongly impact a firm's optimal choice of resource allocation policy, including the projects' market potential and riskiness, the quality of acquired information, and the severity of agency issues. We find that increasing resource allocation flexibility is not always a prudent strategy and that maintaining a combination of dedicated and flexible resource buckets may be an effective way for firms to limit their cost of information acquisition without compromising the scope and composition of their NPD portfolios. We complement these foundational insights with recommendations on how to provide appropriate incentives during the resource allocation process.

2.1. Introduction

New product development (NPD) processes regularly impose daunting challenges upon companies that even the most innovative companies find difficult to overcome (Simon 1969, Wheelwright and Clark 1992, Shane and Ulrich 2004, Loch and Kavadias 2008, Manso 2011, Kavadias and Hutchison-Krupat 2020). Among these challenges, one of the most fundamental issues is the allocation of a firm's scarce resources to competing NPD projects (Cooper et al. 2001, Chao and Kavadias 2008, Klingebiel and Rammer 2014, Sengul et al. 2019, Markou et al. 2021); that is, which NPD projects should a firm invest in, and which projects should it forgo? This question is particularly important for firms contemplating an investment in both internal and external NPD projects—a trend that, e.g., the pharmaceutical/biotech industry and the IT sector exhibit (Boudreau and Lakhani 2009, Rohrbeck 2010, Petrova 2014, Tufféry 2015). The benefits of simultaneously pursuing NPD projects that are promoted internally (e.g., via internal R&D units) and projects that originate outside a firm's boundaries are plentiful, including, inter alia, economies of scale, efficiency gains, access to complementary technologies, and improved market understanding (Kessler et al. 2000, Howe 2009, West and Bogers 2014). However, perhaps the most important benefit is that considering external NPD projects for investment allows firms to choose from a larger set of project opportunities (Chesbrough 2003, Cabral et al. 2006).

Given the high level of uncertainty inherent to most NPD projects, it is almost impossible for a firm to identify—and thus invest in—the most successful projects upfront (Nelson 1961, Sommer and Loch 2004, Drakeman and Oraiopoulos 2020, Klingebiel 2022). However, firms can engage in two crucial activities that help them attenuate the adverse effects of project uncertainty and hence promote better resource allocation (Balakrishnan 1991, Huchzermeier and Loch 2001, Chao et al. 2009, Friebel and Raith 2009, Klingebiel and Adner 2015): (i) collecting as much information as possible about the market potential of their NPD projects, and (ii) implementing a resource allocation policy that facilitates the direction of resources to the most promising projects based on acquired information. Unfortunately, however, it is an empirical reality that these two measures are oftentimes conflicting (see, e.g., Cooper et al. 2001, Santiago and Vakili 2005, Hutchison-Krupat and Kavadias 2015, Schlapp et al. 2015): increasing allocation flexibility in the second phase intensifies the competition for resources among different NPD projects, which implies that a project's chances of receiving necessary resources deteriorate (Gaynor 1989, Rotemberg and Saloner 1994, Birkinshaw 2001). This increased funding uncertainty, in turn, undermines incentives to exert information acquisition efforts during the first phase because those efforts might be futile (Hörner and Samuelson 2013, Gomes et al. 2016, Hutchison-Krupat 2018, Hutchison-Krupat and Kavadias 2018).

For firms that simultaneously explore internal and external NPD projects it is particularly challenging to effectively control that tension for two reasons. First, such firms must manage (and coordinate) two very distinct information acquisition channels: while firms usually rely on the recommendations of their project managers—who oftentimes champion their own projects (see, e.g., Sharpe and Keelin 1998, Lombardino and Lowe 2004, Lefley 2006, Pinto and Patanakul 2015, Drakeman et al. 2022)—for internal projects, they obtain information about external projects primarily through due diligence investigations that are performed by auditors with no direct affiliation to those projects. As a result, the managerial challenges inherent to both information acquisition channels differ considerably. A firm's information acquisition process for internal projects typically suffers from strong agency issues and strategic information manipulation (Chao et al. 2009, Mihm 2010, Schlapp et al. 2015, Hasija and Bhattacharya 2017, Hutchison-Krupat 2018, Rahmani and Ramachandran 2021); in contrast, due diligence auditors have little motive to strategically manipulate information, yet they oftentimes have only limited access to relevant information and may not be able to perfectly interpret the data they obtain, which compromises the quality of this information for external projects (Coff 1999, Caskey et al. 2010, Jeppesen and Lakhani 2010, Moeller and Brady 2014, Reuer and Sakhartov 2021). Second, and even more importantly, when a firm decides to invest in and thus allocate resources to external projects, it deprives internal projects of those resources. As an immediate consequence, internal projects enter into fiercer competition for the remaining resources, which further negatively impacts internal project managers' incentives to engage in upfront information acquisition (Stein 1997, 2002, Friebel and Raith 2009, Schlapp and Schumacher 2022). Thus, when establishing resource allocation policies, firms must address a set of important questions that impact the efficiency (and quality) of their information acquisition processes: Should a specific amount of resources be exclusively reserved for internal and external projects? Or should some (or all) of a firm's resources remain fungible so that the firm can guarantee funding for its most promising projects? And what constitutes an adequate incentive for project managers to acquire and disseminate the information that the firm crucially needs for effective resource allocation?

It is widely acknowledged by prior research on resource allocation that for firms, the right level of upfront resource commitment is critical for building successful NPD portfolios with an appropriate scope and project composition.

In fact, many scholars support the view that firms should refrain from committing their resources upfront to reap the full benefits of an ex post efficient allocation of resources (see, e.g., Schmidt and Freeland 1992, Klingebiel and Rammer 2014, Schlapp et al. 2015, Levinthal 2017, Sengul et al. 2019, and references therein). However, this view is not uncontested: for instance, Cooper et al. (2001), Chao and Kavadias (2008), and Hutchison-Krupat and Kavadias (2015) support the idea that firms should divide their resources upfront and dedicate them to “strategic buckets”—based on individual NPD projects’ risk profiles—to better balance, and debias, their portfolio composition. However, a firm’s (degree of) resource commitment not only influences the scope and composition of its NPD portfolio but also strongly impacts the accuracy (and cost) of its information acquisition efforts (Balakrishnan 1991, Van Nieuwerburgh and Veldkamp 2010). Rather surprisingly, despite its practical relevance, this latter link between a firm’s resource commitment and its information acquisition efficiency has received scant attention in the prior literature. We make a novel contribution in that we provide an initial systematic analysis of how varying degrees of resource commitment influence a firm’s ability to extract, ex ante, important information about the NPD projects that it considers for investment. In that regard, we seek to explore how resource commitment enhances—or compromises—a firm’s information acquisition efficiency and thus how it ultimately supports (or hinders) the firm in making better resource allocation decisions.

2.1.1. Our Contributions

The goal of this paper is to identify which resource allocation policies can best support a firm in coordinating its (ex ante) information acquisition efforts with flexibility to direct resources to the most promising projects. To address this issue, we develop a stylized principal-multiagent model that enables us to study the features of different resource allocation policies—defined by varying degrees of resource commitment and different incentive structures—and to analyze their impact on a firm’s information acquisition processes. We identify different contingencies involving the efficiency of internal and external information acquisition and the market potential of projects that affect a firm's optimal choice of resource allocation policy. Thus, we are led to the following questions: What is the market potential of internal and external projects? How difficult is it to evaluate the potential of NPD projects, and does informational quality vary appreciably across internal and external projects? Additionally, how broad (or narrow) is the target scope of a firm's NPD portfolio? In short, we identify a contingency plan for how best to (i) acquire information about and (ii) allocate scarce resources to different internal and external NPD projects and thus for how to construct optimal NPD portfolios. We complement this contingency plan by detailing recommendations for implementing the optimal resource allocation policy.

Our paper makes the following novel contributions to our understanding of resource allocation processes. First, we establish how different resource allocation policies influence (a) the scope and composition of a firm's NPD portfolio and (b) the firm's information acquisition efficiency. Based on these insights, we determine the optimal degree of resource commitment and show how it depends on relevant contextual factors, including the market potential and riskiness of different types of projects, the accuracy of firms' information acquisition processes, and the severity of firms' agency issues. Second, we characterize how (if at all) a firm should commit its resources. In particular, we show that it is not a prudent strategy to simply reserve resources for different types of projects but that firms should rather establish a combination of permeable (i.e., flexible) and non-permeable (i.e., dedicated) resource buckets. Alternatively, firms may also find it optimal to entirely deprive certain types of projects of resources. Finally, we combine these foundational insights with guidelines on how to structure the incentives of project managers so that they acquire the information that their firms need to make good resource allocation decisions.

2.1.2. Related Literature

How to allocate (scarce) resources to NPD projects has been a question of long-standing academic concern (Wheelwright and Clark 1992, Krishnan and Ulrich 2001, Shane and Ulrich 2004, Adner 2007, Loch and Kavadias 2008, Klingebiel and Rammer 2014, Kavadias and Hutchison-Krupat 2020). Over time, scholars have studied a rich set of factors that critically influence the efficacy of firms' resource allocation decisions, including inter alia, technology and market risks (Wheelwright and Clark 1992), the involvement of senior management (Cooper et al. 2001, Klingebiel and Rammer 2014), competition intensity and (competitors') investment priorities (Ali et al. 1993, Zschoke et al. 2014, Markou et al. 2021), the degree of resource availability/scarcity (Ding and Eliashberg 2002, Girotra et al. 2007, Chao and Kavadias 2008), path-dependencies (Bhaskaran and Ramachandran 2011, Oraiopoulos and Kavadias 2014), and the presence of conflicting NPD projects (Gao et al. 2022). For a more extensive literature review, we refer the interested reader to Sengul et al. (2019) and Kavadias and Hutchison-Krupat (2020).

More closely related to our work, however, is a strand of literature—pioneered by Bower (1970)—that examines the adverse impact of organizational dynamics on a firm's resource allocation process. Scholars who have made contributions to this stream of work have established that firms compose more successful NPD portfolios if they assign funding authority to the right people (Chao et al. 2009, Hutchison-Krupat and Kavadias 2015), if they install systematic allocation procedures (Chao et al. 2014, Oraiopoulos and Kavadias 2020, Klingebiel 2022), if they exhibit sufficient tolerance for failure (Manso 2011, Ederer and Manso 2013), and if they can effectively manage incentive and communication issues (Friebel and Raith 2009, Schlapp et al. 2015, Hutchison-Krupat and Kavadias 2018, Hutchison-Krupat 2018).

We concur with the aforementioned papers in that (a) resource allocation decisions are typically shrouded in adverse organizational issues and that (b) firms must therefore carefully design their resource allocation policies to enable the construction of successful NPD portfolios. However, the extant work has almost exclusively concentrated on (i) the allocation of resources to *internal* NPD projects and (ii) the effect of different resource allocation policies on the scope and composition of a firm's NPD portfolio. That is, we currently do not have a sound understanding of how to compose NPD portfolios that include internal *and* external projects and how different resource allocation policies affect a firm's ability to obtain relevant information about the promise of the NPD projects that it contemplates investing in. Obviously, without accurate information, allocating resources to only the most promising projects is impossible for a firm (see, e.g., Balakrishnan 1991, Friebel and Raith 2009, Schlapp et al. 2015). But acquiring such vital information can be very challenging, particularly when a firm has to simultaneously manage internal and external information channels that also suffer from strong information asymmetries (see, e.g., Caskey et al. 2010, Hörner and Samuelson 2013, Gomes et al. 2016, Reuer and Sakhartov 2021, Schlapp and Schumacher 2022). In this paper, we develop the first systematic analysis of how different resource allocation policies—identified by varying degrees of resource commitment and different incentive structures—affect the efficacy of firms' information acquisition efforts in relation to internal and external NPD projects. Furthermore, we establish how firms that simultaneously consider investing in both internal and external NPD projects exacerbate their information acquisition challenges by intensifying the competition for (scarce) resources among their projects.

Our study of the implications of external NPD projects on the efficacy of firms' resource allocation decisions also brings our work close to the literature on markets for technology (for a good overview of this literature, see Arora and Gambardella 2010 and Arora et al. 2022). The research in this area has primarily studied how firms can best gain access to external innovation (e.g., Katz and Shapiro 1986, Arora and Fosfuri 2003) and how they should internalize these external innovations (e.g., Cohen and Levinthal 1989, Cassiman and Veugelers 2006). The aforementioned scholars have thus focused chiefly on the *transactional* aspects of acquiring external innovation. Along similar lines, there is also a growing body of work that investigates how different contractual arrangements—such as licensing deals or R&D partnerships—and incentive misalignments between partners impact the efficacy of such transactions (Crama et al. 2008, Bhaskaran and Krishnan 2009, Bhattacharya et al. 2015, Crama et al. 2017, Taneri and Crama 2021). Our work, in contrast, is less concerned with the transactional details of acquiring external NPD projects. Instead, our principal contribution consists of adopting a portfolio view and uncovering how external NPD projects interact with internal NPD projects when they are both fighting for the same scarce resources. Most importantly, we shed light on the crucial role of resource allocation policies in (a) containing the negative implications of fierce resource competition and (b) promoting effective information acquisition processes.

2.2. Model Setup

We consider a firm that contemplates building an NPD portfolio by allocating (scarce) resources to novel NPD initiatives. The set of potential NPD initiatives that the firm can invest in comprises two different types of projects: (i) *internal* projects that originate from within the firm (e.g., projects promoted by internal R&D teams) and (ii) *external* projects that are created by external innovators and that can be acquired by the firm. The firm seeks to maximize its expected profits by allocating its limited resources to the most promising projects.

The market potential of all available NPD projects is initially unknown; hence, to make an informed allocation decision, the firm must first collect valuable information about each project's market potential. Toward that end, the firm engages in *project evaluation*, which allows it to acquire costly but *imperfect* information regarding each project's market potential. A core feature of our model that reflects an empirical reality is that the project evaluation process differs structurally between internal and external projects (see, e.g., Sharpe and Keelin 1998, Birkinshaw 2001, Caskey et al. 2010, Reuer and Sakhartov 2021).

For internal projects, project evaluation is usually delegated to the respective project managers, who collect information about their projects through research (Lambert 1986, Schlapp et al. 2015, Kavadias and Hutchison-Krupat 2020). The outcomes of their research efforts equips these project managers with more refined information about their projects' market potential, which allows them to provide informed recommendations regarding the firm's decisions on whether to allocate resources to their projects. Unfortunately, however, the delegated nature of this evaluation process introduces agency issues that the firm must overcome: (a) project evaluation is costly for a project manager, who may therefore choose to be less diligent than desired; and (b) a project manager may be reluctant to share her evaluation results truthfully with the firm and may instead do so "strategically".

In contrast, for external projects, the firm must resort to due diligence investigations to obtain more information. The auditors who are tasked with conducting this due diligence are usually not affiliated with the projects under investigation, and they thus have no motive to strategically manipulate the outcomes of their due diligence analyses (Brown et al. 2012). However, as a downside, the informational quality of such auditors' recommendations is typically inferior because these auditors do not have access to all relevant information or may not be able to perfectly interpret the data they obtain (see, e.g., Coff 1999, Caskey et al. 2010, Reuer and Sakhartov 2021)

Once the firm has collected enough information about its candidate projects, it allocates resources to the most promising projects in accordance with its resource allocation policy. In our setup, the firm's resource allocation policy specifies (i) the quantity of resources that will be reserved for different types of projects and (ii) the way in which project managers are incentivized so that they will acquire the necessary information and truthfully share it with the firm. In the rest of this section we provide more detail on our model setup and assumptions. Figure 2.1 summarizes the sequence of events.

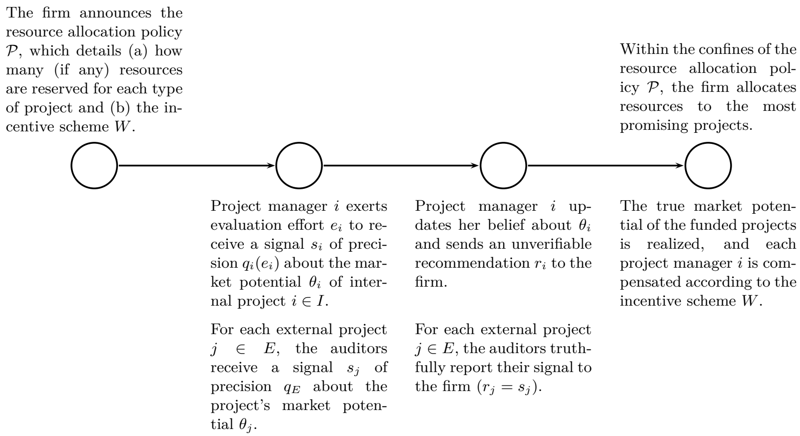


Figure 2.1.: Sequence of events

2.2.1. Internal and External Project Evaluation

To cast the firm's resource allocation problem into a concise model, we assume that the firm is currently considering four different NPD initiatives—including two internal projects ($I = \{1, 2\}$) and two external projects ($E = \{3, 4\}$)—but that resource scarcity limits the firm such that it can invest in *at most* two of those projects. As is common for NPD projects, each project $i \in N = \{1, 2, 3, 4\}$ has an ex ante unknown market potential, which can be either good ($\theta_i = G$) or bad ($\theta_i = B$), and we assume that the firm initially perceives both states to be equally likely.[1] To obtain more precise information about each project's true market potential, the firm must engage in project evaluation.

For internal projects, project evaluation is performed by the respective project managers. Following Friebel and Raith (2009) and Schlapp and Schumacher (2022), we assume that initially, project manager $i \in I$ shares the firm's prior belief about her project's market potential and that she must exert costly and unverifiable evaluation effort $e_i \in \{h, l\}$ to receive an imperfect and private signal $s_i \in \{g, b\}$ about her project's true market potential θ_i. The quality q_i of project manager i's signal s_i depends on her evaluation effort as follows: high evaluation effort ($e_i = h$) endows the project manager with a signal of quality $q_I \in (1/2, 1]$ (i.e., $q_i(e_i = h) = q_I$) but also leads to private effort costs of $c > 0$; in contrast, low evaluation effort ($e_i = l$) results in a costless but uninformative signal (i.e., $q_i(e_i = l) = 1/2$). Based on the received signal s_i, project manager i updates her belief about her project's market potential θ_i according to Bayesian rationality: $\mathbb{P}(\theta_i = G \mid s_i = g) = \mathbb{P}(\theta_i = B \mid s_i = b) = q_i(e_i)$. She then uses her refined beliefs to send an unverifiable recommendation $r_i \in \{g, b\}$ to the firm, indicating whether she believes project i to have good ($r_i = g$) or bad ($r_i = b$) market potential. We say that project manager i is truth telling if her recommendation matches her received signal (i.e., if $r_i = s_i$).

Unlike internal projects, for external projects, the firm cannot mandate a project manager for project evaluation because these projects are not under the firm's direct control. Instead, the firm evaluates the market potential of each external project $j \in E$ by conducting a due diligence investigation, for which the firm incurs a cost of $d \geq 0$ (Caskey et al. 2010, Jeppesen and Lakhani 2010). Because the auditors who perform this due diligence analysis are not directly associated with the evaluated project, they typically have no motive to misrepresent the information that they receive during their investigation (Coff 1999, Brown et al. 2012). Hence, we assume that for each project $j \in E$, the recommendation of the due diligence report $r_j \in \{g, b\}$ matches the signal $s_j \in \{g, b\}$ that the auditors have received; that is, $r_j = s_j$ for all $j \in E$. However, it is a well-known fact that due diligence investigations often suffer from informational deficiencies because auditors have access to only select information or are unable to perfectly interpret the available information (see, e.g., Caskey et al. 2010, Jeppesen and Lakhani 2010, Moeller and Brady 2014, Reuer and Sakhartov 2021). We capture this empirical reality by assuming that the quality $q_E > 1/2$ of a due diligence report is never superior to the (maximum) level of informational quality that can be obtained through internal project evaluation: $\mathbb{P}(s_j = G \mid \theta_j = g) = \mathbb{P}(s_j = B \mid \theta_j = b) = q_E \leq q_I$.

2.2.2. Project Value and Resource Allocation

After receiving (a) the internal project managers' recommendations and (b) the external projects' due diligence reports, the firm must decide how to allocate—within the confines of its resource allocation policy—its resources to the different projects. In particular, the firm can invest in at most two projects, and it can allocate resources to project $i \in N$ only if its resources are not committed to other projects.

The value $V_i(a_i, \theta_i)$ that the firm obtains from project $i \in N$ depends on that project's inherent market potential θ_i, the origin of the project, and whether the project receives resources ($a_i = 1$) or not ($a_i = 0$). More specifically, we assume that investing in an *internal* project $i \in I$ allows the firm to reap benefits of $v_I > 0$ if the project has good market potential ($\theta_i = G$) but that the firm receives only $w_I < v_I$ if that product's market potential is bad ($\theta_i = B$). Similarly, for an investment in an *external* project $j \in E$, the firm gains $v_E > 0$ (resp. $w_E < v_E$) if project j's market potential is good (resp. bad). In addition, the firm must pay acquisition costs of $K \geq 0$ if it decides to invest in an external project.[2] Finally, any project that does not receive resources from the firm generates no value for the firm; that is, $V_i(0, \theta_i) = 0$ for all $i \in N$.

To exclude trivial cases, we invoke two additional assumptions. First, we assume that, irrespective of project origins, a project with good market potential always generates more value for the firm than a project with bad market potential (i.e., $\min\{v_I, v_E\} > \max\{w_I, w_E\}$); otherwise, the firm would always invest in only one of the two different project types and ignore the other type. Second, we assume that given truthful recommendations, it is always worthwhile for the firm to invest in a project if it receives positive information about that project's market potential. Formally, this implies that $\mu_I = q_I v_I + (1 - q_I) w_I \geq 0$ and $\mu_E = q_E v_E + (1 - q_E) w_E - K \geq 0$. In contrast, if the firm receives negative information about a project's market potential, it never invests in the project.

2.2.3. The Firm's Resource Allocation Policy

Before engaging in project evaluation, the firm must first choose—and announce—its resource allocation policy $\mathcal{P}$. Drawing on previous results in the literature on NPD portfolio management (Chao and Kavadias 2008, Hutchison-Krupat and Kavadias 2015, Schlapp et al. 2015), we characterize a firm's resource allocation policy based on two key features: (i) the degree of resource commitment and (ii) project managers' incentive schemes. Throughout our analysis, we assume that the firm can credibly commit to its resource allocation policy.

Regarding the degree of resource commitment, the firm's key challenge is to determine whether certain resources—and if so, how many—should be reserved for a specific type of project. More specifically, given that the firm can invest in at most two projects, it can select between resource allocation policies with three different degrees of resource commitment. First, the firm can choose to implement a *full commitment* policy by specifying the maximum number of internal and external projects, respectively, it will invest in upfront—hence, a full commitment policy closely follows the idea of establishing dedicated (or "strategic") resource buckets (Cooper et al. 2001, Chao and Kavadias 2008). For instance, the firm can commit to never investing in external (resp. internal) projects at all and hence to reserving all of its resources for internal (resp. external) projects. Alternatively, the firm can commit to investing in at most one internal and one external project and thus to eventually distributing its resources evenly across the different types of projects.

Second, the firm can opt to maintain a maximum degree of flexibility by not reserving any resources at all. In this case, the firm waits until it has received all project recommendations and due diligence reports before it allocates its resources to the most promising projects, irrespective of the origins of those projects. We refer to such a resource allocation policy as a *full flexibility* policy. Last, the firm can implement a *partial commitment* policy by reserving some (but not all) of its resources for a specific type of project while keeping the remaining resources unassigned.

Clearly, the degree of resource commitment associated with a specific resource allocation policy has an immediate impact on the firm's internal competition for resources and thus on internal project managers' inclination to evaluate their projects thoroughly and to give truthful recommendations. For this reason, the firm must construct an incentive scheme that entices project managers to devote high effort to evaluating their projects and to subsequently share their information truthfully with the rest of the organization.[3] With regard to the incentive scheme, we consider the most general contract possible by allowing the firm to define a distinct payment for any verifiable outcome of the allocation process.[4] In particular, we assume that the firm's allocation of resources (or lack thereof) to a project is verifiable, as is the true market potential of a project that has received resources from the firm. It is then sufficient to consider incentive schemes of the form $W = (w_0, \alpha(\theta_i), \beta(\theta_{3-i}), \gamma(\theta_j))$. Here, (i) w_0 is a fixed wage; (ii) $\alpha(\theta_i) \in \{\alpha_0, \alpha_g, \alpha_b\}$ is an *individual* bonus that project manager i receives contingent upon the value $V_i(a_i, \theta_i)$ of her own project $i \in I$; (iii) $\beta(\theta_{3-i}) \in \{\beta_0, \beta_g, \beta_b\}$ is a *shared* bonus that project manager i receives for the value $V_{3-i}(a_{3-i}, \theta_{3-i})$ of the competing internal project $3-i$; and (iv) $\gamma(\theta_j) \in \{\gamma_0, \gamma_g, \gamma_b\}$ is an *external* bonus that project manager i receives based on the value $V_j(a_j, \theta_j)$ of each external project $j \in E$.

To better understand the operation of our incentive scheme, consider an example scenario in which the firm has allocated resources to internal project $i = 1$ and external project $j = 4$ (i.e., $a_1 = a_4 = 1$) but has not invested in projects 2 or 3 (i.e., $a_2 = a_3 = 0$). Furthermore, project 1 ultimately has good market potential (i.e., $\theta_1 = G$), whereas project 4 has bad market potential (i.e., $\theta_4 = B$); the true market potential of projects 2 and 3 is not observable. In this case, project manager $i = 1$ receives a fixed wage w_0, a success bonus α_g for her own good project, consolation payments β_0 and γ_0 for projects 2 and 3, and an allowance γ_b for the bad external project 4. In contrast, project manager $i = 2$ receives a fixed wage w_0, consolation payments α_0 and γ_0 for her own project and external project 3, a success bonus β_g for her peer's successful project, and an allowance γ_b for project 4.

2.2.4. The Firm's Incentive Design Problem

The total wage that project manager i receives from the firm is given by the sum of all her bonus payments: $w_i(a,\theta) = w_0 + \alpha(\theta_i) + \beta(\theta_{3-i}) + \sum_{j\in E}\gamma(\theta_j)$. We assume that project managers are shielded by limited liability, which implies that their wage must be nonnegative; that is, $w_i(a,\theta) \geq 0$ for any $a = (a_i)_{i\in N}$ and $\theta = (\theta_i)_{i\in N}$. Furthermore, each project manager's expected utility u_i includes her expected wage net of her effort costs; thus, $u_i = \mathbb{E}_\theta[w_i] - c1_{\{e_i=h\}}$, with $1_{\{A\}}$ being the indicator function of event A. Following the literature on delegated experimentation (e.g., Gerardi and Maestri 2012, Gershkov and Perry 2012), we assume that each project manager is risk-neutral and seeks to maximize her expected utility. Similarly, the firm is also risk-neutral and maximizes its expected profits $\Pi(a,W) = \mathbb{E}_\theta\big[\sum_{i\in I}(V_i(a_i,\theta_i) - w_i) + \sum_{j\in E}(V_j(a_j,\theta_j) - Ka_j - d1_{\{\mathcal{P}\}})\big]$, which are a function of the firm's resource allocation policy $\mathcal{P}$, its resource allocation a, and the project managers' incentives W.

For a given resource allocation policy $\mathcal{P}$, the optimal incentive scheme that (i) maximizes the firm's expected profits and (ii) incentivizes all internal project managers to exert a high level of effort during project evaluation and to truthfully report their signals solves the following optimization problem:

$$\max_W \; \Pi_{\mathcal{P}}(W \mid a^*) = \mathbb{E}_\theta\Big[\sum_{i\in I}(V_i(a_i^*,\theta_i) - w_i) + \sum_{j\in E}(V_j(a_j^*,\theta_j) - Ka_j^* - d1_{\{\mathcal{P}\}}) \mid \mathcal{P}\Big] \quad \text{(P)}$$

$$\begin{aligned}
\text{s.t. } & u_i(r_i = g \mid e_i = e_{3-i} = h, s_i = g, r_{3-i} = s_{3-i}, \mathcal{P}) \geq \\
& u_i(r_i = b \mid e_i = e_{3-i} = h, s_i = g, r_{3-i} = s_{3-i}, \mathcal{P}) && \text{(IC-g)}\\
& u_i(r_i = b \mid e_i = e_{3-i} = h, s_i = b, r_{3-i} = s_{3-i}, \mathcal{P}) \geq \\
& u_i(r_i = g \mid e_i = e_{3-i} = h, s_i = b, r_{3-i} = s_{3-i}, \mathcal{P}) && \text{(IC-b)}\\
& u_i(e_i = h, r_i = s_i \mid e_{3-i} = h, r_{3-i} = s_{3-i}, \mathcal{P}) \geq \\
& u_i(e_i = l, r_i = s_i \mid e_{3-i} = h, r_{3-i} = s_{3-i}, \mathcal{P}) && \text{(IC-e)}\\
& w_i(a^*,\theta) \geq 0 && \text{(LL)}\\
& a^* \in \operatorname*{arg\,max}_{\sum_{i\in N} a_i \leq 2} \Pi_{\mathcal{P}}(a \mid W, r); \quad a_i \in \{0,1\}. && \text{(RA)}
\end{aligned}$$

Constraints (IC-g) and (IC-b) negate the firm's adverse selection problem at the recommendation stage by making it optimal for the project managers to communicate good signals and bad signals truthfully, as is applicable. Similarly, constraint (IC-e) eliminates the moral hazard problem during project evaluation because it ensures that each project manager prefers high-effort evaluation to low-effort evaluation. Furthermore, project managers are shielded by limited liability and thus guaranteed to receive nonnegative wages (per condition (LL))—irrespective of their projects' true market potential θ and the firm's resource allocation a. Finally, constraint (RA) guarantees that the firm, after receiving all recommendations and due diligence reports $r = (r_i)_{i \in N}$ and while adhering to its resource allocation policy $\mathcal{P}$, conducts an ex post optimal allocation of resources a^* to the different projects. If certain projects are equally attractive to the firm, we assume that the firm decides between them with equal probability.

2.3. Allocation Policies with Full Resource Commitment

When composing its NPD portfolio, the firm can choose between four different NPD projects—including two internal projects and two external projects—but due to severe resource constraints, the firm can allocate resources to at most two of these projects. In this section, we study the properties of resource allocation policies that require the firm to divide its resources between internal and external projects upfront. Such a *full commitment* policy completely shields the different types of projects from one another and is thus relatively easy to implement, which explains why such policies are frequently employed in practice (Cooper et al. 2001, Chao and Kavadias 2008, Hutchison-Krupat and Kavadias 2015). More specifically, we consider three different options that the firm can pursue: (i) reserve all resources for internal projects (Section 2.3.1); (ii) reserve all resources for external projects (Section 2.3.2); and (iii) split the resources evenly between internal and external projects (Section 2.3.3). For each of these resource allocation policies, we first characterize the associated optimal incentive structure that guarantees a thorough information acquisition process before we compare the different full commitment policies with one another in terms of performance (Section 2.3.4). For better readability, we have relegated all formal derivations and mathematical proofs to Appendix A.

2.3.1. Reserving All Resources for Internal Projects

When the firm reserves all of its resources for internal projects and thus effectively prohibits investment in external projects, it can restrict its information acquisition efforts to two internal projects, which should facilitate a more efficient information acquisition process. However, the firm forgoes the opportunity to use external projects as "back-up" projects if it receives a negative recommendation for—and hence does not invest in—at least one of the internal projects, which may adversely affect the firm's resulting portfolio scope.

We now proceed to study the optimal incentive scheme for a resource allocation policy $\mathcal{P} = (I, I)$ that reserves all resources for internal projects; this incentive scheme solves the following optimization problem, which is a special case of problem (P)-(RA):

$$\max_{W} \; \Pi_{(I,I)}(W) = \mu_I - q_I\alpha_g - (1 - q_I)\alpha_b - \alpha_0 - 2w_0 \tag{2.1}$$

$$\text{s.t.} \; q_I\alpha_g + (1 - q_I)\alpha_b \geq \alpha_0 \tag{2.2}$$

$$(1 - q_I)\alpha_g + q_I\alpha_b \leq \alpha_0 \tag{2.3}$$

$$(2q_I - 1)(\alpha_g - \alpha_b) \geq 4c \tag{2.4}$$

$$w_i(a^*, \theta) \geq 0. \tag{2.5}$$

The incentive compatibility constraints (2.2)-(2.4) reveal that when all resources are reserved for internal projects, individual incentives $\alpha(\theta_i)$ are sufficient for the firm to motivate each project manager $i \in I$ to engage in high-effort project evaluation and to give truthful recommendations. The reasons are twofold. First, since the firm—by definition—never allocates resources to external projects, promising an external bonus $\gamma(\theta_j)$ that depends on the performance of external project $j \in E$ is futile. Second, and even more importantly, there is no internal competition for resources: resources are abundant, and each project manager who gives a positive recommendation for her project receives the desired resources, which renders shared incentives $\beta(\theta_i)$ unnecessary.

The firm's objective is to maximize the expected value of its project portfolio net of the project managers' incentive payments. However, because project managers are incentivized to thoroughly evaluate and accurately recommend (or not recommend) their projects, the expected value of the firm's project portfolio is fixed and given by $\mu_I = q_I v_I + (1 - q_I)w_I$. Here, μ_I denotes the expected value of an internal project with a good signal; obviously, this value is independent of the firm's incentive scheme. Thus, the firm's expected portfolio value is determined entirely by the firm's choice of resource allocation policy; hence, the firm aims only to minimize its total agency costs.

Proposition 2.1. *Define $\phi_I = 4c/(2q_I - 1)$ and assume that the firm reserves all its resources for internal projects. Then:*

(i) *An optimal incentive scheme $W_{(I,I)}$ that incentivizes all project managers to exert high effort and engage in truth telling is $\alpha_g = \phi_I$, $\alpha_0 = (1 - q_I)\phi_I$, and all other incentives are zero.*

(ii) *On expectation, the firm invests in $n_I = 1$ internal projects and never invests in external projects ($n_E = 0$).*

(iii) *The firm's expected profits are $\Pi_{(I,I)} = \mu_I - \phi_I$.*

Proposition 2.1 characterizes the firm's optimal incentive scheme and derives the firm's expected portfolio scope plus the ensuing profits. First, part (i) of the proposition reveals that the optimal incentive scheme has a very simple structure: each project manager $i \in I$ is rewarded with (a) a bonus α_g if project i receives resources and the project has good market potential ($\theta_i = G$) and (b) a consolation payment α_0 if the firm does not invest in project i (for structurally similar results, see Levitt and Snyder 1997, Friebel and Raith 2009). Thus, α_g incentivizes a project manager to exert a high level of effort and to truthfully reveal a good signal, whereas α_0 guarantees that the project manager will not misrepresent a bad signal. As one could intuitively expect, the incentive payments increase with the severity of the firm's agency issues; that is, α_g and

α_0 increase in a project manager's effort costs c and decrease in her quality of information q_I.

Perhaps the most important result of Proposition 2.1 concerns the firm's expected portfolio scope: on average, the firm invests in only one project (i.e., $n_I + n_E = 1$, per part (ii) of the proposition), even though it has sufficient resources to fund two projects. This implies that, on average, half of the firm's resources remain idle, and those resources hence do not create any value for the firm. This happens because each project is equally likely to have good or bad market potential; thus, the firm can expect to discover only one good project out of its two internal projects.

In regard to (at least partially) offsetting the negative repercussions of such a narrow portfolio scope on the firm's expected profits, Proposition 2.1(iii) shows that the firm is able to limit its expected agency costs to $\phi_I = 4c/(2q_I - 1)$. In fact, one can show that ϕ_I is the minimum agency cost that the firm necessarily incurs whenever it contemplates investing in internal NPD projects. Intuitively, ϕ_I measures a project manager's effort cost per unit of information during project evaluation, and that cost increases in the cost of effort c and decreases in the quality of information q_I. This also implies that the firm's expected profits $\Pi_{(I,I)}$ decrease in c but increase in q_I.

2.3.2. Reserving All Resources for External Projects

Suppose that the firm excludes all internal NPD projects from receiving resources, reserving all its resources for external projects instead. It is clear that under such a resource allocation policy—referred to as $\mathcal{P} = (E, E)$—the firm has no reason to acquire information about internal projects, and it should hence not offer any incentives to its internal project managers. In fact, agency costs are then zero, and the firm has to pay for only (a) the due diligence investigations of its external projects and (b) the acquisition of an external project if the firm decides to allocate resources to that project. However, despite their fundamental differences, an (E, E)-policy shares a major downside with an (I, I)-policy: both policies lead to a narrow portfolio scope because they completely exclude half of all available NPD projects from consideration. The following proposition formalizes this intuition.

Proposition 2.2. *Assume that the firm reserves all its resources for external projects. Then:*

(i) *The firm never pays bonuses to project managers:* $W_{(E,E)} = 0$.

(ii) *On expectation, the firm invests in* $n_E = 1$ *external projects and never invests in internal projects* ($n_I = 0$).

(iii) *The firm's expected profits are* $\Pi_{(E,E)} = \mu_E - 2d$.

2.3.3. Splitting Resources

In this section, we study a resource allocation policy $\mathcal{P} = (I, E)$ that reserves resources for both internal and external projects. In particular, we assume that the firm commits to allocating its resources to at most one internal project and to at most one external project and that resources that are originally reserved for internal (resp. external) projects can never be allocated to external (resp. internal) projects. Put differently, the firm creates dedicated and non-permeable resource buckets for internal and external projects, respectively, and within each bucket, the internal (resp. external) projects compete for available resources (this policy is akin to the idea of strategic buckets presented, e.g., in Chao and Kavadias 2008, Hutchison-Krupat and Kavadias 2015). When compared to the previously discussed resource allocation policies, a key advantage of the (I, E)-policy is that ex ante, the firm does not exclude any projects from consideration; thus, the firm is more likely to identify projects with good market potential, which can ultimately lead to a broader portfolio scope. However, before discussing the costs and benefits associated with an (I, E)-policy in more detail, we must first derive the firm's optimal incentive scheme by solving the following optimization problem:

$$\max_{W} \ \Pi_{(I,E)}(W) =$$
$$\frac{3}{4}(\mu_I + \mu_E) - \frac{3}{4}\big(q_I(\alpha_g + \beta_g) + (1 - q_I)(\alpha_b + \beta_b)\big) - \frac{5}{4}(\alpha_0 + \beta_0) - 2w_0 - 2d \tag{2.6}$$

$$\text{s.t. } 3(q_I\alpha_g + (1 - q_I)\alpha_b) + \beta_0 \geq 3\alpha_0 + (q_I\beta_g + (1 - q_I)\beta_b) \tag{2.7}$$
$$3((1 - q_I)\alpha_g + q_I\alpha_b) + \beta_0 \geq 3\alpha_0 + (q_I\beta_g + (1 - q_I)\beta_b) \tag{2.8}$$
$$3(2q_I - 1)(\alpha_g - \alpha_b) \geq 16c \tag{2.9}$$
$$w_i(a^*, \theta) \geq 0. \tag{2.10}$$

By establishing dedicated resource buckets for internal and external projects, the firm effectively shields its internal project managers from competing with external projects for resources. For the firm, it is therefore not advisable to have project managers partake in the success (or failure) of external projects; that is, the firm should not offer any external incentives $\gamma(\theta_i)$. However, for an (I, E)-policy, the firm must use—besides individual incentives $\alpha(\theta_i)$—shared incentives $\beta(\theta_i)$ to induce thorough project evaluation. As in Friebel and Raith (2009) and Schlapp et al. (2015), the need for shared incentives emerges from the fact that *at most* one internal project will be funded; hence, project managers have a strong incentive to always ask for resources, even when they receive negative information about their projects.

Proposition 2.3. *Assume that the firm reserves resources such that at most one internal project and at most one external project can be funded. Then:*

(i) *An optimal incentive scheme $W_{(I,E)}$ that incentivizes all project managers to exert high effort and engage in truth telling is $\alpha_g = 4\phi_I/3$, $\alpha_0 = 2(1-q_I)\phi_I$, $\beta_g = \beta_b = -2(1 - q_I)\phi_I$, and all other incentives are zero.*

(ii) *On expectation, the firm invests in $n_I = 3/4$ internal projects and $n_E = 3/4$ external projects.*

(iii) *The firm's expected profits are $\Pi_{(I,E)} = 3(\mu_I + \mu_E)/4 - \phi_I - 2d$.*

The first part of Proposition 2.3 establishes the optimal incentive scheme for an (I, E)-policy: project manager i obtains a bonus α_g for the successful completion of her own project but receives no wage at all if the competing internal project is funded (in that case, $w_i = \alpha_0 + \beta(\theta_{3-i}) = 0$). Hence, we conclude that the optimal incentive scheme—when compared to the optimal incentive scheme under an (I, I)-policy—is much more aggressive in promoting individual performance; the firm (a) pays a higher individual bonus α_g and (b) even penalizes a project manager for her competitor's success in acquiring resources (i.e., $\beta_g, \beta_b < 0$). Thus, the firm predominantly uses shared incentives to further the competition between internal project managers, which ensures that project managers thoroughly engage in information acquisition.

The possibility of establishing such a highly competitive incentive scheme leads to perhaps the most surprising result of Proposition 2.3: the high efficiency of internal project evaluation under resource competition. More specifically, even though project managers compete with one another for resources, the firm is able to minimize agency costs at ϕ_I (see part (iii) of the proposition). Moreover, the firm can broaden its expected portfolio scope by 50 percent when compared to an (I, I)- or (E, E)-policy (see the second part of Proposition 2.3): the firm now invests, on average, in 3/4 internal projects and 3/4 external projects, which leads to significantly fewer idle resources and a more balanced portfolio composition. The firm is able to reap those benefits because it does not exclude any projects at the outset of the allocation process and thus retains a higher level of resource flexibility. The positive effects of a broader portfolio scope on the firm's expected profits are reflected in part (iii) of the proposition.

2.3.4. The Optimal Allocation Policy with Full Resource Commitment

Thus far, we have investigated the optimal design of three different resource allocation policies that require the firm to specify, ex ante, the maximum number of internal and external projects that it can invest in. To find the optimal *full commitment* policy, the firm must balance the benefits of a specific policy's NPD portfolio scope and composition with the associated information acquisition costs. The following proposition establishes how the firm's optimal resource allocation policy changes with our key contextual parameters; Figure 2.2 illustrates the results.

Proposition 2.4. *Under full resource commitment, the firm's optimal resource allocation policy* $\mathcal{P}^*$ *is as follows:*

(i) *Suppose that* $\mu_I \leq 3\phi_I/2 + d$*. Then,* $\mathcal{P}^* = (I, I)$ *if* $\mu_E \leq \mu_I - \phi_I + 2d$*; and* $\mathcal{P}^* = (E, E)$ *otherwise.*

(ii) *Suppose that* $\mu_I > 3\phi_I/2 + d$*. Then,* $\mathcal{P}^* = (I, I)$ *if* $\mu_E \leq (\mu_I + 8d)/3$*;* $\mathcal{P}^* = (I, E)$ *if* $(\mu_I + 8d)/3 < \mu_E \leq 3\mu_I - 4\phi_I$*, and* $\mathcal{P}^* = (E, E)$ *otherwise.*

The value of a firm's NPD portfolio depends critically on the scope and composition of the portfolio (i.e., on the number and origin of the funded projects). As discussed in Section 2.3.3, dedicating resources to separate resource buckets for internal and external projects allows the firm to create a broader expected portfolio scope. However, in that case, the firm also invests in fewer internal (resp. external) projects than it does under an (I, I)-policy (resp. (E, E)-policy). Hence, the firm faces a trade-off between its overall portfolio scope and portfolio composition.

Proposition 2.4 confirms this tradeoff, but it also underscores the crucial role of the firm's information acquisition costs in selecting the optimal resource allocation policy. Specifically, portfolio breadth is most important—and thus an (I, E)-policy is optimal—when (a) internal and external projects are of equaling value (i.e., $\mu_I \approx \mu_E$) and (b) the firm's agency costs and due diligence expenses are sufficiently low. In contrast, the firm should opt for a narrower NPD portfolio by reserving resources for internal (resp. external) projects if (a) internal (resp. external) projects are much more valuable than external (resp. internal) projects or (b) if information acquisition burdens the firm with undue costs. In such cases, focusing exclusively on one type of project allows the firm

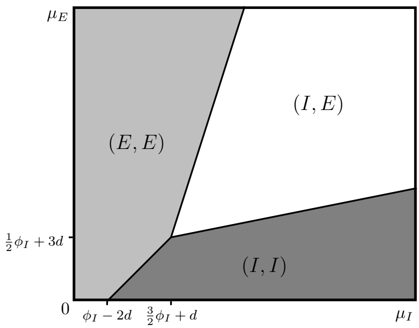


Figure 2.2.: Optimal Allocation Policy with Full Resource Commitment

Note. The graph shows a firm's optimal resource allocation policy with full resource commitment as a function of μ_I and μ_E. The firm prefers an (I, I)-policy in the gray area, an (E, E)-policy in the light gray area, and an (I, E)-policy in the white area.

to better mitigate the costs—and thus increase the efficiency—of information acquisition.

2.4. Allocation Policies with Full Resource Flexibility

Instead of dedicating resources to certain projects upfront, the firm may select a diametrically opposed resource allocation policy that promotes full allocation flexibility (a policy advocated by, e.g., Klingebiel and Rammer 2014, Schlapp et al. 2015). When implementing such a *full flexibility* policy, which we denote as a $(\cdot, \cdot)$-policy, the firm does not commit any resources to projects until it has received all internal project recommendations and external due diligence reports. A full flexibility policy hence allows the firm to fully leverage the information it obtains and allocate—without any restrictions—resources to the most promising projects. Our analysis proceeds to establish the characteristics of an optimal full flexibility policy (Section 2.4.1); we then determine when the firm should (and should not) strive for full allocation flexibility (Section 2.4.2).

2.4.1. Incentives for Full Resource Allocation Flexibility

Under a full flexibility policy, the firm obtains the project managers recommendations r_i for all internal projects $i \in I$ and the due diligence reports r_j for all external projects $j \in E$ before it directs resources to any available projects. This postponement of the allocation decision enables the firm to invest its resources in only the most promising projects—irrespective of whether those projects originate from within or outside the firm—which, based on the firm's information, always leads to an optimal allocation of resources. However, full allocation flexibility does not come free of charge: incentivizing information acquisition becomes substantially more difficult. To see this, note that the value that the firm obtains from investing in project $i \in N$ depends not only on that project's exogenous characteristics (such as $V_i(a_i, \theta_i)$ and q_i) but also on the firm's choice of incentive scheme W. The relative attractiveness of each project for the firm is thus not given a priori but is instead an outcome of the firm's incentive optimization. And because a project manager's propensity to engage in information acquisition depends not only on her incentives but also on her project's relative attractiveness, the firm must take great care in crafting a functional incentive scheme that incentivizes thorough project evaluation. The following proposition summarizes the optimal incentive scheme associated with a full flexibility policy, and it establishes other key features of that policy. Due to its complexity, we relegate the precise mathematical formulation of the firm's incentive design problem to Appendix A.

Proposition 2.5. *Assume that the firm does not reserve resources for any available projects and define $\Delta\mu = \mu_I - \mu_E$. Table 2.1 summarizes the firm's investment preference (I or E projects), optimal incentive scheme $W_{(\cdot,\cdot)}$, expected portfolio composition (n_I, n_E), and expected profits $\Pi_{(\cdot,\cdot)}$ as a function of $\Delta\mu$. Here, four different cases are relevant:* (i) $\Delta\mu \geq 4c$; (ii) $\max\{(5q_I - 4)\phi_I, 4(3q_I - 2)\phi_I/7\} \leq \Delta\mu < 4c$; (iii) $(17q_I - 12)\phi_I/8 \leq \Delta\mu < (5q_I - 4)\phi_I$;

and (iv) $\Delta\mu < \max\{4(3q_I - 2)\phi_I/7, (17q_I - 12)\phi_I/8\}$.

The first noteworthy result of Proposition 2.5 is that the structure of the optimal incentive scheme and the firm's expected portfolio composition change appreciably with the expected value difference between internal and external projects $\Delta\mu = \mu_I - \mu_E$ (cf. Table 2.1). Intuitively, $\Delta\mu$ measures the firm's propensity to invest in an internal project rather than an external project (assuming a positive recommendation for both projects). This fact is nicely displayed in the second column of Table 2.1, which shows that for relatively high values of $\Delta\mu$ the firm always prefers to invest in internal projects (cases (i)-(iii)), whereas the firm prefers external projects for sufficiently low values of $\Delta\mu$ (case (iv)). As an immediate consequence of the firm's varying investment preference, the firm's expected portfolio composition changes with $\Delta\mu$ (see column 4 of Table 2.1). Unsurprisingly, when the firm prefers to invest in internal (resp. external) projects, its NPD portfolio eventually includes, on expectation, more internal (resp. external) projects. Perhaps more remarkably, irrespective of $\Delta\mu$, the firm's expected overall portfolio scope is always the same (i.e., $n_I + n_E = 13/8$), and this scope is broader than the portfolio scope emerging under any full commitment policy (which is at most 3/2). The firm achieves this broadening of its portfolio scope under a full flexibility policy due to its greater allocation flexibility, which guarantees that promising projects are more likely to receive resources.

A second intriguing finding of Proposition 2.5 concerns the magnitude of the firm's agency costs and how those costs change with $\Delta\mu$. Clearly, the firm's agency costs are primarily determined by (a) the firm's optimal incentive scheme $W_{(\cdot,\cdot)}$, as displayed in column 3 of Table 2.1, and (b) by how fiercely project managers compete for resources. As a starting point for our discussion, consider case (i), in which the firm strongly prefers to invest in internal projects; that is, external projects serve as only "back-up" projects in case the firm does not allocate all of its resources to internal projects (e.g., due to negative recommendations from the internal project managers). In other words, project managers know that their projects will always receive the required resources

Table 2.1.: The Optimal Full Flexibility Policy.

Case	Pref.	Incentive Scheme $W_{(\cdot,\cdot)}$	(n_I, n_E)	Expected Profits $\Pi_{(\cdot,\cdot)}$
(i)	I	$\alpha_g = \phi_I$ $\alpha_0 = (1 - q_I)\phi_I$	(1, 5/8)	$\mu_I + 5\mu_E/8 - \phi_I - 2d$
(ii)	I	$\alpha_g = \phi_I$ $\alpha_0 = (\mu_I - \mu_E - (5q_I - 4)\phi_I)/3$ $\gamma_g = \gamma_b = (8c - 2(\mu_I - \mu_E))/3$	(1, 5/8)	$\mu_I + 5\mu_E/8$ $-((2q_I + 1)\phi_I - (\mu_I - \mu_E))/2 - 2d$
(iii)	I	$\alpha_g = \phi_I$ $\gamma_g = \gamma_b = (q_I\phi_I - (\mu_I - \mu_E))/2$	(1, 5/8)	$\mu_I + 5\mu_E/8$ $-(13q_I\phi_I - 5(\mu_I - \mu_E))/8 - 2d$
(iv)	E	$\alpha_g = 8\phi_I/5,$ $\alpha_0 = \beta_0 = 2(1 - q_I)\phi_I$ $\gamma_g = \gamma_b = -2(1 - q_I)\phi_I$	(5/8, 1)	$5\mu_I/8 + \mu_E - (3 - q_I)\phi_I/2 - 2d$

Note. The conditions that differentiate cases (i)-(iv) are given in Proposition 2.5. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

as long as they submit a positive recommendation to the firm; hence, there is no competition for resources. As a result, the firm can offer exactly the same incentive scheme as it offers under an (I, I)-policy—which relies on only individual incentives—and thus minimize agency costs at ϕ_I (cf. column 5 of Table 2.1).

One could naively expect that a similar argument holds for cases (ii) and (iii), in which the firm still prefers to invest in internal projects. However, in those cases, the firm's investment preference is much weaker: in addition to $\Delta\mu$ being smaller, strong individual incentives start to interfere with the relative attractiveness of internal projects, and thus, project managers' inclination to acquire information deteriorates. In particular, project managers become more reluctant to truthfully reveal negative information about their projects. To counterbalance that negative effect, the firm must introduce external incentives $\gamma(\theta_j)$ that compensate project managers when they give negative recommendations for their projects, which results in resources being allocated to external projects. Naturally, those additional external incentives increase the firm's agency costs.

Finally, when the firm prefers to invest in external projects (see case (iv) in Table 2.1), then project managers must compete fiercely for resources. In fact, internal projects take on the role of merely "back-up" projects that compete for the residual resources that have not been invested in external projects. Obviously, the prospect of not being able to attract resources severely undermines a project manager's motivation to exert a high level of effort in relation to project evaluation—eventually, her information acquisition efforts might be futile. The firm must thus increase project managers' individual incentives (as represented by α_g and α_0) to induce high-effort project evaluation; in contrast, truth telling is less of an issue, and the firm can establish additional shared and external incentives to limit project managers' rent extraction opportunities (note that $\gamma_g, \gamma_b < 0$). Nonetheless, the firm incurs agency costs that exceed the minimum level ϕ_I due to the strong individual incentives that are necessary to induce meaningful information acquisition.

2.4.2. Full Allocation Flexibility vs. Full Resource Commitment

Having characterized the properties of an optimal full flexibility policy, we are now in a position to compare that policy's expected profits to the profits generated by the full commitment policies introduced in Section 2.3. The following proposition presents our formal results; Figure 2.3 visualizes the findings.

Proposition 2.6. *Define* $\hat{\mu} = \max\{\phi_I + 6d/5, (8q_I - 3)\phi_I/5 + 14d/5, (13q_I - 8)\phi_I/5 + 16d/5\}$ *and* $\breve{\mu} = 4(3 - q_I)\phi_I/5$*, and suppose that the firm can choose between full resource commitment and full allocation flexibility. Then, the firm's optimal resource allocation policy* $\mathcal{P}^*$ *is as follows:*

(i) *Suppose that* $\mu_I \leq \min\{\hat{\mu}, \breve{\mu}\}$*. Then,* $\mathcal{P}^* = (I, I)$ *if* $\mu_E \leq \mu_I - \phi_I + 2d$*; and* $\mathcal{P}^* = (E, E)$ *otherwise.*

(ii) *Suppose that* $\hat{\mu} < \mu_I < \breve{\mu}$*. Then,* $\mathcal{P}^* = (I, I)$ *if* $\mu_E \leq \max\{16d/5, -4\mu_I + 16(c+d)\}$*;* $\mathcal{P}^* = (E, E)$ *if* $\mu_E \geq \min\{8(\mu_I - \phi_I)/3, 4(3\mu_I - (2q_I + 1)\phi_I)/7, 13(\mu_I - q_I\phi_I))/8\}$*; and* $\mathcal{P}^* = (\cdot, \cdot)$ *otherwise.*

(iii) *Suppose that* $\breve{\mu} < \mu_I < \hat{\mu}$*. Then,* $\mathcal{P}^* = (I, I)$ *if* $\mu_E \leq 3\mu_I/8 + (1 - q_I)\phi_I/2 + 2d$*; and* $\mathcal{P}^* = (\cdot, \cdot)$ *otherwise.*

(iv) *Suppose that* $\mu_I \geq \max\{\hat{\mu}, \breve{\mu}\}$*. Then,* $\mathcal{P}^* = (I, I)$ *if* $\mu_E \leq \max\{16d/5, -4\mu_I + 16(c + d)\}$*; and* $\mathcal{P}^* = (\cdot, \cdot)$ *otherwise.*

The key result of Proposition 2.6 is as follows: the firm should never simultaneously establish dedicated resource buckets for internal and external projects; that is, an (I, E)-policy is never optimal. Much to the contrary, the firm should either implement a full flexibility policy so that resources can be allocated in the ex post optimal way, or it should reserve all resources for a specific type of project. To understand the rationale behind these findings, recall that the firm's expected profits are chiefly driven by the properties of its NPD portfolio (i.e., the scope and composition of the portfolio) and the costs of information acquisition. Now, when the expected value of the available projects (i.e., μ_I and μ_E) is relatively low, then it is most important for the firm to limit its costs of information acquisition; here, it is the (I, I)- and (E, E)-policies that

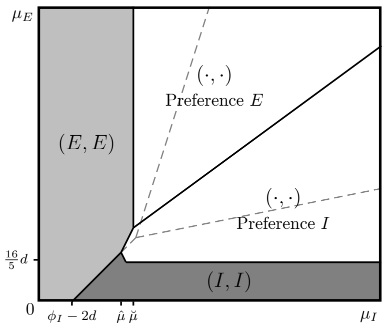


Figure 2.3.: Full Resource Commitment vs. Full Allocation Flexibility

Note. This graph shows the firm's optimal resource allocation policy when it can choose between a full commitment and a full flexibility policy. The firm prefers an (I, I)-policy in the gray area, an (E, E)-policy in the light gray area, and an $(\cdot, \cdot)$-policy in the white area. The dashed lines indicate, for comparison, the firm's optimal choice under full resource commitment.

perform best toward that goal because they always minimize overall agency and due diligence costs. In contrast, when one type of project is highly valuable while the other is not (i.e., $\mu_I \gg \mu_E$ or $\mu_I \ll \mu_E$), then the firm's top priorities are to (a) maximize its portfolio value by investing in only highly profitable projects and (b) minimize the information acquisition costs of inferior projects. The firm can again best accomplish those two targets by exclusively reserving all its resources for the most valuable projects.

Finally, when both types of projects are of sufficiently high value to the firm, then the firm does not truly need to worry about the costs of information acquisition. Instead, it seeks to maximize its portfolio value by increasing its expected portfolio scope as much as possible. Clearly, it is the full flexibility policy that best supports that goal because it allows the firm to allocate—without any restrictions—resources to the most promising projects.

From a managerial perspective, perhaps the most important implication of

Proposition 2.6 is that firms should significantly adjust their resource allocation policies based on the relative difficulty of information acquisition. The higher (resp. lower) the costs of information acquisition are, the more a firm should limit (resp. promote) allocation flexibility. Moreover, when committing resources upfront, the firm should be cautious about establishing completely non-permeable resource buckets for internal and external projects; indeed, it might be better to deprive one type of project of resources entirely. At first glance, these recommendations may seem at odds with the idea of strategic buckets promoted by Cooper et al. (2001) and Chao and Kavadias (2008). However, this is not entirely true, as we will demonstrate in the next section.

2.5. Allocation Policies with Partial Resource Commitment

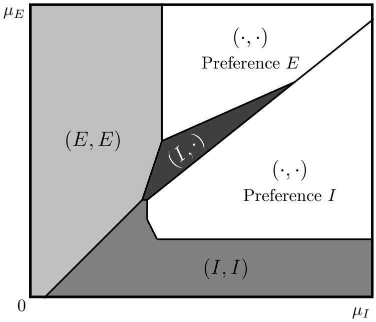
One of the key insights of the previous section was that the firm should never install dedicated, non-permeable resource buckets for both internal and external projects simultaneously. We will now study a refined resource allocation policy, referred to as a *partial commitment* policy, that allows the firm to create two distinct types of resource buckets: one that is dedicated to a particular type of project and one that can be tapped by both internal and external projects. Put differently, could it be optimal to reserve some resources for a particular type of project while leaving the remaining resources unassigned? The following proposition and Figure 2.4 answer this question in the affirmative.

Proposition 2.7. *Refer to a resource allocation policy that reserves resources for at most one internal* (*resp. external*) *project while keeping all other resources unassigned as an* $(I,\cdot)$*-policy* (*resp.* $(E,\cdot)$*-policy*)*.*

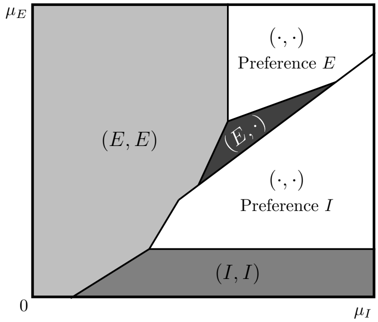
(i) *The firm's optimal resource allocation policy is* $\mathcal{P}^* = (I,\cdot)$ *if and only if* (a) $q_I \geq 68/77$*,* (b) $(224-129q_I)\phi_I/65 \leq \mu_I \leq (69q_I-44)\phi_I/10$*,* (c) $13\mu_I/12-(81q_I-56)\phi_I/30 \leq \mu_E \leq \min\{13\mu_I/4-4(7-2q_I)\phi_I/5, 3\mu_I/4+2(1-q_I)\phi_I/5\}$*, and* (d) $d \leq 3(4\mu_E-\mu_I)/32-(1-q_I)\phi_I/5$*. Moreover, in this case,* $n_I = 13/16$ *and* $n_E = 3/4$*, and the firm prefers to allocate unassigned resources to external* *projects.*

(ii) *The firm's optimal resource allocation policy is* $\mathcal{P}^* = (E, \cdot)$ *if and only if* (a) $q_I \leq 51/62$, (b) $\max\{(10q_I - 3)\phi_I/3, (25 - 6q_I)\phi_I/12\} \leq \mu_I \leq \min\{4(12 - 13q_I)\phi_I/3, 4(8-5q_I)\phi_I/7\}$, (c) $\max\{(12\mu_I - 32c)/11, 8\mu_I/7 - 8(3-2q_I)\phi_I/21\} \leq \mu_E \leq \min\{4\mu_I - 16\phi_I/3, 16\mu_I/7 - 64q_I\phi_I/21, 6\mu_I/7 - 8(11q_I - 9)\phi_I/21, 2\mu_I/3 + 8(1 - q_I)\phi_I/3\}$, *and* (d) $d \leq \max\{13\mu_E/32 - \mu_I/8, 9\mu_E/32 - (4q_I - 3)\phi_I/6\}$. *Moreover, in this case,* $n_I = 3/4$ *and* $n_E = 13/16$, *and the firm prefers to allocate unassigned resources to internal projects.*

The conditions presented in Proposition 2.7 appear somewhat unwieldy, but their interpretation is intuitive. For a partial commitment policy to be optimal, both types of projects must be of similar and middling value (as per conditions (b) and (c) of the proposition), and the firm's due diligence costs d must be relatively low (as per condition (d) of the proposition). Clearly, whenever $\mu_I \approx \mu_E$, the firm is somewhat indifferent between investing in internal or external projects; hence, the firm focuses mainly on balancing its information acquisition costs with the expected portfolio scope. It turns out that a partial commitment policy manages this tradeoff particularly well: it induces a relatively broad NPD portfolio (i.e., $n_I + n_E = 25/16$) and effectively contains the firm's agency costs. More specifically, the firm should pursue an $(I, \cdot)$-policy if its project managers' information quality q_I is high (see condition (a) in part (i) of Proposition 2.7), whereas an $(E, \cdot)$-policy is optimal if q_I is relatively low (see condition (a) in part (ii) of the proposition). In the former case, project managers can access very accurate information about their projects, and they thus have no real motive to conceal negative evaluation outcomes—after all, an investment in a project with bad market potential is pointless. Hence the firm must ensure only that its project managers actually acquire information, which can most effectively be done by reserving some resources for internal projects. In contrast, in the latter case, project managers have a much stronger tendency to misrepresent their information (because that information is not very accurate in the first place), and the firm finds it optimal to mitigate the repercussions of this adverse effect by dedicating some resources to external projects.



(a) $q_I \geq 68/77$



(b) $q_I < 51/62$

Figure 2.4.: The Optimal Resource Allocation Policy

Note. These graphs show a firm's optimal resource allocation policy for different values of q_I. In the left panel, the firm prefers an (I, I)-policy in the gray area, an (E, E)-policy in the light gray area, an $(\cdot, \cdot)$-policy in the white area, and an $(I, \cdot)$-policy in the dark gray area. In the right panel, the firm prefers an (I, I)-policy in the gray area, an (E, E)-policy in the light gray area, an $(\cdot, \cdot)$-policy in the white area, and an $(E, \cdot)$-policy in the dark gray area.

It is also worth mentioning that any optimal partial commitment policy mimics, to a certain extent, an (I, E)-policy: the firm reserves some resources for one type of project but prefers to invest the unassigned resources in the other type of project. As a direct consequence, the firm's expected portfolio composition is quite evenly balanced between internal and external projects. However, a partial commitment policy is set apart from an (I, E)-policy in that it offers the additional benefit of sustaining "back-up" projects, helping the firm increase its overall portfolio scope.

From a practical perspective, Proposition 2.7 extends the notion of "strategic" buckets by introducing the idea of simultaneously creating permeable and non-permeable resource buckets. Having these different types of buckets allows a firm to diversify its NPD portfolio composition by reserving some resources for projects that (a) may not be the firm's immediate investment priority or (b) suffer from severe information acquisition costs. Moreover, a partial commitment policy also ensures that the remaining resources are deployed most efficiently and that resources are unlikely to remain idle due to faulty preallocation, benefiting the firm's overall portfolio scope.

2.6. Conclusions

What degree of resource commitment best supports a firm in allocating its scarce resources to competing internal and external NPD projects? Extant work on resource allocation has derived important insights into how varying degrees of resource commitment affect a firm's propensity to invest in different types of *internal* NPD projects, leading to a coherent theory of how firms determine the scope and composition of their (internal) NPD portfolios (e.g., Chao and Kavadias 2008, Van Nieuwerburgh and Veldkamp 2010, Klingebiel and Rammer 2014, Hutchison-Krupat and Kavadias 2015, Schlapp et al. 2015). We complement existing theory by studying two additional questions that are of great practical importance for building successful NPD portfolios: (i) How does the simultaneous availability of internal *and* external NPD projects affect a firm's optimal degree of resource commitment? (ii) How do varying degrees of resource commitment influence the efficiency (i.e., cost and quality) of a firm's information acquisition processes? The novel contribution of our paper is its characterization of a firm's optimal degree of upfront resource commitment that simultaneously promotes the efficient acquisition of project-related information and the ex-post optimal allocation of resources to projects.

More precisely, we establish how different resource allocation policies—defined by their degree of resource commitment and the associated incentive structures—help a firm optimally balance (a) the scope and composition of its NPD portfolio with (b) the quality and cost of information acquisition. We find that the firm should largely ignore the cost of information acquisition and implement a full flexibility policy only if all available NPD projects are of high value. In that case, the firm's primary aim is to construct an NPD portfolio with maximum scope. In all other scenarios, however, the firm should commit some resources upfront—and thus reduce its portfolio scope—to limit the costs of information acquisition. We also establish how, exactly, the firm should commit resources to different types of projects. Most notably, the firm should not simply reserve resources for internal and external NPD projects. Instead, it should rather (i) completely deprive one type of project of resources whenever information acquisition costs are excessive or the other type of project is much more promising or (ii) simultaneously establish permeable and non-permeable resource buckets when expected project values are middling.

We complement our structural results with insights into how the quality of a firm's resource allocation decisions can be improved through the design of appropriate incentives. Most importantly, we show that the optimal balance between individual, shared, and external incentives changes appreciably depending on the degree of resource commitment inherent to the firm's resource allocation policy.

Of course, our research has some limitations. In particular, we focus exclusively on the value creation motive of an NPD portfolio, which is arguably very important in practice. However, there may be other reasons that a firm invests in NPD projects, including access to new technologies, competitive pressure, regulatory requirements, or market protection (Schilling 2017). Those other motives may very well impact the firm's optimal choice of resource allocation policy. We also disregard the dynamic nature of many resource allocation processes: over time, a firm may remove resources from failing projects, or it may assign additional resources to succeeding projects (Cooper et al. 2001, Klingebiel 2022). Studying the effects of these dynamics on the optimal degree of resource commitment and the costs of information acquisition is a promising avenue for future research. Last, we model the firm's interactions with external innovators in a very parsimonious way in that we ignore (a) the incentives of external innovators to exaggerate the promise of their projects (West and Bogers 2014) and (b) the possibility of more collaborative contractual arrangements (Bhaskaran and Krishnan 2009, Bhattacharya et al. 2015). Accounting for these factors would make the firm's information acquisition challenge even more difficult.

In summary, we believe that our research has deepened our theoretical understanding of how different resource allocation policies facilitate (or hinder) a firm's information acquisition efforts and that it offers practical insights for executives on how to manage the allocation of resources to competing internal and external NPD projects. Thus, we hope to be able to give advice on how to best coordinate the two essential phases of the resource allocation process: the information acquisition phase and the resource allocation phase.

Chapter III

Composing New Product Development Portfolios: To Reveal or Not to Reveal Information?

Abstract

When composing their innovation portfolios, firms often select from a pool of internally developed and externally acquired initiatives. The potential value of the initiatives is very uncertain in the beginning. Senior management of the organization eventually obtains more refined information about the value of external projects. The question is: Should she subsequently reveal this information to the internal project managers, or not? We investigate senior management's optimal communication strategy in combination with financial incentives to see how portfolio composition and agency costs are affected. We find that choosing to reveal information leads to reduced portfolio scope. However, revealing may entail agency costs and, thus offset the downsides of a smaller portfolio scope. The optimal strategy depends on two key factors: the types of projects the firm pursues and the severity of agency issues in internal R&D.

3.1. Introduction

New product development (NPD) initiatives often suffer from immense technical and market uncertainties and require a skyrocketing investment of resources. Therefore, selecting the *right* projects to include in the NPD portfolio is a challenging task for the senior management (she) of most innovative firms (Thomke 1995, Kavadias and Loch 2003, Shane and Ulrich 2004, Kavadias and Hutchison-Krupat 2020). At the same time, resource allocation to NPD projects is generally a decentralized process involving different parties within and across firm boundaries, each holding private information needed for the effective development of the portfolio (Hutchison-Krupat and Kavadias 2015, Schlapp et al. 2015, Hutchison-Krupat and Kavadias 2018, Kavadias and Hutchison-Krupat 2020). In this environment, senior management must carefully coordinate different players, acquire relevant information, and effectively influence their actions to successfully implement the firm's innovation strategy. To this end, she can utilize two main mechanisms: incentives and communication (Hutchison-Krupat 2018). The natural question is, how these mechanisms, incentives, and communication work in concert with one another to align the interests of different parties with those of the firm.

When building their NPD portfolio, firms can tap different sources of NPD initiatives: They can rely on their internal research and development (R&D) units and invest in projects that are promoted internally; alternatively, firms can access external innovations and strategically acquire projects that originate outside the firm (Hasija and Bhattacharya 2017). In practice, firms seek to balance those two sources; they frequently include both internal and external initiatives in their respective NPD portfolios. The intrinsic differences between the projects coming from these two sources and the interplay between them have far-reaching implications for the performance of a firm's NPD portfolio. In particular, with respect to an internal project manager (he), the organizational dynamics and misaligned incentives can lead to substantial agency costs for the firm (Hasija and Bhattacharya 2017, Kavadias and Hutchison-Krupat

2020). At the same time, the inclusion of external projects in the selection process, although beneficial for the firm as it allows senior management to draw from a larger pool of projects, intensifies competition over resources. Whether this inflated competition worsens the agency issues the firm faces or not depends critically on the internal project managers' understanding of the value of the external candidate projects (Nikpayam et al. 2022). That is, if they believe the external projects under consideration of senior management are far more valuable than their internal projects, the incentive misalignment between the senior and project managers broadens, considerably increasing the firm's agency costs. However, if they believe the external projects are not as valuable and the senior management only considers them as fall-back options in case internal projects do not yield, they do not see any real threat from outside the firm and the agency issues are not exacerbated.

Senior management's access to expansive knowledge inside and outside the firm and her ability to interpret strategic information on new projects are well established in the literature (O Reilly and Tushman 2004, Hutchison-Krupat 2018). Particularly, she can obtain more refined information about the true value of the candidate external projects than other stakeholders lower in the firm's hierarchy, *i.e.* project managers. As such, once she has acquired such information, she would like to exploit this information asymmetry to narrow down the incentive misalignment between herself and the project managers. To this end, she must devise a communication strategy and decide what information to convey to them. However, this is not trivial and in doing so, she primarily faces two challenges: First, her communication must be held credible to have any effect on managers' actions. Second, communication does not always induce managers to take the actions preferred by senior management (Hutchison-Krupat 2018).

Thus, we investigate senior management's optimal communication strategy in this paper and seek to understand how this, in combination with financial incentives, impacts the problem of resource allocation to NPD projects. To this end, we build a principal-agent model in which senior management (principal) allocates resources across internal and external projects while dealing with moral hazard during project evaluation and adverse selection during recommendation by the internal project manager (agent). Both the principal and the agent share a prior belief about the uncertain value of the external project. However, the principal obtains more refined information on the matter. We compare two communication strategies: To reveal, or not to reveal the value to the agent?

Our paper offers the following contributions to the literature. First, we reiterate a key condition for effective communication already discussed in the literature; for the senior management's communication decision to have any effect on the project manager's actions, not only must her messages be credible but also the value of the external project must be sufficiently uncertain. This is, in nature, very similar to the results from Crawford and Sobel (1982) and Hutchison-Krupat (2018). Second, we define the conditions under which either strategy, to reveal or not to reveal, becomes optimal. Our results are particularly important here because they indicate that, unlike omnipresent advocacy for higher clarity in communication (Loch 2008, Schlickel et al. 2013, O Reilly and Tushman 2004), revealing is not always optimal. In particular, there is no one-size-fits-all solution, and the optimal strategy depends critically on two factors: the types of initiatives a firm goes after and the severity of the agency issues. Specifically, we identify a trade-off between both strategies: Choosing to reveal the information leads to a reduced portfolio scope relative to not revealing; however, revealing may contain agency costs and, thus, offset the downside of a smaller portfolio scope. We find that if the internal R&D is prone to high agency costs, *i.e.* quality of info is bad or the private effort is too costly, the firm can curb the costs by revealing the information. Otherwise, senior management would be better off not revealing the information.

3.2. Related Literature

Research on NPD, particularly resource allocation to innovation projects, has been the focus of many works in the literature of multiple disciplines (Clark and Fujimoto 1991, Wheelwright and Clark 1992, Shane and Ulrich 2004, Hauser et al. 2006, Loch 2008, Klingebiel and Rammer 2014, Kavadias and Hutchison-Krupat 2020). The implicit assumption in a large part of this literature is that senior managers in charge of strategic NPD decisions should always direct the flow of high-specificity information through the organization and assert that such high clarity brings about better performance (Mihm 2010, Hutchison-Krupat 2018). Although this general recommendation is useful in many settings, it may not be always the optimal strategy. In particular, due to the information asymmetry inherent to the NPD process and the incentive misalignment between different decision-making parties, full disclosure of information by senior management can lead to decisions on part of other parties that are not in the firm's best interest (Mihm 2010).

Our work is mostly related to the literature on the role of organizational dynamics in NPD. These works recognize the decentralized nature of NPD activities and focus on its inevitable consequence– information asymmetry through organizational hierarchy (Siemsen 2008, Mihm 2010, Kavadias and Chao 2007, Chao et al. 2009, Hutchison-Krupat and Kavadias 2015, Schlapp et al. 2015, Hutchison-Krupat and Kavadias 2018, Hutchison-Krupat 2018, Nikpayam et al. 2022). They discuss agency issues in a broad range of R&D activities and settings, including assessment of task difficulty (Siemsen 2008, Hutchison-Krupat and Kavadias 2015), product design and cost characteristics (Mihm 2010), and quality evaluation (Schlapp et al. 2015, Nikpayam et al. 2022). In the majority of such works, implicit and explicit incentives are investigated as senior management's tool to align the interests of different parties with the firm's objectives. The common theme across this body of literature is the focus on settings where only those players in the organizational hierarchy lower than senior management, *i.e.* project managers, have private knowledge and not the other way around (Hutchison-Krupat 2018). We also consider this important factor, and similar to Schlapp et al. (2015) and Nikpayam et al. (2022), assume the project manager's effort in the evaluation and his understanding of the project's quality are hidden from senior management and that he tries to extract informational rent on them, *i.e.* moral hazard and adverse selection. However, as established in the broader literature, the senior management of the company also has access to expansive useful knowledge that is often not visible to others lower in the hierarchy (O Reilly and Tushman 2004).

Conversely, we acknowledge the private knowledge of senior management in our paper and argue that her access to strategic knowledge about the value of external projects to the firm can be useful leverage for her to exploit. In this regard, our work is most related to Hutchison-Krupat (2018); they model an NPD portfolio problem in which a principal in charge of selection decisions combines financial incentives with an information-sharing strategy of either vague or detailed communication to motivate higher efforts by an agent in product development. On a high level, our work shares similarities with this setting; however, there are major differences: Importantly, their model captures communication that is unidirectional, whereas we analyze bidirectional communication where senior management has superior knowledge about the value of external projects, but project managers have a better understanding of the quality of their own projects, the information that is critical for an effective resource allocation decision by senior management. As such, we capture additional dynamics that impact the optimal communication strategy. Furthermore, they consider two internal projects, one known and one uncertain. In contrast, we are interested in the interplay between internal and external projects, and both initiatives are assumed to be uncertain. Consequently, we incorporate competition over resources in our model and study how different communication strategies impact this key effect. As such, the resulting underlying trade-offs also differ from one another. Furthermore, they consider a moral hazard problem with respect to the agent's choice of effort level in product development, whereas we look at moral hazard and adverse selection together at the evaluation stage. In this way, we investigate the impact of communication strategy on both of these agency problems and show that the direction and magnitude of the effects are very context-dependent and nontrivial.

There are few other streams of literature that look at similar problems but with different research objectives and foci. A group of earlier works in the operations literature have looked into lateral communication problems among team members working on NPD projects. This stream focuses on both fidelity of information flow as well as the decisions to share or not to share private knowledge (Ha and Porteus 1995, Krishnan et al. 1997, Loch and Terwiesch 1998). Our paper, in contrast, focuses on vertical communication and investigates the interplay between communication and financial incentives. Our work also shares some similarities with the *strategic information transmission* and *cheap talk* literature in economics, built upon seminal works by Crawford and Sobel (1982) and Farrell and Rabin (1996), respectively. In this regard, we also consider a case of costless communication in which, the interests of the game players are misaligned. However, different from this stream, we do not look at the communication problem in isolation but in concert with financial incentives. As a result, we study both of these mechanisms at the same time and see how their combination impacts the incentive misalignment problem in NPD.

3.3. Model

Consider a firm that faces the challenge of composing an R&D portfolio; that is, it has to decide on how to allocate scarce resources across two different NPD initiatives, one sourced from within and one from outside the firm. We know that, depending on the relative value of the external projects, the firm may face higher agency costs considering both internal and external initiatives at the same time (Nikpayam et al. 2022). In particular, on the one hand, if the candidate external project is considerably more valuable than the internal one, the in-house project manager would face stronger competition in obtaining funding, hence he would have greater incentives not to put significant effort into evaluating his project and to misrepresent its quality, *i.e.*, moral hazard and adverse selection. On the other hand, if he knows that the external initiative is less valuable than his own project, the project manager no longer feels threatened by the presence of external partners, and hence, the agency issues would not be exacerbated. Due to the initial high uncertainties, both the senior management and the project manager have a noisy understanding of the value of the external project. However, senior management obtains more refined information over time and updates his belief on the value of the external initiative accordingly. This better understanding is mainly the result of two key factors. First, as captured by Hutchison-Krupat (2018), "Once the decision to add a new initiative to the portfolio has been made, senior leadership can pursue discussions both within and outside the organization to better understand the initiative's true value." Second, since the managers of internal projects as well as the external ones often *report* to a single executive, senior management (see e.g. O Reilly and Tushman 2004), she is better suited than others within the organization to judge the *relative* value of the external initiative. In this environment, a natural question arises: Should senior management reveal her private knowledge to the project manager? Understandably, this decision has implications for the firm's agency costs and she prefers to reveal the information when her new knowledge indicates a lower-than-expected value for the external project and not to reveal when there is an indication for higher values. However, for the message to be credible, she has to make the decision, to reveal or not, before knowing the true value and has to commit to it by offering the project manager an appropriate compensation scheme. In other words, for either strategy, senior management must set the organizational systems, processes, and norms suited to that strategy. That is, if such incentives have been put in place that are tailored to the strategy of not revealing the information, senior management never chooses to reveal, and vice versa; For instance, inflexible resource allocation and rigid compensation schemes discourage communication, whereas more flexible allocation policies and performance measurement systems facilitate the communication of more specific information when it becomes available (Hutchison-Krupat 2018). This implies that this decision should be made at a strategic level and cannot be easily modified at any point in time. Then, after the decision is made, senior management learns about the true value of the external project and reveals (or does not reveal) the information according to the chosen strategy. The project manager updates his beliefs, the projects are evaluated, senior management obtains information on the quality of projects, and finally based on them, she allocates resources to the best initiative while forgoing investments in bad ones, maximizing her profits (see Figure 3.1).

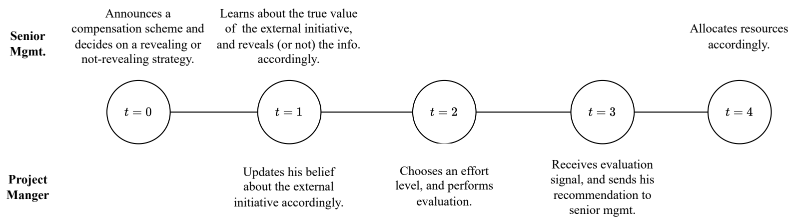


Figure 3.1.: Timeline of events

To cast this challenge into an analytically tractable model, we assume that senior management is contemplating two projects $\{I, E\}$, of which one is internal and one is external. The firm seeks to fund projects having good market potential ($\theta = G$) and avoid bad projects ($\theta = B$) and has resources to invest in at most one project. Due to high uncertainty, the true quality is unknown to everyone. However, both senior management and the project manager hold a prior common belief about it. Senior management requires information from the (imperfect) evaluation of projects to decide how to allocate resources. The evaluation process and the information acquisition procedure are different from internal to external projects.

With regard to the *internal* project, the project manager acquires such information from extensive product evaluations performed by his team. From the evaluation, he receives a signal about the project quality that can be either good ($s = g$) or bad ($s = b$). The signal is imperfect, meaning its message is correct with a specific probability called signal precision q_I. This can be stated mathematically in the following form $Pr(s_I = g|\theta_I = G) = Pr(s_I = b|\theta_I = B) = q_I$ and $Pr(s_I = b|\theta_I = G) = Pr(s_I = g|\theta_I = B) = 1 - q_I$. The internal signal precision depends on the evaluation effort level e chosen by the project manager, which can be either high $e = h$ or low $e = l$. A high effort would result in a signal precision of $q_I \in (1/2, 1]$, for which the project manager incurs a private cost of $c > 0$. A low effort evaluation on the other hand would result in an uninformative signal (*i.e.,* $q_I = 1/2$), for which he does not incur any costs. After observing the signal, the project manager updates his prior belief regarding the project's quality accounting for the new information based on Bayes' rule. The posterior beliefs are given by $Pr(\theta_I = G|s_I = g) = Pr(\theta_I = B|s_I = b) = q_I$. Then, the project manager sends his recommendation $m_I \in \{g, b\}$ to the firm. There could be substantial information asymmetries between senior management (principal) and the project manager (agent). Particularly, we assume that the principal cannot observe how much (costly) effort is exerted by the agent in evaluation, nor can verify the project mangers' recommendation. As such, we consider moral hazard in acquiring information and adverse selection in recommendation as potential agency issues in our model. Therefore, and to invoke high-effort and truthful evaluation, the principal needs to provide the agent with sufficient incentives through a compensation scheme. The senior management receives a similar signal regarding the *external* project's potential with the precision of q_E. The firm does not face the same severe agency issues present in the internal case; we assume that there are no information asymmetries between the senior management and the external partner (for further discussion of this point, refer to Nikpayam et al. 2022).

The payoff of each project upon realization of all uncertainties (z_j, $\forall j \in \{I, E\}$) depends on three factors: (i) its inherent market potential (whether it is a high or low quality project), (ii) the origin of the project (internal or external), and (iii) whether it receives funding. The notation is presented in Table 3.1. The payoff of the project that receives no investment is always zero. Funding a high-quality project always generates greater value than funding any low-quality project, *i.e.*, $min\{v_I, v_E\} > max\{w_I, w_E\}$. These values are known to all involved parties prior to the game.

Table 3.1.: A project's market value ($v_E^h > v_E^l$)

	No investment	*Funded high quality* ($\theta_j = G$)	*Funded low quality* ($\theta_j = B$)
Internal project	0	v_I	w_I
External project	0	$v_E = v_E^h$ or v_E^l	w_E

The principal and the agent share a prior belief about v_E; that is, $v_E = v_E^h$ with probability p and $v_E = v_E^l$ with probability $1-p$. However, the principal will learn later in the game about the true value of v_E (either v_E^h or v_E^l). The principal needs to announce an information revelation strategy $\mathcal{P}$ at the beginning of the game, deciding whether she will reveal the true value of v_E ($\mathcal{P} = R$) or not ($\mathcal{P} = N$). Furthermore, let $\mu_I = q_I v_I + (1-q_I)w_I$, $\mu_E^h = q_E v_E^h + (1-q_E)w_E - k$, and $\mu_E^l = q_E v_E^l + (1-q_E)w_E - k$ denote the expected values of internal and external projects when $v_E = v_E^h$ and when $v_E = v_E^l$, respectively.

The principal offers the agent a compensation scheme that determines the payments to him after the realization of projects' market value. Similar to the related literature (Schlapp et al. 2015, Hutchison-Krupat 2018, Nikpayam et al. 2022), we consider a general form of a linear compensation scheme which makes the agent's wage contingent on his own project's performance as well as the performance of the external project. We assume the compensation scheme has the following form:

$$\hat{\omega} = \delta + \alpha + \gamma$$

Where δ is a fixed wage, α is the wage parameter related to the performance of the agent's own project, and γ is related to the external project's performance. These parameters have different realizations, depending on whether the respective project receives no funding, receives funding and is of high quality, and receives funding and is of low quality. Such realizations are represented in Table 3.2. It is assumed that the agent is protected by limited liability, so the wage cannot be negative, *i.e.*, $\hat{\omega} \geq 0$.

Table 3.2.: Wage parameters values

	α	γ
high quality	α^h	γ^h
low quality	α^l	γ^l
no investment	α^n	γ^n

The internal agent's utility comprises the wage he receives and the private cost that he incurs when exerting high effort $\hat{\mathcal{U}} = \hat{\omega} - c \cdot \mathbb{1}_{\{e=h\}}$, where $\mathbb{1}_{\{\cdot\}}$ is an indicator function. It is assumed that the agent is risk neutral and seeks to maximize his expected utility. The principal's profit is the sum of projects payoffs minus the manager's wage and external project's acquisition costs $\hat{\Pi} = (z_I(r_I) - \omega) + (z_E(r_E) - k_E)$, in which k_E is the acquisition cost of the external project for the firm, which is zero if the firm does not invest in the project and equals $k > 0$ if it does. Furthermore, r_I and r_E are binary variables determining whether projects I and E are funded (*i.e.*, $r = 1$) or not (*i.e.*, $r = 0$). In the rest of this document we refer to the agent's expected wage and utility, and the principal's expected profits by ω, $\mathcal{U}$, and Π, respectively.

3.4. Analysis

In this section, we characterize the firm's optimal information revelation strategy. We first discuss when the decision between the two strategies is relevant, and then we formally introduce the strategies and define the equilibrium solutions under each. Finally, we investigate the optimal choice between the two.

3.4.1. When is the decision relevant?

The principal's decision to reveal the new information or not is relevant and consequential only if the agent believes that the principal prefers investing in the internal project if the external project is of the low value $v_E = v_E^l$ and prefers the external project if it is of high value $v_E = v_E^h$. That is, if the principal has a weak preference. The key point here is that the principal's preference determines whether the agent faces competition over funding. Naturally, then, the agent's incentives and hence the firm's agency costs are tied to the principal's preferences. In contrast, if the principal has a strong preference, prefers the internal project even if $v_E = v_E^h$ or prefers the external project even if $v_E = v_E^l$, revealing the true value of v_E will not change the agent's incentive, and hence the decision will not have any impact on the agent's actions.

3.4.2. Strategy Characterization

If the principal decides *to not reveal* the real value of v_E, she solves the following optimization problem to obtain the optimal compensation scheme (the detailed derivation can be found in the proof of Proposition 3.1):

$$\begin{aligned}\max_{\alpha,\gamma,\delta} \pi_N = \; & (2-p)\mu_I/4 + p\mu_E^h/2 + (1-p)\mu_E^l/4 \\ & - (2-p)(q_I\alpha^h + (1-q_I)\alpha^l)/4 - (2+p)\alpha^n/4 \\ & - (1+p)(q_E\gamma^h + (1-q_E)\gamma^l)/4 - (3-p)\gamma^n/4 - \delta\end{aligned} \tag{O}$$

s.t.

$$\begin{aligned}& q_I(v_I - \alpha^h) + (1-q_I)(w_I - \alpha^l) - \gamma^n \geq \\ & q_E(v_E^l - \gamma^h) + (1-q_E)(w_E - \gamma^l) - k - \alpha^n\end{aligned} \tag{Pref.}$$

$$(2-p)(q_I\alpha^h + (1-q_I)\alpha^l - \alpha^n) \geq (1-p)(q_E\gamma^h + (1-q_E)\gamma^l - \gamma^n) \tag{IC-g}$$

$$(2-p)((1-q_I)\alpha^h + q_I\alpha^l - \alpha^n) \leq (1-p)(q_E\gamma^h + (1-q_E)\gamma^l - \gamma^n) \tag{IC-b}$$

$$(2q_I - 1)(\alpha^h - \alpha^l) \geq 8c/(2-p) \tag{IC-e}$$

$$\begin{aligned}& \delta + \alpha^h + \gamma^n \geq 0, \delta + \alpha^l + \gamma^n \geq 0, \delta + \alpha^n + \gamma^n \geq 0, \\ & \delta + \alpha^n + \gamma^h \geq 0, \delta + \alpha^n + \gamma^l \geq 0\end{aligned} \tag{LL}$$

The objective function (O) maximizes the firm's expected profits over the wage parameters δ, α, and γ given the strategy not to reveal N; the first term is the expected return on projects, and the second and third terms are expected agency costs. Constraint (Pref.) ensures that the principal always prefers the internal project over the external one when $v_E = v_E^l$. Constraints (IC-g) and (IC-b) ensure that the internal manager truthfully reveals a good and a bad signal, respectively. These constraints are necessary to address the adverse selection problem at the recommendation stage. Similarly, the moral hazard problem at the product evaluation stage is addressed by constraint (IC-e), which ensures that the manager is better off exerting a high-effort product evaluation. The limited liability constraints (LL) guarantee that the manager's wage is nonnegative. The following proposition characterizes the optimal contracting under this strategy.

Proposition 3.1. *Let $\phi = 2c/(2q_I - 1)$, and that principal commits to* ***not revealing*** *the information about the external project's value. The optimal compensation scheme is characterized in four cases depending on the value of $(\mu_I - \mu_E^l)$, presented in table 3.3, where case (i) applies for $8q_I c/((2q_I - 1)(2-p)) \leq \mu_I - \mu_E^l$, case (ii) applies for $8((1-p)q_I - (2-p)(1-q_I))c/((1-p)(2-p)(2q_I - 1)) \leq \mu_I - \mu_E^l < 8q_I c/((2q_I - 1)(2-p))$, case (iii) applies for $-8q_I c/((1-p)(2-p)(2q_I - 1)) \leq \mu_I - \mu_E^l < 8((1-p)q_I - (2-p)(1-q_I))c/((1-p)(2-p)(2q_I - 1))$, and case (iv) applies for $\mu_I - \mu_E^l < -8qc/((1-p)(2-p)(2q_I - 1))$.*

Proof. Appendix B.

We explain the solution structure of both strategies jointly after Proposition 3.2. When the principal decides to *reveal* the real value of v_E, she solves the following optimization problem to obtain the optimal compensation scheme

Table 3.3.: Optimal characterization of 'not revealing' strategy

	Optimal contract	*Profits* $\Pi_N^* = \frac{2-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l$
(i)	$\alpha^{h*} = 4\phi/(2-p)$, $\alpha^{n*} = 4(1-q_I)\phi$, $\gamma^{h*} = \gamma^{l*} = -4(1-q_I)\phi$.	$-\phi$
(ii)	$\alpha^{h*} = 4\phi/(2-p)$, $\alpha^{n*} = -4(-2pq_I + p + 3q_I - 2)\phi/(2-p)$ $+(1-p)(\mu_I - \mu_E^l)$, $\gamma^{h*} = \gamma^{l*} = 8c - (2-p)(\mu_I - \mu_E^l)$.	$-(\frac{(p(2q_I-1)+2)\phi}{2-p} - \frac{p(\mu_i - \mu_e^l)}{2})$
(iii)	$\alpha^{h*} = 4\phi/(2-p)$, $\gamma^{h*} = \gamma^{l*} = -(\mu_I - \mu_E^l) + 4q_I\phi/(2-p)$.	$-(\frac{3q_I\phi}{2-p} - \frac{(1+p)(\mu_I - \mu_E^l)}{4})$
(iv)	$\alpha^{h*} = -(1-p)(\mu_I - \mu_E^l) + 4(1-q_I)\phi/(2-p)$, $\alpha^{l*} = -(\mu_I - \mu_E^l)(1-p) - 4q_I\phi/(2-p)$, $\gamma^{h*} = \gamma^{l*} = -(\mu_I - \mu_E^l)(2-p)$.	$-(\frac{-(2-p)(\mu_I - \mu_E^l)}{2})$

(the detailed derivation can be found in the proof of Proposition 3.2):

$$\begin{aligned}
\max_{\alpha,\gamma,\delta} \pi_R = \; & (1-p)\mu_I/4 + p\mu_E^h/2 + (1-p)\mu_E^l/4 \\
& - (1-p)(q_I\alpha^h + (1-q_I)\alpha^l)/2 - (1+p)\alpha^n/2 \\
& - (1+p)(q_E\gamma^h + (1-q_E)\gamma^l)/4 - (3-p)\gamma^n/4 - \delta
\end{aligned} \tag{O}$$

$s.t.$

$$q_I(v^I - \alpha^h) + (1-q_I)(w^I - \alpha^l) - \gamma^n \geq$$
$$q_E(v_E^l - \gamma^h) + (1-q_E)(w^E - \gamma^l) - k - \alpha^n \tag{Pref.}$$
$$q_I\alpha^h + (1-q_I)\alpha^l - \alpha^n \geq (q_E\gamma^h + (1-q_E)\gamma^l - \gamma^n)/2 \tag{IC-g}$$
$$(1-q_I)\alpha^h + q_I\alpha^l - \alpha^n \leq (q_E\gamma^h + (1-q_E)\gamma^l - \gamma^n)/2 \tag{IC-b}$$
$$(2q_I - 1)(\alpha^h - \alpha^l) \geq 4c \tag{IC-e}$$
$$\delta + \alpha^h + \gamma^n \geq 0, \delta + \alpha^l + \gamma^n \geq 0, \delta + \alpha^n + \gamma^n \geq 0,$$
$$\delta + \alpha^n + \gamma^h \geq 0, \delta + \alpha^n + \gamma^l \geq 0 \tag{LL}$$

The structure of the optimization problem is very similar to the strategy to not reveal. It is important to note that under the reveal strategy, the principal incentivizes the agent to be truthful and hard-working only when she reveals that $v_E = v_E^l$, and she completely disregards the internal project when $v_E = v_E^h$, hence providing no incentives. The reason is that the principal has to offer the compensation scheme before she learns about the value of v_E; so, if she wants to ensure that the agent's interests will always be aligned with hers for any uncertain outcome, she has to offer an overly conservative compensation scheme considering the worst case in terms of agency issues, *i.e.* $v_E = v_E^h$. Such a strategy is always dominated by not revealing since it incurs the highest agency costs without bringing any additional benefits to the firm. Therefore, if the principal decides to reveal the information, she forgoes investing in the internal project when the external project is of high quality, *i.e.* narrower portfolio scope, in return for lower agency costs compared with a strategy to not reveal. The following proposition characterizes the optimal contracting under this strategy.

Proposition 3.2. *Let* $\phi = 2c/(2q_I - 1)$ *and that principal commits to* ***revealing*** *the information about the external project's value. Then, the optimal compensation scheme is characterized in four cases depending on the value of* $(\mu_I - \mu_E^l)$, *presented in table 3.4, where case (i) applies for* $4q_I c/(2q_I - 1) \leq \mu_I - \mu_E^l$, *case (ii) applies for* $4(3q_I - 2)c/(2q_I - 1) \leq \mu_I - \mu_E^l < 4q_I c/(2q_I - 1)$, *case (iii) applies for* $-4q_I c/(2q_I - 1) \leq \mu_I - \mu_E^l < 4(3q_I - 2)c/(2q_I - 1)$, *and case (iv) applies for* $\mu_I - \mu_E^l < -4q_I c/(2q_I - 1)$ *become relevant.*

Table 3.4.: Optimal characterization of 'revealing' strategy

	Optimal contract	*Profits* $\Pi_R^* = \frac{1-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l$
(i)	$\alpha^{h*} = 2\phi$, $\alpha^{n*} = 4(1-q_I)\phi$, $\gamma^{h*} = \gamma^{l*} = -4(1-q_I)\phi$.	$-(1+p-2pq_I)\phi$
(ii)	$\alpha^{h*} = 2\phi$, $\alpha^{n*} = -2(3q_I-2)\phi + (\mu_I - \mu_E^l)$, $\gamma^{h*} = \gamma^{l*} = 8c - 2(\mu_I - \mu_E^l)$.	$-(1+p-2pq_I)\phi$
(iii)	$\alpha^{h*} = 2\phi$, $\gamma^{h*} = \gamma^{l*} = -(\mu_I - \mu_E^l) + 2q_I\phi$.	$-(q_I(3-p)\phi/2 - (1+p)(\mu_I - \mu_E^l)/4)$
(iv)	$\alpha^{h*} = -(\mu_I - \mu_E^l) + 2(1-q_I)\phi$, $\alpha^{l*} = -(\mu_I - \mu_E^l) - 2q_I\phi$, $\gamma^{h*} = \gamma^{l*} = -2(\mu_I - \mu_E^l)$.	$-(-(\mu_I - \mu_E^l))$

Proof. Appendix B.

Propositions 3.1 and 3.2 characterize the optimal contract design and the firm's expected profits under each strategy. Profits consist of two parts, namely, the portfolio value and the expected agency costs. The structure of the portfolio value, namely, the coefficients of μ_I, μ_E^h, and μ_E^l, is an indicator of the portfolio composition under each strategy. On expectation, both strategies invest in the same number of external projects; that is, $p/2$ and $(1-p)/4$ external projects of high and low quality, respectively, receive funding. However, as mentioned earlier, the revealing strategy disregards the internal project when the external project one is of high quality, so it invests in a smaller number of internal projects than the strategy to not reveal $(1-p)/4 < (2-p)/4$.

The results show that the structure of the optimal contract critically depends on the value of $\mu_I - \mu_E^h$. Under both strategies, the principal picks the optimal contract from a menu of four alternatives. Any optimal contract must satisfy Pref. constraint, ensuring that the internal project is more profitable than the low quality external project. Therefore, as $\mu_I - \mu_E^l$ decreases below a certain threshold, the principal needs to keep the preference to the internal side by rewarding the agent when she invests in the external project, *i.e.* Pref. constraint is binding under cases (ii)-(iv). This in turn influences the agency costs, which increase as $\mu_I - \mu_E^l$ decreases.

Under all cases, $\alpha^{h*} - \alpha^{l*}$ serves to motivate a high effort; that is, constraint IC-e is always binding. Under cases (i) and (ii), the combination of α^{n*}, γ^{l*}, and γ^{h*} incentivizes the agent to disclose a bad signal, *i.e.* constraint IC-b is binding. Under cases (iii) and (iv), γ^{l*} and γ^{h*} are set so high, due to Pref. constraint, that the agent not only does not have any incentives to misrepresent a bad signal but also the principal needs to make sure that he discloses his good signal under case (iv), *i.e.* IC-g is binding.

While the portfolio value is always lower under the strategy to reveal than not to reveal, there is no such straightforward relation with regard to agency costs. In particular, it is always cheaper to incentivize high effort in evaluation and more expensive to motivate truth-telling in the recommendation stage when revealing rather than not revealing. Therefore, given the value of $\mu_I - \mu_E^l$, one factor can dominate the other, and the total agency costs under one strategy can be higher or lower than the other one. This is directly linked to the lack of competition under the revealing strategy; the agent is incentivized only for the case of $\mu_E = \mu_E^l$, when he knows sending a good recommendation to the senior manager would guarantee him getting funding. This has a double-edged effect on agency issues. First, since there is a higher chance of winning the resources, the agent is more inclined to put a high effort in the evaluation, maximizing the chances of winning α^{h*}. Second, due to high levels of uncertainty about each project's quality, it is always possible for a project with a bad signal to turn successful in the end. Therefore, the lack of competition increases the agent's utility from lying about his obtained signal; hence, it is more expensive to motivate him otherwise. This effect is in line with prior literature (Nikpayam et al. 2022).

Under both strategies, keeping projects' expected values constant, all optimal compensation terms are decreasing in q_I. In other words, if the manager can acquire better information, he gets paid less. This happens because, on the one hand, a higher q_I makes exerting greater effort more rewarding (higher chances of winning α^h) for the manager. Consequently, the firm can now lower the manager's wage while still ensuring that he puts in high effort. On the other hand, a higher q_I means that the probability that the manager's project ends up successful, given that he observes a bad signal, is lower now. Therefore, incentives not to reveal a bad signal weaken and he is paid less for it. We also observe that payment terms are increasing in effort cost c and that managers' expected utility, contrary to the firm's profits, decreases in q_I and increases in c (more uncertainty and more costly effort widen incentive misalignment). This observation is consistent with prior literature (Schlapp et al. 2015, Nikpayam et al. 2022).

3.4.3. To reveal or not?

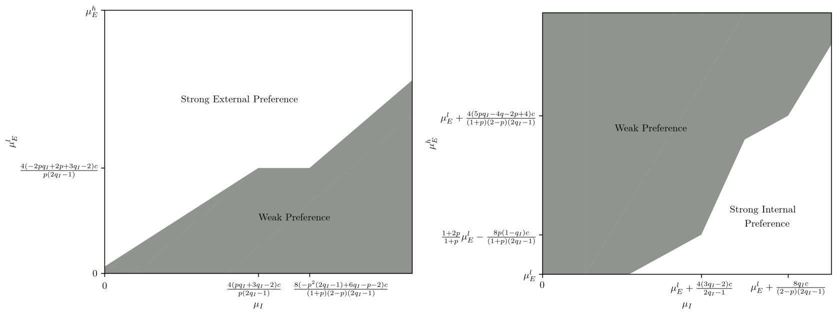
In this part, we investigate the optimal strategy. As discussed earlier, we first should see when the decision to reveal or not is relevant, *i.e.* when the principal has a weak preference, and then compare the two strategies to obtain the optimal solution. The following proposition characterizes the problem of relevance.

Proposition 3.3. *For principal to have a weak preference for the internal project, μ_E^h and μ_E^l need to be sufficiently **higher** and **lower** relative to μ_I, respectively.*

Proof. Appendix B.

The above proposition states an intuitive result; that is, there should be a meaningful difference between the high and low values of the external project so that the decision to reveal or not reveal is not inconsequential. Otherwise, such knowledge has no added value for either party. The results are visualized in Figure 3.2, and explicit limits on μ_E^h and μ_E^l can be found in the proof of Proposition 3.3. This proposition can be interpreted as conditions on the distribution of μ_E as a random variable. That is, the mean of μ_E should not be too different from μ_I, and its variance should be sufficiently large; the higher the mean is, the larger the variance must be. This is an important result as it reiterates an established notion in the literature that the information asymmetry should be larger than a certain threshold for the more detailed communication to have any effect on the agent's actions (Hutchison-Krupat 2018). Otherwise, following a revealing strategy would not bring any additional benefits to the firm in compared with a not revealing strategy.

We have established thus far when the principal can impact the agent's actions through communication. However, we have not investigated whether a reveal strategy outperforms a strategy to not reveal. To obtain the optimal strategy, we compare the optimal solutions to the optimization problems above in Propositions 3.1 and 3.2 and determine the conditions under which each option yields higher profits. The following proposition formalizes the optimal information revelation strategy:



(a) limit on μ_E^l **(b)** limit on μ_E^h

Figure 3.2.: The relevant region of weak preference.

Note. The gray areas in (a) and (b) represent the weak preference, and the white areas in (a) and (b) represent, respectively, the strong external and internal preference.

Proposition 3.4. *When choosing* ***to reveal*** *or* ***not to reveal*** *the external project's value, the principal's optimal strategy is as follows:*

- *Suppose that* $q_I \geq \frac{4-2p}{5-3p}$,
  - *if* $\mu_I \leq 8c$ *then it is optimal to reveal iff* $\mu_E^l \leq \frac{3-2p}{3-p}\mu_I + \frac{24q_I c}{(3-p)(2-p)(2q_I-1)}$,
  - *if* $8c < \mu_I \leq \frac{4q_I(5-p)c}{(2-p)(2q_I-1)}$ *then it is optimal to reveal iff* $\min\{\frac{3}{2}\mu_I - \frac{4(-2pq_I+p+6q_I-2)c}{(2-p)(2q_I-1)}, \frac{1+2p}{1+p}\mu_I - \frac{8(3q_I-(2-p)(1+p-2pq_I))c}{(1+p)(2-p)(2q_I-1)}\} \leq \mu_E^l \leq \frac{3-2p}{3-p}\mu_I + \frac{24q_I c}{(3-p)(2-p)(2q_I-1)}$,
  - *otherwise, it is always optimal not to reveal.*
- *Suppose that* $\frac{4-2p}{4-2p+(1-p)(4-p)} \leq q_I \leq \frac{4-2p}{5-3p}$,
  - *if* $\mu_I \leq 8c$ *then it is optimal to reveal iff* $\mu_E^l \leq \frac{3-2p}{3-p}\mu_I + \frac{24q_I c}{(3-p)(2-p)(2q_I-1)}$,
  - *if* $8c < \mu_I \leq \frac{4q_I(5-p)c}{(2-p)(2q_I-1)}$ *then it is optimal to reveal iff* $\frac{3}{2}\mu_I - \frac{4(-2pq_I+p+6q_I-2)c}{(2-p)(2q_I-1)} \leq \mu_E^l \leq \frac{3-2p}{3-p}\mu_I + \frac{24q_I c}{(3-p)(2-p)(2q_I-1)}$,

– *if* $\frac{4q_I(5-p)c}{(2-p)(2q_I-1)} < \mu_I \leq \frac{8(pq_I-p+2)c}{(2-p)(2q_I-1)}$ *then it is optimal to reveal iff* $\frac{3}{2}\mu_I - \frac{4(-2pq_I+p+6q_I-2)c}{(2-p)(2q_I-1)} \leq \mu_E^l \leq \frac{1-2p}{1-p}\mu_I - \frac{4(p(pq_I-9q_I+2)+6q_I-4)c}{(1-p)(2-p)(2q_I-1)}$,

– *otherwise, it is always optimal not to reveal.*

- *Suppose that* $q_I \leq \frac{4-2p}{4-2p+(1-p)(4-p)}$,

  – *if* $\mu_I \leq \frac{8(-p^2q_I+6pq_I-p-4q_I+2)c}{p(2-p)(2q_I-1)}$ *then it is optimal to reveal iff* $\frac{3}{2}\mu_I - \frac{4(-2pq_I+p+6q_I-2)c}{(2-p)(2q_I-1)} \leq \mu_E^l \leq \max\{\frac{3-2p}{3-p}\mu_I + \frac{24q_Ic}{(3-p)(2-p)(2q_I-1)}, \frac{4-3p}{4-2p}\mu_I + \frac{4(2pq_I-p+2)c}{(2-p)^2(2q_I-1)}\}$,

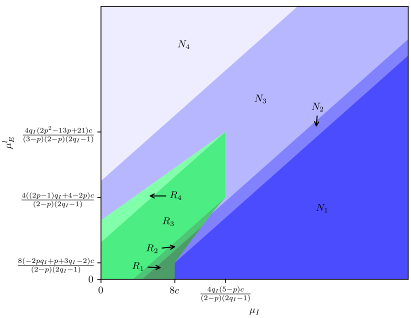
  – *if* $\frac{8(-p^2q_I+6pq_I-p-4q_I+2)c}{p(2-p)(2q_I-1)} < \mu_I \leq \frac{8(pq_I-p+2)c}{(2-p)(2q_I-1)}$ *then it is optimal to reveal iff* $\frac{3}{2}\mu_I - \frac{4(-2pq_I+p+6q_I-2)c}{(2-p)(2q_I-1)} \leq \mu_E^l \leq \frac{1-2p}{1-p}\mu_I - \frac{4(p(pq_I-9q_I+2)+6q_I-4)c}{(1-p)(2-p)(2q_I-1)}$,

  – *otherwise, it is always optimal not to reveal.*

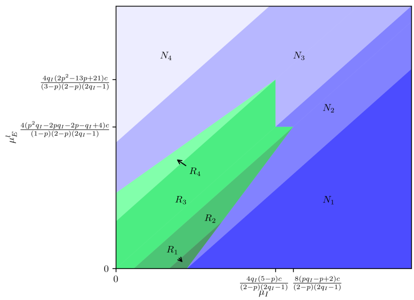
Proof. Appendix B.

Figure 3.3 illustrates the key properties of the optimal information revelation strategy, presented in Proposition 3.4. There is a key trade-off in play: The strategy not to reveal always invests in more (internal) projects, hence creates a higher portfolio value; revealing, on the other hand, can lead to lower agency costs. When μ_I and μ_E^l are moderately low relative to agency costs, revealing helps to alleviate agency issues, and cost savings dominate lost portfolio value; therefore, the senior manager is better off revealing the information. In particular, under such conditions, revealing is more efficient than not revealing in incentivizing high effort in evaluation. That is, when the process is prone to high agency issues, *i.e.* high uncertainty and high evaluation costs, revealing avoids paying high wages when the manager faces competition as he has a strong incentive not to exert high effort, and compensates him only when incentive misalignment is at its lowest.

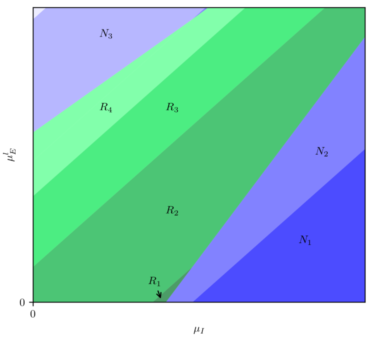
When μ_I increases, revealing starts to lose its appeal as the lost portfolio value under this strategy becomes larger. Thus, for a high-value internal project, it is worthwhile for the senior manager not to reveal. As such, she



(a) $q_I \geq \frac{4-2p}{5-3p}$



(b) $\frac{4-2p}{4-2p+(1-p)(4-p)} \leq q_I \leq \frac{4-2p}{5-3p}$



(c) $q_I \leq \frac{4-2p}{4-2p+(1-p)(4-p)}$

Figure 3.3.: The optimal strategy to reveal or not to reveal.

Note. The shades of blue represent the strategy to reveal, and the shades of green represent the strategy not to reveal. Each shade represents a solution from Propositions 3.1 and 3.2

incurs higher agency costs but keeps the internal project as a fall-back option when the external project is of the high-value type. While keeping other components constant, increasing μ_E^l impacts the portfolio value resulting from both strategies identically. However, the impact on agency costs differs across strategies. Generally, when μ_E^l increases, agency costs are exacerbated as the senior manager, by setting the contract parameters, must make sure that the internal project remains more profitable than a low quality external project. This, in turn would make it more expensive to incentivize truth-telling. Then, as the adverse selection is stronger under the revealing strategy, the resulting agency costs grow faster than under the not revealing strategy. Therefore, for high values of μ_E^l, the senior manager would be better off not revealing any information.

Our results provide managerial insights into the benefits and challenges of implementing communication strategies as incentive aligning tools that the senior management of a firm can utilize in developing new products. That is, first, one necessary condition for senior management to be able to capitalize on an information revelation strategy is that there should be enough *meaningful* information asymmetry in place with regard to the value of the external initiatives the firm pursues. This is intuitive, as lower levels of asymmetry imply that there is not enough information rent for her to exploit.

Then, within this context, and given enough information asymmetry, senior management can, in fact, impact the incentives of the project manager through a combination of communication and financial incentives and ultimately direct his actions. However, this does not mean that revealing *always* outperforms a strategy to not reveal. This is particularly different from the predominant view that more information is always better, as it allows different players to obtain a better understanding of the firm's objectives (Loch 2008, Schlickel et al. 2013, O Reilly and Tushman 2004). The main reason why this rationale might not hold in NPD is the presence of interest misalignment between different parties and that these parties often hold essential private knowledge and take actions hidden from one another. That is, more information might translate into broader misalignment and hence make it more expensive to direct actions preferred by senior management.

Specifically, the choice of a communication strategy impacts the ultimate

NPD portfolio composition, as well as the agency costs the firm incurs in the process. Therefore, the optimal choice is very context-dependent and hinges on what initiatives the firm pursues as well as how severe different agency issues in internal R&D are. Establishing an environment of more clarity, the revealing strategy, is most beneficial when, on the one hand, the projects pursued by the firm do not have very high values, and on the other hand, agency costs are relatively high. Otherwise, in an environment of less clarity, the strategy to not reveal, in fact achieves greater performance. Importantly, the type of agency issues faced by senior management also plays a role in determining her choice of communication strategy; when confronted with a strong moral hazard while adverse selection is less of a problem, a revealing strategy is more appealing.

3.5. Conclusion

In this paper, we investigate the effectiveness of strategic communication in combination with financial incentives in the problem of resource allocation to NPD initiatives. Firms often invest their scarce resources in both internally developed projects and those acquired from external partners. The value of such external projects determines how fierce the competition over resources is for internal project teams; the stronger the competition is, the higher a firm's agency costs. However, both the senior management and project teams have a noisy understanding of the value of the external project. Nonetheless, the senior manager can obtain more refined information about the true value later. The question is: Should she share the information with the project teams, or not? We seek to determine the optimal information revelation strategy.

In doing so, we conceptualize a principal-agent setting where the senior management of a firm seeks to effectively allocate its limited resources to a set of two NPD projects based on imperfect information about their quality, where one is internal and one is external. We incorporate moral hazard in the evaluation and adverse selection in the recommendation stage on the part of the internal project manager. The senior management must decide in advance on a compensation scheme in combination with a communication strategy to reveal (or not) the true value of the external project as a means to ensure high effort and truthfulness by the agent. We find that, first, for her revelation decision to have any impact on the agent's actions, there needs to be sufficient uncertainty about the value of the external project. Second, the optimal strategy is to reveal information when the projects under consideration have relatively moderate values and the agency costs are high; otherwise, not revealing is optimal. We also identify a main trade-off between the two strategies: choosing to reveal the information leads to reduced portfolio scope. Not revealing comes with an increased portfolio scope. However, revealing may also entail agency costs and, thus, offset the downside of a smaller portfolio scope.

Our work offers some managerial insights as well. First, we find that senior management of a firm can, in fact, couple communication with financial incentives to reduce incentive misalignment in the organization, especially when dealing with NPD processes, as they give considerable rise to agency issues. However, for communication to have any impact on the incentives of those lower in the organizational hierarchy, the communication must be deemed credible by them. Senior management can overcome the credibility issue by establishing organizational systems, processes, and norms that suit her preferred communication strategy. That is, she needs to show her commitment to a certain strategy, for example, full transparency, by offering project managers compensation schemes suited to that strategy. This implies that the choice of a communication strategy is a vital long-term decision that must be made in advance and cannot be modified easily and quickly. This becomes even more critical, as we find that there is no one-size-fits-all solution in regard to the optimal strategy and that it is essentially context-dependent, resting not only on the type of initiatives a firm pursues but also on the R&D environment of the company and how prone it is to agency problems.

Our research, of course, also has some limitations. Particularly, we incorporate resource allocation to NPD initiatives, agency problems in this process, competition between internal and external projects, a combination of financial incentives and communication, and interaction between them in our model. However, we look at full disclosure and complete obfuscation of information as the only communication strategies. This does not fully acknowledge the wide range of options senior management has between these extreme cases, *i.e.* partial information disclosure. Such strategies have been the focus of Bayesian Persuasion literature in economics (Kamenica and Gentzkow 2011), and future research should evaluate in more detail the dynamics of different communication strategies in an NPD environment. This said we would suspect that our main result, that there is no single optimal strategy, would remain robust. Furthermore, while we consider and model the added value to the portfolio of projects as the rationale for acquiring external NPD projects, in practice firms have often a multitude of motivations for such a move. This can include strategic motives to stand out against competitors in the market, "killer acquisitions", risk diversification, etc. Nonetheless, we still believe such considerations would not change our major findings as, independent from the firm's *real* motives for acquiring an external project, it is the internal teams' *understanding* of the firm's investment priorities and the perceived competition that drives the trade-off in our model. Thus, if we replace senior management's private knowledge about the value of external projects in our model with knowledge about her preferences, we would reach the same conclusions. On a different note, we investigated the impact different communication strategies have on portfolio composition and agency costs; however, we did not consider the long-term effects this decision might have on organizational dynamics. In this regard, we open the way for future work to shed more light on the short- and long-term impacts of different communication strategies on an organization. Another practically relevant point is that we assume perfect information on both senior management and the project managers about the value of internal projects throughout the whole game. However, as the literature has argued before (Hutchison-Krupat 2018), top management might also have superior knowledge about the value of new internal projects. Such discrepancies from our basic setting might pose limitations on the applicability of our main results.

It would be helpful to explore how different settings impact the optimal choice of communication strategy.

In conclusion, our work emphasizes the role of communication in reducing incentive misalignment in the NPD environment and sheds light on core trade-offs underlying why there could be different levels of transparency within distinct innovative organizations. Our analysis also provides managerial insights into the choice of an appropriate communication strategy while accounting for the primary role of agency issues in portfolio building processes. We hope that the research presented in this paper has made some headway toward a better understanding of the underpinnings of the organizational dynamics in new product development processes.

Chapter IV

Optimal Stochastic Feedback in Asymmetric Dynamic Contests

with Jochen Schlapp, and Jürgen Mihm

Abstract

Contests, in which contestants compete at their own expense for prizes offered by a contest holder, have become the foundational primitive of many theories of competition. Recently, the focus in contest research has turned to the role of in-contest performance feedback. The extant literature on feedback has focused on specific ad-hoc policies in symmetric contests and hence failed to more broadly characterize optimal feedback policies. In this paper we solve a general formulation of an asymmetric contest involving feedback, and thus characterize the optimal feedback policy in a very wide class of (stochastic) feedback policies. We find that, in many settings where informative feedback is useful, feedback is optimal when it is both truthful and fully informative.

4.1. Introduction

In a contest, contestants compete—at their own expense (of effort)—for a limited number of prizes. The prizes are awarded to contestants whose efforts produce the best solution to the contest challenge. A contest can provide incentives even in those unstructured settings in which traditional pay-for-performance schemes fail (e.g., when output is noncontractible). Not surprisingly, contests have become a standard tool for analyzing competition. Starting with the pioneering work of Lazear and Rosen (1981), Green and Stokey (1983), and Nalebuff and Stiglitz (1983), the contest has become the archetypal primitive for analyzing a wide variety of settings: lobbying, promotional competition, litigation, military conflict, sports, education, internal labor markets, and R&D management (see e.g. Konrad and Kovenock (2009)).

Extant work has yielded extensive insight into designing optimal contests, and many aspects of contest design are by now well studied; these aspects include the optimal number of contestants (e.g., Taylor 1995, Fullerton and McAfee 1999, Moldovanu and Sela 2001, Che and Gale 2003, Terwiesch and Xu 2008, Körpeoğlu and Cho 2018), the optimal award structure (Che and Gale 2003, Moldovanu and Sela 2006, Siegel 2009, 2010, Ales et al. 2017), mechanisms for limiting access to contests (Fullerton and McAfee 1999, Gavious et al. 2002, Che and Gale 2003), and the contest's temporal structure (Moldovanu and Sela 2006, Konrad and Kovenock 2009). However, in the past the literature has largely focused on designing actions that the contest holder must take before the contest begins. In contrast, more attention is now being paid to how the contest holder can influence contestants during the contest (e.g., Gürtler et al. 2013, Mihm and Schlapp 2019). Perhaps the most important among the contest holder's options is the provision of interim performance feedback, which equips contestants with more refined information about the intermediate competitiveness of the contest.

To date, the growing literature on feedback in contests (Yildirim 2005, Gershkov and Perry 2009, Aoyagi 2010, Ederer 2010, Goltsman and Mukherjee 2011, Marinovic 2015, Jiang et al. 2021, Mihm and Schlapp 2019) has two shortcomings: (i) the limited number of feedback policies it considers is highly specific, and (ii) it mainly ignores ability asymmetry among contestants. In particular as for the former point, Yildirim (2005), Aoyagi (2010), Ederer (2010), and Jiang et al. (2021) all simply assume that feedback policies are fully truthful and accurate (i.e., divulging all available information to all contestants). Goltsman and Mukherjee (2011), Marinovic (2015), and Mihm and Schlapp (2019) consider certain specific types of noisy or less fine-grained feedback policies. However, the extant literature has ignored the entire class of feedback policies that rely on (partial) misinformation and fails to consider policies that rely on general forms of reduced information or that incorporate general forms of noise. As a consequence, we do not know whether the policies that have been studied are indeed optimal and hence whether those policies are even (the most) relevant ones. For the latter point, Ederer (2010) looks into certain ability asymmetries. However, his approach is limited and does not provide broadly general results. As such, the literature has not fully explored the impact of asymmetric abilities on the optimal design of contests.

Our main contribution in this paper is to analyze asymmetric contests while allowing for a broad class of feedback policies and then to characterize a contest holder's optimal choice of (potentially stochastic) feedback in such contests. We thereby extend the literature on feedback in contests in two directions. First, we incorporate deterministic and stochastic asymmetries among contestants. Second, for a broad class of contests, we identify the optimal feedback policy among the set of all (stochastic) feedback policies.

The remainder of the paper is structured as follows. The general model and its components are introduced in Section 2. In Section 3, we analyze the contestants' equilibrium effort choices given any interim feedback policy and in the presence of ability heterogeneity. Section 4 then discusses the optimal choice of feedback policies, and the impact of different classes of such policies on contestants' effort choices.

4.2. Asymmetric Dynamic Contest Model

We consider a contest holder organizing a contest for a fixed award $A > 0$ between two risk-neutral contestants $i \in \{a, b\}$ over two rounds $t \in \{1, 2\}$.

At the end of round $t = 2$, the contest holder compares the contestants' final performance and then presents the award A to the best contestant; ties can be broken by invoking any rule. These and all other primitives of the contest are common knowledge unless explicitly noted otherwise.

The Contestants. Contestant i's first- and second-round performance v_{it} is a function of his inherent ability $(\sigma_i, \alpha_i) \in (\mathbb{R}, \mathbb{R}^+)$, his first- and second-round solution effort $(e_{i1}, e_{i2}) \in [0, \bar{e}]^2$, and the first- and second-round performance shocks $(\omega_{i1}, \omega_{i2}) \in \Omega^2$. $\bar{e}$ is strictly larger than zero and is equivalent to the point that the private cost of effort equates to the contest award A, and the state space Ω is a compact metric space in $\mathbb{R}$. In particular, we let $v_{it} = \sigma_i + \sum_{\tau=1}^{2}(\alpha_i \cdot r_\tau(e_{i\tau}) + \omega_{i\tau})$; here, σ_i and α_i are additive and multiplicative abilities, respectively. Without loss of generality, we assume $\alpha_a = \alpha > 1$ and $\alpha_b = 1$, and each contestant's abilities are public knowledge. r_t is a deterministic round-t reward function, which we assume to be continuously differentiable, strictly increasing, and concave with $r_t(0) = 0$. Contestant i's effort choices e_{i1} and e_{i2} are his private knowledge and are unobservable to both his opponent and the contest holder. The realization of the random performance shocks ω_{it} is unobservable to the contest holder and to both contestants for all i and t. For each $t \in \{1, 2\}$, moreover, $\omega_t = (\omega_{at}, \omega_{bt})$ follows a commonly known continuous bivariate distribution $\mu_0^t \in \Delta(\Omega^2)$[5]. Although we allow performance shocks to be correlated across contestants, we assume that ω_t is stochastically independent across rounds. The cost incurred by contestant i for exerting effort e_{it} in round t is $c_t(e_{it})$, which is continuously differentiable, increasing, and strictly convex. Furthermore, we have $c_t(0) = 0$, $c_t'(0) = 0$, and $c_t'(\bar{e})/r_t'(\bar{e}) > A \cdot \sup g_{\omega_{bt} - \omega_{at}}$. The utility that contestant i derives from participating in the contest is $U_i = A \cdot \mathbb{1}_{\{v_{i2} > v_{j2}\}} - \sum_{t=1}^{2} c_t(e_{it})$; here, $\mathbb{1}_{\{X\}}$ is the indicator function of event X, and the utility of the outside option is normalized to zero.[6]

The Contest Holder. The objective of the risk-neutral contest holder is to maximize expected profits, which are a weighted sum of the contestants' average and best performances. Formally,

$$\Pi = \beta \mathbb{E}[(v_{a2} + v_{b2})/2] + (1 - \beta)\mathbb{E}[max\{v_{a2}, v_{b2}\}], \text{ with } \beta \in [0, 1]. \tag{4.1}$$

After the first round, the contest holder observes each contestant's intermediate performance v_{i1} (although not all its constituent parts) and can thus provide contestants with *public* feedback about $v_1 = (v_{a1}, v_{b1})$.

The Feedback Policies. A feedback policy $P \in \mathcal{P}$ consists of a finite realization space S and a family of distributions $\{P(\cdot|v_1)\}_{v_1}$ over S. A feedback policy as such defines a game. The timing is as follows: 1. The contest holder announces his feedback policy P. 2. The contestants exert their first-round effort e_{i1}. 3. Nature selects ω_1 from Ω^2 according to μ_0^1. 4. The contest holder privately observes the first-round performance v_1, and a signal realization $s \in S$ is generated from $P(\cdot|v_1)$. 5. The contestants observe s, using information on P and s to update their beliefs about v_1 in accordance with Bayesian rationality and choose their second-round effort e_{i2} accordingly. 6. Finally, ω_2 from Ω is realized, the contest holder observes second-round performance v_2 and declares the winner.

Without loss of generality, we restrict our attention to a particular class of policies. A policy is *straightforward* if the contestants' equilibrium action equals the signal realization. In other words, a straightforward policy produces a "recommended action", and contestants always follow the recommendation. This definition is closely analogous to the revelation principle (Kamenica and Gentzkow 2011). We are interested in pure-strategy, perfect Bayesian equilibria of the game just described. Thus, the feedback on first-round performance is essentially feedback on first-round performance shocks. As such, the contestants, after the first round, use the information on P and s to form a posterior belief $\mu^1(\omega_1|P, s) \equiv \mu_s$ regarding ω_1.

Similar to Kamenica and Gentzkow (2011), given a feedback policy, each signal realization s leads to a posterior belief $\mu_s \in \Delta(\Omega^2)$. Accordingly, each policy leads to a distribution over posterior beliefs. We denote a distribution of posteriors by $\tau \in \Delta(\Delta(\Omega^2))$.[7] We say a distribution of posteriors τ, a CDF, is Bayes-plausible if:

$$\int_{\mu \in \Delta(\Omega^2)} \mu d\tau(\mu) = \mu_0^1 \tag{4.2}$$

We say that P induces τ if each $s \in S$ induces posterior μ_s and the distribution of μ_s is τ. Since Ω^2 is a compact metric space, according to Kamenica and Gentzkow (2011), for any Bayes-plausible τ, there exists a P that induces it. Therefore, the contest holder's optimization problem can be reformulated as $\max_\tau \Pi$, *s.t.* $\int_{\mu \in \Delta(\Omega^2)} \mu d\tau(\mu) = \mu_0^1$.

4.3. Contestants' Equilibrium Efforts

Before we can discuss the contest holder's optimal choice of a feedback policy, we need to characterize the contestants' effort choices while assuming a given feedback policy. We first show in the following lemma the necessary conditions for the existence of a pure-strategy equilibrium, and address the contestants' optimal choices.

Lemma 4.1. *Provided that* $\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)|$ *is small enough and* $\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_{a2}-v_{b2})]$ *is sufficiently large, for all signal realizations* $s \in S$ *of any feedback policy* $P \in \mathcal{P}$*, there exists pure-strategy perfect Bayesian equilibrium for contestants' first- and second-round effort.*

Proof. Proof. Appendix C. □

The first condition of the lemma, in line with the literature on stochastic contests, requires that the random performance shocks ω_{it} be sufficiently variable. It is intuitive that if this condition is not satisfied, then exerting any infinitesimally small additional amount of effort leads to winning the contest almost certainly, which would preclude the existence of any pure-strategy equilibria (see also Nalebuff and Stiglitz 1983). For more concrete thresholds related to ω_{it}'s minimum required variability, refer to the proof of lemma (see also the insightful discussions in Aoyagi 2010, Ales et al. 2021). The second condition, however, becomes necessary as a result of the multiplicative ability asymmetry present in our model and has not been discussed in the relevant literature. Nonetheless, this condition can be interpreted in a similar manner, requiring the second-round performance shocks to be sufficiently dispersed.

Second-round effort. In the second round, contestant i chooses an effort e_{i2} that maximizes his utility (in the rest of the document, by g_X and G_X, we denote, respectively, the probability density function (PDF) and the cumulative distribution function (CDF) of any random variable X):

$$u_{i2} = A\mathbb{E}_{\mu_s}[G_{\omega_{j2}-\omega_{i2}}(v_{i1} - v_{j1} + \alpha_i r_2(e_{i2}) - \alpha_j r_2(e_{j2}))] - c_2(e_{i2}), \quad \forall i \in \{a, b\} \tag{4.3}$$

The first-order condition for the second-period effort is:

$$c_2'(e_{i2})/r_2'(e_{i2}) = \alpha_i A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta e_1 + \omega_{a1} - \omega_{b1} + \alpha r_2(e_{a2}) - r_2(e_{b2}))], \quad \forall i \in \{a, b\} \tag{4.4}$$

Here, $\Delta e_1 = \alpha \cdot r_1(e_{a1}) - r_1(e_{b1}) + \sigma_a - \sigma_b$ is the *return difference* of the first-round effort of both contestants plus the marginal additive ability. Additionally, note that $g_{\omega_{b2}-\omega_{a2}}(z) = g_{\omega_{a2}-\omega_{b2}}(-z)$ for all z. We cannot solve the above equation in closed-form in such a general setting. However, we can address some of the key characteristics of the solution.

Proposition 4.1. *Given that equilibrium exists, Lemma 4.1, the second-round equilibrium effort of player i is denoted by $e_{i2|s}$, which is a real differentiable function of first-round effort Δe_1 and the posterior belief μ_s:*

$$e_{i2|s} = \gamma_{i2}(\Delta e_1, \mu_s), \quad \forall i \in \{a, b\} \tag{4.5}$$

Proof. Proof. Appendix C. □

Under a given feedback strategy, each contestant uses the information about the employed feedback policy P together with the received performance signal s to update his belief about the distribution of first-round shocks. This is the direct way through which the contest holder can strategically influence the contestants' choices of second-round effort. If she can also influence the first-round effort, then this strategy would indirectly also impact the second-round effort through Δe_1.

Corollary 4.1. *There exist constants* $n \geq k \geq m > 1$ *such that* $\alpha = n/m$, $e_{a2|s} = k \cdot e_{b2|s} = k \cdot e_2^*$, $r_2(e_{a2|s}) = m \cdot r_2(e_{b2|s})$, *and* $c_2(e_{a2|s}) = n \cdot c_2(e_{b2|s})$.

Proof. Proof. Appendix C. □

The equilibrium effort in the second round differ across contestants. In particular, it is independent of the first-round effort, the marginal additive ability, and the contestants' posterior belief. The driver of this asymmetry is the known multiplicative ability imbalance, namely, α. Due to the complementarity between effort and the multiplicative ability, the more able contestant exerts more effort than the less able contestant, as he has a larger marginal return on effort. This outcome is similar to the results in Ederer (2010). It is also interesting to note that the two contestants' effort choices are always positively correlated. This relation implies an intuitive notion that when the posterior belief signals a close race between the two, they would both put more effort in the second-round to win the contest, and when it signals a less competitive environment then the contestants are less incentivized to put high effort, as it is almost clear which contestant is the final winner. This pattern is in line with prior literature (e.g., Aoyagi 2010).

The second-round effort in equilibrium is also a function of the first-round effort. It would be insightful to investigate this relation more closely. Assuming $\Delta v_2 = \Delta e_1 + \omega_{a1} - \omega_{b1} + \alpha r_2(e_{a2|s}) - r_2(e_{b2|s})$, since e_2^* is a differentiable function of Δe_1, according to the implicit function theorem, we can derive the following from 4.4:

$$de_2^*/d\Delta e_1 = \frac{-\frac{\partial u'_{b2}}{\partial \Delta e_1}}{\frac{\partial u'_{b2}}{\partial e_2^*}} = \frac{A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]}{\eta'_2(e_2^*) - (\alpha m - 1) r'_2(e_2^*) A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]} \tag{4.6}$$

The denominator of the right-hand-side fraction is always positive (refer to proof of lemma 4.1). Then, the sign of the expectation in the numerator determines the sign of the derivative. The sign of the expectation is an indicator of the competitiveness of the contest. Positive values indicate a stochastic advantage for contestant b over contestant a, and negative values indicate the opposite. If the sign is positive, with each additional unit of Δe_1, the race becomes tighter, and therefore, both contestants put more effort in second-round. If it is negative, with each additional unit of Δe_1 contestant a gets even a larger advantage, and therefore, they put less effort in order to incur lower costs.

To better understand this effect, we can think of a special case of the performance shock distributions. Assuming $g^s_{\omega_{b1}-\omega_{a1}}$ is the posterior PDF of the random variable $\omega_{b1} - \omega_{a1}$, imagine both $g^s_{\omega_{b1}-\omega_{a1}}$ and $g_{\omega_{b2}-\omega_{a2}}$ are normal distributions with the same standard deviation but with different means (Figure 4.1). Assuming $g^s_{\omega_{b1}-\omega_{a1}}$ has a sufficiently larger mean than the mean of $g_{\omega_{b2}-\omega_{a2}}$ (more biased in favor of contestant b), then, in the expectation, $g^s_{\omega_{b1}-\omega_{a1}}$ assigns higher probabilities to positive instances of $g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)$ and lower probabilities to negative ones. Thus, the expectation would have a positive sign, indicating an advantage for contestant b.

First-round effort. In the first round, contestant i chooses effort e_{i1} that maximizes his utility:

$$\begin{aligned} u_{i1} = A\mathbb{E}_{\tau,\mu_s}[G_{\omega_{j2}-\omega_{i2}}(\sigma_i + \alpha_i r_1(e_{i1}) + \omega_{i1} + \alpha_i r_2(e_{i2|s}) - \sigma_j - \alpha_j r_1(e_{j1}) \\ -\omega_{j1} - \alpha_j r_2(e_{j2|s}))] - c_1(e_{i1}) - \mathbb{E}_{\tau,\mu_s}[c_2(e_{i2|s})], \end{aligned} \tag{4.7}$$

The first-order condition for the first-round effort is:

$$\begin{aligned} c_1'(e_{i1}) =& A\alpha_i r_1'(e_{i1})\mathbb{E}_{\tau,\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] \\ &+ A\mathbb{E}_{\tau,\mu_s}[\{\alpha_i r_2'(e_{i2|s})g_{\omega_{b2}-\omega_{a2}}(\Delta v_2) - c_2'(e_{i2|s})\}de_{i2|s}/de_{i1}] \\ &- A\mathbb{E}_{\tau,\mu_s}[\alpha_j r_2'(e_{j2|s})g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)de_{j2|s}/de_{i1}] \end{aligned} \tag{4.8}$$

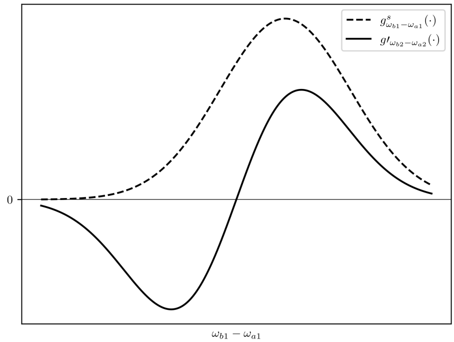


Figure 4.1.: An example for distributions of $g^s_{\omega_{b1}-\omega_{a1}}$ and $g_{\omega_{b2}-\omega_{a2}}$

The first term is the direct return of effort in the first round contributing to contestant i's chances of winning the contest, and the two remaining terms are strategic effects of the first-round effort on the second round. We know from equation 4.4 that the second term is equal to zero (envelope theorem). Again, from 4.4, we know that $c_2'(e_{j2|s}) = \alpha_j r_2'(e_{j2|s}) A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$ and $\eta_2(e_2^*) = A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$. Then, we can reformulate 4.8 for contestants a and b as follows:

$$\begin{aligned} c_1'(e_{a1})/r_1'(e_{a1}) =& \alpha \cdot \mathbb{E}_\tau[\eta_2(e_2^*)] - \alpha \cdot \mathbb{E}_\tau[c_2'(e_2^*)de_2^*/d\Delta e_1] \\ c_1'(e_{b1})/r_1'(e_{b1}) =& \mathbb{E}_\tau[\eta_2(e_2^*)] + n \cdot \mathbb{E}_\tau[c_2'(e_2^*)de_2^*/d\Delta e_1] \end{aligned} \tag{4.9}$$

Again, we cannot solve the above equations in closed-form in such a general setting. However, we can address some of the key characteristics of the solution.

Proposition 4.2. *Given that equilibrium exists, Lemma 4.1, the first-round equilibrium effort of player i is denoted by $e_{i1|P}$ and is a real differentiable function of the distribution τ induced by the given feedback policy P:*

$$e_{i1|P} = \gamma_{i1}(\tau), \qquad \forall i \in \{a, b\} \tag{4.10}$$

Proof. Proof. Appendix C. □

By comparing 4.9 with 4.4, we see that the multiplicative ability asymmetry is also present here in the choice of first-round effort, as the expectation terms in 4.9 for contestant a (the more able one) are multiplied by α. This pattern results from the fact that the two contestants are *ex-ante* asymmetric in abilities. Additionally, comparing the second terms in the two equations in 4.9 immediately shows that they also differ by a double-edged *strategic effect*. An increase in the contestants' first-round effort return difference would have an effect on the optimal second-round effort. We know that $c_t(\cdot)$ is increasing, then $c_t'(\cdot) \geq 0$. Therefor, the derivative determines the sign of the right-hand-side expectation term. From our earlier discussion of 4.6, we know that the sign of $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$ decides the sign of the derivative and thus in turn imposes the impact direction of the strategic effect on each contestant's choice of first-round effort. If for *every* $s \in S$, $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] > 0$ the strategic effect has an increasing impact on contestant b's and a decreasing impact on a's first-round effort. If $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] < 0$, vice versa, and if $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] = 0$ there would not be any strategic effect between first- and second-round effort. If for some $s \in S$, the sign of this expectation $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$ changes, then we should look at the sign of $\mathbb{E}_{\tau}[c_2'(e_2^*)de_2^*/d\Delta e_1]$.

This double-edged effect that increases one of the contestants' first-round effort and decreases the other's first-round effort, is induced by implicit incentives that are similar in nature to the *signal-jamming* effect in Ederer (2010) but with a major difference. In their model, this effect always leads to an increase in the effort of *both* players. The strategic effect in our model works as follows: As mentioned earlier, to form a posterior belief about the first-round performance shocks, the contestants must speculate the first-round effort choice of their rival. As long as the true distribution of the shock is unknown, each agent has an additional incentive to manipulate effort for any given conjecture of their rival about first-round effort choice. By considering this strategic agenda, each contestant can potentially bias the process of inference of the other contestant in his favor. Assuming that the expectation has a positive sign, when contestant b increases his effort beyond the level contestant a expects, the total first-round output difference will tend to move in his favor which in turn will lead to a more pessimistic perception by contestant a of a stochastic bias to his rival's advantage. Recall from 4.4 that the second-round effort is an increasing function of $\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$. A more pessimistic perception about the shock distribution to b's advantage would lead contestant a to underestimate $\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$ and put lower effort in the second-round, thereby increasing contestant b's probability of winning the contest (Figure 4.2). Basically, contestant b wants his rival to believe that by virtue of the first-round shocks, the environment is not very competitive and that contestant a is almost the certain loser of the competition, and he should not put too much effort into the second-round. A very similar argument can be stated as to why the strategic effect works in the opposite direction for contestant a. He, counterintuitively, puts lower effort in the first-round so that his rival believes that he is winning already and he should not put unnecessarily high effort into the second-round. Of course, in equilibrium, neither will be able to mislead the other because the contestants will know what effort levels to expect in equilibrium and adjust their beliefs accordingly.

The two above propositions and the discussions followed by them characterize the equilibrium under any precommitted (stochastic) feedback policy $P \in \mathcal{P}$. Thus, the propositions subsume and generalize previous results in the literature that are limited to specific feedback policies, specific distributional assumptions, and symmetric settings (Aoyagi 2010, Ederer 2010, Goltsman and Mukherjee 2011, Marinovic 2015, Mihm 2010).

Before going to the next section, we introduce two definitions that help us to first classify different feedback policies and then (partially) order them based on their informativeness.

Definition 4.1. *(i) A feedback policy $P \in \mathcal{P}_I$ is fully informative if it induces*

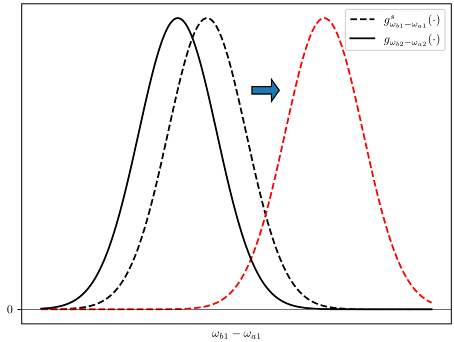


Figure 4.2.: Strategic effect in estimation of $\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$

Note. $\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$ is the summation over $\omega_{b1}-\omega_{a1}$ of the product of the solid and dotted lines. Both contestants want their rival to believe that the distribution of $\omega_{b1}-\omega_{a1}$ is the red one on the right and hence induce them to underestimate $\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$.

τ^i, which in turn for any $s \in S$ induces $\mu_s \equiv \mu_1$, which assigns probability 1 on a single realization of ω_1 and zero on the rest. (ii) A feedback policy $P \in \mathcal{P}_U$ is completely uninformative if it induces τ^u, which in turn for any $s \in S$ induces $\mu_s \equiv \mu_0^1$; the induced posterior belief will be the same as the prior. (iii) Any other feedback policy $P \in \mathcal{P}_M$ that is neither fully informative nor completely uninformative induces τ^m, and we refer to it as a partially informative feedback policy.

If the contest holder employs a fully informative feedback policy $P \in \mathcal{P}_I$, then each contestant perfectly learns the realization of $(\omega_{a1}, \omega_{b1})$. That is, there remains no uncertainty regarding the contestants' first-round performance v_1. In contrast, a completely uninformative feedback policy $P \in \mathcal{P}_U$ prevents contestants from refining their beliefs about $(\omega_{a1}, \omega_{b1})$ because the resulting feedback does not depend on contestants' actual first-round performance.

Definition 4.2. *Based on definition 4.1, we now introduce a partial ordering* *among different feedback policies of interest (Davey and Priestley 2002). For the set of all Bayes-plausible distributions $\tau \in T$ that are induced by straightforward feedback policies, the following binary relations hold:*

$$\tau^i \succeq \tau^m \succeq \tau^u$$

For any $\tau, \tau' \in T$, the binary relation $\tau \succeq \tau'$ holds if τ is more informative than τ'.

Based on definition 4.2, distributions induced by fully informative policy, τ^i, and completely uninformative policy, τ^u, are the maximal and minimal members of the set $(T, \succeq)$, respectively. Then, a function f from the partially ordered set $(T, \succeq)$ to $\mathbb{R}$ is (weakly) increasing if $\tau \succeq \tau'$ implies $f(\tau) \geq f(\tau')$ and decreasing if $f(\tau) \leq f(\tau')$ (Burkill 1984).

4.4. Optimal Feedback Strategy

In this section, we first discuss how the contest holder's choice of a feedback policy would impact the contestants' effort choices and finally we will characterize the sufficient conditions for the optimality of different classes of feedback policies.

4.4.1. Auxiliary Results

In the following part, we will present a group of minor propositions as stepping stones to the main results later. Although such results are treated as accessory means, they also help us better understand the dynamics of asymmetric contests. In particular, we first investigate the impact of different feedback policies on the first-round effort (lemma 4.2). Then, we study the properties of the equilibrium second-round effort (lemma 4.4, and corollaries 4.2 and 4.3). Thereafter, we provide the conditions required for maximizing the first-round return difference (lemma 4.3) and effort complementarity across rounds (lemma 4.5).

Lemma 4.2 (maximizing first-round effort)**.** *Suppose that* $\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_{a2} - v_{b2})]$ *is sufficiently large:*

(i) If $(\eta_2 \circ \gamma_{i2})(\cdot)$ *is convex in* μ_s*, and* $\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)|$ *is small enough, both contestants' equilibrium first-round efforts are respectively maximized and minimized by fully informative and completely uninformative policies.*

(ii) If $(\eta_2 \circ \gamma_{i2})(\cdot)$ *is concave in* μ_s*, and* $\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)|$ *is small enough, both contestants' equilibrium first-round efforts are respectively maximized and minimized by completely uninformative and fully informative policies.*

Proof: Appendix C. □

The above distributional conditions on the performance shocks are similar to those stated in Lemma 4.1 regarding the existence of equilibrium and should be interpreted similarly. However, they are stricter here. As such, the above lemma states that, given that the random performance shocks are sufficiently variable, promising to disclose all information maximizes first-round effort if the composite function $(\eta_2 \circ \gamma_{i2})(\cdot)$ is convex, and minimizes the effort if concave. This result clearly depends on the properties of the functions η_2 and γ_{i2}.

Lemma 4.3 (maximizing first-round return difference)**.** *If lemma 4.2 (i) holds,* Δe_1 *is increasing and if lemma 4.2 (ii) holds, it is decreasing in* τ *when* $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$ *is sufficiently small.*

Proof: Appendix C. □

This lemma states that if the strategic effect present in the choice of the optimal first-round effort is small enough, maximizing the first-round effort is equivalent to maximizing the effort return difference in favor of contestant a (the more able one). This result is important, as the second-round effort is a function of Δe_1.

Lemma 4.4 (functional properties of equilibrium second-round effort)**.** *Assume* $\lim_{x\to\pm\infty} g_{\omega_{b2}-\omega_{a2}}(x) = 0$ *and let* $F = A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(v_{a1}+(n-1)r_2(e_2^*) - v_{b1})] - \eta_2(e_2^*)$*, where* F *is the modified second-round marginal utility of contestant* b *in equilibrium. Then, the first and second derivatives of the equi-*

librium second-round effort e_2^* with respect to μ_s are $d\gamma_{b2}/d\mu_s = -A/F_e$ and $d^2\gamma_{b2}/d\mu_s^2 = -A^2 F_{ee}/F_e^3$, respectively, where F_e and F_{ee} are partial derivatives of the first- and second-order of function F with respect to e_2^*, respectively.

Proof: Appendix C. □

By applying the partial derivatives we obtain:

$$
\begin{aligned}
F_e =& (n-1)r_2'(e_2^*)A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] - \eta_2'(e_2^*) \\
F_{ee} =& (n-1)r_2''(e_2^*)A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] + \{(n-1)r_2'(e_2^*)\}^2 A\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_2)] \\
& - \eta_2''(e_2^*)
\end{aligned}
\tag{4.11}
$$

It can be easily checked from the proof of Lemma 4.1 that $F_e < 0$ (due to the concavity of the utility function). Then it is clear that the sign of F_{ee} determines whether the equilibrium second-round effort is convex or concave in μ_s.

Corollary 4.2 (convexity/concavity of second-round effort)**.** *Let the overline and underline indicate the suprimum and infimum of the functions below. The second-round effort in equilibrium, $\gamma_{i2}(\Delta e_1, \mu_s)$,*

- *is convex in μ_s, if* $\eta_2''(e) < (n-1)r_2''(e)A\overline{\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\cdot)]} + \{(n-1)r_2'(e)\}^2 A\underline{\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(\cdot)]}$ *for any e.*

- *is concave in μ_s, if* $\eta_2''(e) > (n-1)r_2''(e)A\underline{\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\cdot)]} + \{(n-1)r_2'(e)\}^2 A\overline{\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(\cdot)]}$ *for any e.*

The above corollary shows that the convexity/concavity of the equilibrium second-round effort depends mainly on the convexity/concavity of $\eta_2(\cdot)$, which is the relative marginal disutility of effort. If we strip the multiplicative asymmetry off our model, the right-hand-side of the two above inequalities becomes zero, and therefore, the concavity (convexity) of $\eta_2(\cdot)$ leads to convexity (concavity) of γ_{i2}. This finding is in line with previous results in the literature (see, for example, Aoyagi 2010, Ederer 2010). It is important to note the implications of such conditions for the results of lemma 4.2, which requires convexity or concavity of the composite function $(\eta_2 \circ \gamma_{i2})(\cdot)$. Now, we see here that the convexity (concavity) of γ_{i2} depends on the concavity (convexity) of η_2.

When there is no ability asymmetry or when it enters only additively, $(\eta_2 \circ \gamma_{i2})(\cdot)$ is both convex and concave at the same time. Therefore, the first-round effort is the same under any completely uninformative or fully informative feedback policies. The reason is that in equilibrium in such a case, $F_e = -\eta_2'$ and $F_{ee} = -\eta_2''$ and therefore $(\eta_2 \circ \gamma_{i2})''(x) = 0$. However, when multiplicative ability asymmetry exists this equivalence does not hold, and $(\eta_2 \circ \gamma_{i2})(\cdot)$ can be convex, concave, or neither.

Corollary 4.3 (special case). *If the terms $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]$ and $\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_2)]$ are adequately small, then the equilibrium first-round effort of an asymmetric contest is only slightly different under any completely uninformative or fully informative feedback policies.*

The above corollary states that, although different feedback policies impact the choice of contestants' first-round effort, if the expectation terms in 4.11 are small enough, then the impact would be negligible.

Lemma 4.5 (effort complementarity across rounds). *Under the following condition, the second-round effort in equilibrium, $\gamma_{i2}(\Delta e_1, \mu_s)$, increases in Δe_1.*

$$\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)] \geq 0 \tag{4.12}$$

If this equation is replaced by $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)] \leq 0$, then effort decreases.

Proof: see the discussions following proposition 4.1. $\square$

Since the contest holder is usually interested in maximizing the effort exerted in both rounds, a straightforward case would be when there is complementarity between first- and second-round effort. In this way, independent from other factors, maximizing first-round effort would increase second-round effort as well. As we discussed in the previous chapter following the proposition 4.1, there would be such complementarity if the contestants expect a stochastic advantage for contestant b (who has lower deterministic return on effort). This finding is intuitive, as it points to the fact that contestants always put higher effort when they perceive the contest to be competitive. If instead there is a stochastic advantage for contestant a, given the deterministic ability difference, we would have a one-sided race with contestant a as the winner already perceived from the beginning. Therefore, an increase in the first-round effort return difference would lower the incentives of both players to exert higher effort in the second-round.

4.4.2. Main Result

Now we turn our attention to the problem of the contest holder maximizing her utility. Let $\hat{\Pi}$ and Π denote the contest-holder's profits and expected profits, respectively. The contest holder tries to maximize his expected profits (Π) by choosing a feedback policy.

$$\max_{\tau} \Pi(\tau) = \mathbb{E}_{\tau,\omega}[\hat{\Pi}(e_{a1|P}, e_{b1|P}, e_{a2|s}, e_{b2|s}, \omega)] \tag{4.13}$$

We know from equation (4.1) that $\Pi = \beta\mathbb{E}[(v_{a2}+v_{b2})/2]+(1-\beta)\mathbb{E}[max\{v_{a2}, v_{b2}\}]$, with $\beta \in [0, 1]$. For ease of exposition, we separate the analysis into two parts dealing first with the case of $\beta = 1$ and then the case of $\beta = 0$. As such, the following two theorems cover these two cases.

Theorem 4.1 (maximizing the average performance)**.** *Let*

$$\tilde{\Pi}_{\beta=1} = \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau)) + \mathbb{E}_\tau[\sum_i \alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1(\tau), \mu_s))]$$

$$l_{i2} : (E^2, \Delta(\Omega^2)) \to \mathbb{R} \textit{ be } l_{i2}(\Delta e_1, x) = (r_2 \circ \gamma_{i2})(\Delta e_1, x).$$

For the case of $\beta = 1$ (maximizing the average performance),

- *If Lemmas 4.2 (i), 4.3, and 4.5 hold, and*
- $l_{i2}(e_1, \mu_s)$ *is convex in* μ_s *for all* i*:*

A feedback strategy with any fully informative policy is optimal.

If we instead have Lemma 4.2 (ii) and concave, a strategy with any uninformative policy would be optimal.

Proof: Appendix C.

When maximizing average performance, theorem 4.1 reveals that the optimal feedback strategy is independent of the award A's size and of contestants' first-round cost of (and returns on) effort. The optimal feedback strategy instead depends on the properties of the function r_2, which characterizes contestants' second-round returns on effort, of c_2, the contestants' second-round cost function, and the distribution of the exogeneous performance shocks. Considering the case of a fully informative policy, the second condition requires that $(r_2 \circ \gamma_{i2})$ be convex to maximize the second-round effort. On the other hand, lemma 4.2 requires $(\eta_2 \circ \gamma_{i2})$ to be convex for this policy to maximize the first-round effort. Note that by lemma 4.4, for γ_{i2} to be convex, $\eta_2''(\cdot)$ should be sufficiently small. Therefore, the only perceivable way for both of these conditions to hold at the same time is that r_2 and η_2 must be not too concave. However, for the completely uninformative policy to maximize both rounds' effort r_2 must be strongly concave, and/or η_2 not too convex.

To build intuition for the theorem, one could consider a specific case of linear return function r_2, which yields $\eta_2''(x) = c_2'''(x)/r_2'(x)$. It is intuitive that the optimal feedback policy balances two opposing effects. On the one hand, precise performance feedback induces contestants to invest substantial second-round effort if the revealed intermediate performance gap is small. Otherwise (i.e., with a larger performance gap), such feedback discourages them from investing effort. On the other hand, imprecise feedback incentivizes the middling effort in response to any feedback signal. Thus we can see that the upside potential of a precise feedback policy is most valuable when the marginal cost of any additional effort does not accelerate too quickly. However, if the marginal cost is too concave (i.e., it decelerates very quickly), then the contestants would put minimal effort in the first-round to wait for more refined information about the state of the contest, i.e., feedback realization, and then put higher effort into the second round. This observation is reminiscent of the phenomenon of *precautionary saving* in economics: to delay consumption and save in the current period and resort to it in the future if needed. Therefore, all in all, the contest holder would prefer a fully informative feedback policy when the marginal cost of any additional effort does not increase too quickly but also not too slowly, i.e., c_2' is mildly concave.

In the same vein, if the marginal cost of any additional effort increases quickly, the contest-holder favors middling effort choices. However, because of the complementarity between first- and second-round effort choices (i.e., the higher the first-round effort, the higher the second-round effort), if the marginal cost is too convex, the contestants would put minimal effort in the first round so that they do not have to put too much effort in the second round. Therefore, the completely uninformative policy maximizes both rounds' effort choices only if the marginal cost is only mildly convex.

However, according to corollary 4.3, if the terms $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]$ and $\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_2)]$ are sufficiently small, then the impact of different feedback policies on the first-round would be negligible, and the effort choices would be virtually the same independent of the chosen policy. Therefore, in such cases, the contest holder prefers a fully informative feedback policy under milder conditions, that is, if c_2 is only mildly convex and r_2 only mildly concave, whereas completely uninformative policies are preferred if c_2 is strongly convex or r_2 is strongly concave. One can imagine that such cases are not too rare and can emerge under a considerably wide range of shock distributions.

Theorem 4.2 (maximizing the best performance)**.** *Let*

$$p_i = G_{\omega_{j1}+\omega_{j2}-\omega_{i1}-\omega_{i2}}(\sigma_i+\alpha_i\cdot r_1(e_{i1})+\alpha_i\cdot r_2(e_{i2})-\sigma_j-\alpha_j\cdot r_1(e_{j1})-\alpha_j\cdot r_2(e_{j2})))$$

$$p_a + p_b = 1$$

$$\omega = \sum_t (\omega_{at} - \omega_{bt}), \quad \lambda_\omega(x) = \mathbb{E}_\omega[\omega | \omega > x]$$

$$\tilde{\Pi}_{\beta=0} = p_a \sum_t \alpha \cdot r_t(e_{at}) + (1 - p_a) \sum_t r_t(e_{bt}) + \lambda_\omega(\sum_t (r_t(e_{bt}) - \alpha \cdot r_t(e_{at})))$$

$$\gamma_2 : (E^2, \Delta(\Omega^2)) \to \mathbb{R}^2 \ \textit{be} \ \gamma_2(\Delta e_1, x) = \langle \gamma_{a2}(\Delta e_1, x), \gamma_{b2}(\Delta e_1, x) \rangle,$$

$$\textit{and} \ \tilde{l}_2 : (E^2, \Delta(\Omega^2)) \to \mathbb{R} \ \textit{be} \ \tilde{l}_2(\Delta e_1, x) = (\tilde{\Pi}_{\beta=0} \circ \gamma_2)(\Delta e_1, x).$$

For the case of $\beta = 0$ (maximizing the max performance),

- *If Lemmas 4.2 (i), 4.3, and 4.5 hold, and*
- *$l_2(e_1, \mu_s)$ is convex in μ_s:*

A feedback strategy with any fully informative policy is optimal.

If in the first and third conditions instead we have Lemma 4.2 (ii) and concave, respectively, a strategy with any uninformative policy would be optimal.

Proof: Appendix C.

The results of this theorem and their interpretation are, in principle, very similar to those of Theorem 4.1. However, there are some differences. First, unlike the previous one, when maximizing the maximum performance, Theorem 4.2 reveals that the optimal feedback strategy might also depend on contestants' first-round returns on effort, r_1. Given the more complex form of the objective function in this case, deriving straight-forward insights from the results is more difficult. Nonetheless, it seems that the aforementioned conflict about maximizing first- and second-round effort is still present.

The findings presented in Theorems 4.1 and 4.2 have immediate implications for real-life contests. First, the second part of both theorems shows the strategic equivalence of two very different feedback strategies. In particular, the same contestant responses (and hence the same contest outcomes) follow regardless of whether the contest holder declines to provide any feedback at all or commits to a completely uninformative feedback policy. Second, they offer strong evidence that, for many contests, two simple deterministic feedback policies outperform any more complex policy that relies on strategic lying, obfuscation, or deliberately reducing information. However, we also show that the extent of such contests is more limited in the presence of ability asymmetries than the extent of symmetric contests primarily studied in the literature. In short, simple feedback policies are, indeed, frequently optimal among the vast set of all (stochastic) feedback policies. This insight has considerable theoretical and practical implications for the design of effective competitions.

Endnotes

1. This assumption does not affect any of our structural results and is thus invoked for expositional clarity only.
2. We have opted for such a parsimonious acquisition process to simplify our mathematical exposition. In reality, firms may rely on more complex options, such as licensing agreements, R&D partnerships, or joint ventures, to "acquire" external NPD projects (Bhaskaran and Krishnan 2009, Crama et al. 2017, Hasija and Bhattacharya 2017). However, whereas the transactional details of those advanced options are much more involved, they are immaterial for our structural results as long as the firm must dedicate some of its resources to acquired external NPD projects.
3. Here, we make use of the revelation principle, which ensures that such a truth-inducing incentive scheme is indeed optimal.
4. Because our incentive scheme allows the firm to specify a distinct payment for any verifiable outcome, it is guaranteed that we will obtain the theoretically optimal incentive scheme.
5. Where μ is a PDF, $\Delta(X)$ denotes the set of Borel probabilities on X, a compact metric space in weak Topology
6. This assumption ensures that each contestant participates in the contest. The reason is that an effort level of $e_i = 0$ guarantees the contestant a nonnegative expected utility and, in equilibrium, he participates.
7. the set of Borel probabilities on the compact metric space $\Delta(\Omega^2)$

Appendix A

Proofs of Chapter II

Proof. Proof of Proposition 2.1. The proof proceeds in two steps. First, we formally derive the firm's incentive design problem (2.1)-(2.5). Second, we then solve the firm's optimization problem and analyze the properties of the optimal solution.

Step 1: *The firm's incentive design problem.* When implementing an (I, I)-policy, the firm (a) bans all external projects $j \in E$ from receiving resources and (b) avoids any competition for resources between the internal projects $i \in I$. As a result, it is never optimal for the firm to pay any external incentives $\gamma(\theta_j)$ or shared incentives $\beta(\theta_i)$; that is, in optimum, $\beta(\theta_i) = \gamma(\theta_j) = 0$ for all $i \in I$ and $j \in E$. We can hence disregard, without loss of optimality, all shared and external incentives in the firm's incentive design problem.

By assumption, the firm always invests in project $i \in I$ if and only if it receives a good recommendation for that project (i.e., if $r_i = g$). Given that we are interested in incentive schemes that induce project managers to exert high effort and truthfully reveal their signals, $r_i = g$ if and only if $s_i = g$. The firm's expected profit is thus $\Pi_{(I,I)}(W) = \sum_{i \in I} \big(\mathbb{P}(s_i = g)(q_I(v_I - \alpha_g) + (1 - q_I)(w_I - \alpha_b)) - \mathbb{P}(s_i = b)\alpha_0 - w_0\big) = \mu_I - q_I\alpha_g - (1 - q_I)\alpha_b - \alpha_0 - 2w_0$. We now turn to the incentive compatibility constraints, and derive the project managers' expected utilities relevant for constraints (IC-g), (IC-b), and (IC-e). In particular, $u_i(r_i = g \mid e_i = e_{3-i} = h, s_i = g, r_{3-i} = s_{3-i}) = q_I\alpha_g + (1 - q_I)\alpha_b + w_0$; $u_i(r_i = b \mid e_i = e_{3-i} = h, s_i = g, r_{3-i} = s_{3-i}) = \alpha_0 + w_0$;

$u_i(r_i = b \mid e_i = e_{3-i} = h, s_i = b, r_{3-i} = s_{3-i}) = \alpha_0 + w_0$; $u_i(r_i = g \mid e_i = e_{3-i} = h, s_i = b, r_{3-i} = s_{3-i}) = (1 - q_I)\alpha_g + q_I\alpha_b + w_0$; $u_i(e_i = h, r_i = s_i \mid e_{3-i} = h, r_{3-i} = s_{3-i}) = (q_I\alpha_g + (1 - q_I)\alpha_b)/2 + \alpha_0/2 + w_0 - c$; and $u_i(e_i = l, r_i = s_i \mid e_{3-i} = h, r_{3-i} = s_{3-i}) = (\alpha_g + \alpha_b)/4 + \alpha_0/2 + w_0$. Finally, we note that project manager i's limited liability requires that $w_i(\theta) \geq 0$ for any realization of θ, and that the (RA) constraint is trivially satisfied because the firm considers only internal projects.

Step 2: *The optimal solution.* (i) The firm's optimization problem (2.1)-(2.5) is a linear program (LP) because the objective function as well as all constraints are linear in $\alpha(\theta_i)$. For LPs, it is a well-known fact that the Karush-Kuhn-Tucker (KKT) conditons are necessary and sufficient optimality conditions (see, e.g., Boyd and Vandenberghe 2004, p. 243). It is now straightforward to verify that the incentive scheme presented in part (i) of the proposition satisfies the KKT conditions and is thus optimal. More precisely, in optimum, constraints (2.3), (2.4) and three of the limited liability constraints (2.5) are binding. To give some intuition for this result, note that the firm pays the minimum possible incentives to motivate each project manager to (a) exert high effort and (b) to reveal a negative signal truthfully (here, truthful revelation of a positive signal can be taken for granted).

(ii) Under an (I, I)-policy, the firm has banned all external projects, which trivially implies $n_E = 0$. In contrast, for internal projects, the firm invests in project $i \in I$ if and only if it receives a positive recommendation (i.e., $r_i = g$), which yields $n_I = \sum_{i \in I} \mathbb{P}(r_i = g) = \sum_{i \in I} \mathbb{P}(s_i = g) = 1$. Here, the second equality follows from the fact that the optimal incentive scheme induces truth telling.

(iii) Inserting the optimal incentive scheme presented in part (i) into (2.1) immediately gives the firm's optimal expected profit $\Pi_{(I,I)} = \mu_I - \phi_I$.

□

Proof. Proof of Proposition 2.2. (i) Under an (E, E)-policy, the firm never allocates any resources to internal projects, and there is thus no reason to incentivize project managers to acquire information about their projects. It follows immediately that $W_{(E,E)} = 0$ in optimum.

(ii) Under an (E, E)-policy, it trivially holds that $n_I = 0$. In contrast, for external projects, the firm invests in project $j \in E$ if and only if it receives a positive recommendation (i.e., $r_j = g$), which yields $n_E = \sum_{j\in E} \mathbb{P}(r_j = g) = \sum_{j\in E} \mathbb{P}(s_j = g) = 1$. Here, the second equality follows from our assumption that due diligence reports are truthful.

(iii) By assumption, the firm always invests in project $j \in E$ if and only if it receives a good recommendation for that project (i.e., if $r_j = g$), or equivalently, if and only if $s_j = g$. The firm's expected profit is thus $\Pi_{(E,E)} = \sum_{j\in E} \big(\mathbb{P}(s_j = g)(q_E v_E + (1 - q_E)w_E - K) - d\big) = \mu_E - 2d$. $\square$

Proof. Proof of Proposition 2.3. The proof is structurally similar to the proof of Proposition 2.1. Again, we first derive the firm's incentive design problem (2.6)-(2.10), before we then solve the firm's optimization problem and analyze the properties of the optimal solution.

Step 1: The firm's incentive design problem. With an (I, E)-policy, the firm fully separates internal from external projects; that is, there is no competition for resources between the different types of projects. As a result, it is never optimal for the firm to pay any external incentives: in optimum, $\gamma(\theta_j) = 0$ for all $j \in E$. We can hence disregard, without loss of optimality, all external incentives in the firm's incentive design problem.

Under an (I, E)-policy, the firm can invest in at most one of the two internal (resp. external) projects; and it will do so if it receives at least one positive recommendation for the internal (resp. external) projects. Assuming truth telling, the firm's expected profit is thus $\Pi_{(I,E)}(W) = \big[(1 - \mathbb{P}(s_1 = b, s_2 = b))(q_I(v_I - \alpha_g - \beta_g) + (1 - q_I)(w_I - \alpha_b - \beta_b) - \alpha_0 - \beta_0) - 2\mathbb{P}(s_1 = b, s_2 = b)(\alpha_0 + \beta_0) - 2w_0\big] + \big[(1 - \mathbb{P}(s_3 = b, s_4 = b))(q_E v_E + (1 - q_E)w_E - K) - 2d\big] = 3(\mu_I + \mu_E)/4 - 3\big(q_I(\alpha_g + \beta_g) + (1 - q_I)(\alpha_b + \beta_b)\big)/4 - 5(\alpha_0 + \beta_0)/4 - 2w_0 - 2d$. We now turn to the incentive compatibility constraints, and derive the project managers' expected utilities relevant for constraints (IC-g), (IC-b), and (IC-e). Here, we assume that for each type of project, the firm is equally likely to allocate resources to any one of the two projects if it receives two good recommendations. In particular, $u_i(r_i = g \mid e_i = e_{3-i} = h, s_i = g, r_{3-i} = s_{3-i}) = 3(q_I\alpha_g + (1-q_I)\alpha_b + \beta_0)/4 + (\alpha_0 + q_I\beta_g + (1-q_I)\beta_b)/4 + w_0$; $u_i(r_i = b \mid e_i = e_{3-i} = h, s_i = g, r_{3-i} = s_{3-i}) = \alpha_0 + (q_I\beta_g + (1-q_I)\beta_b + \beta_0)/2 + w_0$; $u_i(r_i = g \mid e_i = e_{3-i} = h, s_i = b, r_{3-i} = s_{3-i}) = 3((1-q_I)\alpha_g + q_I\alpha_b + \beta_0)/4 + (\alpha_0 + q_I\beta_g + (1-q_I)\beta_b)/4 + w_0$; $u_i(r_i = b \mid e_i = e_{3-i} = h, s_i = b, r_{3-i} = s_{3-i}) = \alpha_0 + (q_I\beta_g + (1-q_I)\beta_b + \beta_0)/2 + w_0$; $u_i(e_i = h, r_i = s_i \mid e_{3-i} = h, r_{3-i} = s_{3-i}) = 3(q_I\alpha_g + (1-q_I)\alpha_b + \beta_0)/8 + (\alpha_0 + q_I\beta_g + (1-q_I)\beta_b)/8 + \alpha_0/2 + (q_I\beta_g + (1-q_I)\beta_b + \beta_0)/4 + w_0 - c$; and $u_i(e_i = l, r_i = s_i \mid e_{3-i} = h, r_{3-i} = s_{3-i}) = 3(\alpha_g + \alpha_b + 2\beta_0)/16 + (\alpha_0 + q_I\beta_g + (1-q_I)\beta_b)/8 + \alpha_0/2 + (q_I\beta_g + (1-q_I)\beta_b + \beta_0)/4 + w_0$. Finally, we note that project manager i's limited liability requires that $w_i(\theta) \geq 0$ for any realization of θ, and that the (RA) constraint is immaterial because the firm has completely separated internal from external projects (i.e., resources are upfront dedicated to the specific types of projects).

Step 2: *The optimal solution.* (i) The firm's optimization problem (2.6)-(2.10) is again an LP, and we can immediately check that the incentive scheme presented in part (i) of the proposition satisfies the KKT conditions and is thus optimal. More precisely, in optimum, constraints (2.8), (2.9) and all but three of the limited liability constraints (2.10) are binding. The same intuition as in the proof of Proposition 2.1(i) applies: the firm pays the minimum possible incentives to motivate each project manager to (a) exert high effort and (b) to reveal a negative signal truthfully (while truthful revelation of a positive signal is guaranteed).

(ii) Under an (I, E)-policy, the firm invests in one internal project if and only if it receives at least one positive recommendation (i.e., $r_i = g$ for some $i \in I$); otherwise it does not allocate resources to any of the internal projects. Hence, $n_I = 1 - \mathbb{P}(r_1 = b, r_2 = b) = 1 - \mathbb{P}(s_1 = b, s_2 = b) = 3/4$, where the second equality follows from the fact that the optimal incentive scheme induces truth telling. The same logic applies to external projects, and thus $n_E = 1 - \mathbb{P}(r_3 = b, r_4 = b) = 1 - \mathbb{P}(s_3 = b, s_4 = b) = 3/4$, the second equality follows from our assumption that due diligence reports are truthful.

(iii) Inserting the optimal incentive scheme presented in part (i) into (2.6) immediately gives the firm's optimal expected profit $\Pi_{(I,E)} = 3(\mu_I + \mu_E)/4 - \phi_I - 2d$. □

Proof. Proof of Proposition 2.4. To find the firm's optimal resource allocation policy under full commitment, we directly compare $\Pi_{(I,I)}$, $\Pi_{(E,E)}$, and $\Pi_{(I,E)}$ as given in Proposition 2.1(iii), 2.2(iii), and 2.3(iii), respectively. In particular, an (I,I)-policy is optimal if and only if $\Pi_{(I,I)} \geq \max\{\Pi_{(E,E)}, \Pi_{(I,E)}\}$, or equivalently, $\mu_E \leq \min\{\mu_I - \phi_I + 2d, (\mu_I + 8d)/3\}$. Similarly, an (E,E)-policy is optimal if and only if $\Pi_{(E,E)} > \max\{\Pi_{(I,I)}, \Pi_{(I,E)}\}$, or equivalently, $\mu_E > \max\{\mu_I - \phi_I + 2d, 3\mu_I - 4\phi_I\}$. Finally, an (I,E)-policy is optimal if and only if $(\mu_I + 8d)/3 < \mu_E \leq 3\mu_I - 4\phi_I$. Rearranging those conditions leads to the case distinction presented in the proposition. □

Proof. Proof of Proposition 2.5. Under a $(\cdot,\cdot)$-policy, the firm first observes for each project $i \in N$ whether an investment in project i is recommended ($r_i = g$) or not ($r_i = b$), and it then has full discretion to select (at most) two projects out of all projects with a positive recommendation. Naturally, the firm only allocates resources to those projects that are ex-post most profitable—constraint (RA) guarantees such an ex-post optimal allocation of resources. In particular, the firm selects the projects with the highest expected value net of any incentive payments triggered by an investment in that project. Mathematically, the firm prefers allocating resources to an internal project over funding an external project if (and only if)

$$\begin{aligned} &q_I(v_I - \alpha_g - \beta_g) + (1 - q_I)(w_I - \alpha_b - \beta_b) - 2\gamma_0 \geq \\ &q_E(v_E - 2\gamma_g) + (1 - q_E)(w_E - 2\gamma_b) - K - \alpha_0 - \beta_0. \end{aligned} \tag{RA'}$$

Because condition (RA') depends on the firm's incentive scheme $W = (w_0, \alpha(\theta_i), \beta(\theta_{3-i}), \gamma(\theta_j))$, it follows immediately that the firm's investment preference (i.e., I or E) is determined endogenously as an outcome of the firm's incentive design.

Hence, to find the firm's optimal incentive scheme, we must solve two separate optimization problems—one for each alternative investment preference—and then compare the optimal profits associated with the different solutions.

Preference for internal projects. Suppose the firm seeks to design an incentive scheme that (a) maximizes its expected profits, but that (b) also guarantees that the firm always prefers internal over external projects (i.e., condition (RA') always holds). In that case, the firm must solve the following optimization problem to derive an optimal incentive scheme (the precise derivation of the required utilities is analogous to Propositions 2.1 and 2.3, and therefore omitted):

$$\begin{aligned} \max_{W}\ \Pi_{(\cdot,\cdot)}(W) &= \mu_I + \frac{5}{8}\mu_E - q_I(\alpha_g + \beta_g) - (1-q_I)(\alpha_b + \beta_b) - (\alpha_0 + \beta_0) \\ &\quad - \frac{5}{4}(q_E\gamma_g + (1-q_E)\gamma_b) - \frac{11}{4}\gamma_0 - 2w_0 - 2d && \text{(A.1)} \\ \text{s.t. } & 2(q_I\alpha_g + (1-q_I)\alpha_b - \alpha_0) \geq q_E\gamma_g + (1-q_E)\gamma_b - \gamma_0 && \text{(A.2)} \\ & 2((1-q_I)\alpha_g + q_I\alpha_b - \alpha_0) \leq q_E\gamma_g + (1-q_E)\gamma_b - \gamma_0 && \text{(A.3)} \\ & (2q_I - 1)(\alpha_g - \alpha_b) \geq 4c && \text{(A.4)} \\ & w_i(a^*, \theta) \geq 0 && \text{(A.5)} \\ & q_I(v_I - \alpha_g - \beta_g) + (1-q_I)(w_I - \alpha_b - \beta_b) - 2\gamma_0 \\ & \quad \geq q_E(v_E - 2\gamma_g) + (1-q_E)(w_E - 2\gamma_b) - K - \alpha_0 - \beta_0. && \text{(A.6)} \end{aligned}$$

This optimization problem is again an LP, and an optimal incentive scheme $W_{(\cdot,\cdot)}$ can thus be found by checking the KKT conditions. It turns out that the optimal incentive scheme changes structurally as a function of $\Delta\mu$. Table A.1 summarizes the properties of the optimal solution to (A.1)-(A.6) by detailing (a) the optimal incentives, (b) the associated expected profits, and (c) the binding constraints. Last, we note that irrespective of $\Delta\mu$, the firm invests, on expectation, in $n_I = 2\mathbb{P}(r_1 = g, r_2 = g) + \mathbb{P}(r_1 = g, r_2 = b) + \mathbb{P}(r_1 = b, r_2 = g) = 1$ internal projects, and $n_E = \big(\mathbb{P}(r_1 = g, r_2 = b) + \mathbb{P}(r_1 = b, r_2 = g)\big)\big(1 - \mathbb{P}(r_3 = b, r_4 = b)\big) + \mathbb{P}(r_1 = b, r_2 = b)\big(2\mathbb{P}(r_3 = g, r_4 = g) + \mathbb{P}(r_3 =$

Table A.1.: Full Flexibility and Preference for Internal Projects.

Case	Condition	Incentive Scheme $W_{(\cdot,\cdot)}$	Expected Profits $\Pi_{(\cdot,\cdot)}$	Binding Constraints
(Ia)	$4c \leq \Delta\mu$	$\alpha_g = \phi_I$ $\alpha_0 = (1 - q_I)\phi_I$	$\mu_I + 5\mu_E/8 - 2d - \phi_I$	(A.3), (A.4), and five of (A.5)
(Ib)	$(5q_I - 4)\phi_I$ $\leq \Delta\mu < 4c$	$\alpha_g = \phi_I$ $\alpha_0 = (\Delta\mu - (5q_I - 4)\phi_I)/3$ $\gamma_g = \gamma_b = (8c - 2\Delta\mu)/3$	$\mu_I + 5\mu_E/8 - 2d$ $-((2q_I + 1)\phi_I - \Delta\mu)/2$	(A.3), (A.4), (A.6), and three of (A.5)
(Ic)	$-3q_I\phi_I \leq \Delta\mu$ $< (5q_I - 4)\phi_I$	$\alpha_g = \phi_I$ $\gamma_g = \gamma_b = (q_I\phi_I - \Delta\mu)/2$	$\mu_I + 5\mu_E/8 - 2d$ $-(13q_I\phi_I - 5\Delta\mu)/8$	(A.4), (A.6), and six of (A.5)
(Id)	$\Delta\mu < -3q_I\phi_I$	$\alpha_g = \phi_I$ $\alpha_0 = -\Delta\mu - 3q_I\phi_I$ $\beta_g = \beta_b = \Delta\mu + 3q_I\phi_I$ $\gamma_g = 2q_I\phi_I/q_E$	$\mu_I + 5\mu_E/8 - 2d$ $-(q_I\phi/2 - \Delta\mu)$	(A.2), (A.4), (A.6), and six of (A.5)

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

Table A.2.: Full Flexibility and Preference for External Projects.

Case	Condition	Incentive Scheme $W_{(\cdot,\cdot)}$	Expected Profits $\Pi_{(\cdot,\cdot)}$	Binding Constraints
(Ea)	$8(5 - 4q_I)\phi_I/5$ $< \Delta\mu$	$\alpha_g = \Delta\mu/(6q_I)$ $\beta_g = \Delta\mu/(30q_I)$	$5\mu_I/8 + \mu_E$ $-5\Delta\mu/8 - 2d$	(A.8), (A.12), and twelve of (A.11)
(Eb)	$8q_I\phi_I/5 < \Delta\mu$ $\leq 8(5 - 4q_I)\phi_I/5$	$\alpha_g = 8\phi_I/5$ $\alpha_0 = -\Delta\mu/4$ $+2(5 - 4q_I)\phi_I/5$ $\beta_0 = -5\Delta\mu/4 + 2\phi_I$ $\gamma_g = \gamma_b = \Delta\mu/4$ $-2(5 - 4q_I)\phi_I/5$	$5\mu_I/8 + \mu_E - 7\Delta\mu/16$ $-3(5 - 4q_I)\phi_I/10 - 2d$	(A.10), (A.12), and four of (A.11)
(Ec)	$\Delta\mu \leq 8q_I\phi_I/5$	$\alpha_g = 8\phi_I/5$ $\alpha_0 = \beta_0 = 2(1 - q_I)\phi_I$ $\gamma_g = \gamma_b = -2(1 - q_I)\phi_I$	$5\mu_I/8 + \mu_E$ $-(3 - q_I)\phi_I/2 - 2d$	(A.9), (A.10), and ten of (A.11)

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

$g, r_4 = b) + \mathbb{P}(r_3 = b, r_4 = g)\big) = 5/8$ external projects.

Preference for external projects. Now suppose that the firm seeks to design an incentive scheme that (a) maximizes its expected profits, but that (b) guarantees that the firm always prefers external over internal projects (i.e., condition (RA') is reversed). In that case, the firm must solve the following optimization problem to derive an optimal incentive scheme:

$$\begin{aligned}
\max_{W}\ \Pi_{(\cdot,\cdot)}(W) = \frac{5}{8}\mu_I + \mu_E - \frac{5}{8}\big(q_I(\alpha_g+\beta_g) + (1-q_I)(\alpha_b+\beta_b)\big) - \frac{11}{8}(\alpha_0+\beta_0)& \\
- 2(q_E\gamma_g + (1-q_E)\gamma_b) - 2\gamma_0 - 2w_0 - 2d& \quad \text{(A.7)}\\
\text{s.t. } 5(q_I\alpha_g + (1-q_I)\alpha_b - \alpha_0) \geq q_I\beta_g + (1-q_I)\beta_b - \beta_0& \quad \text{(A.8)}\\
5((1-q_I)\alpha_g + q_I\alpha_b - \alpha_0) \leq q_I\beta_g + (1-q_I)\beta_b - \beta_0& \quad \text{(A.9)}\\
5(2q_I-1)(\alpha_g-\alpha_b) \geq 32c& \quad \text{(A.10)}\\
w_i(a^*,\theta) \geq 0& \quad \text{(A.11)}\\
q_I(v_I - \alpha_g - \beta_g) + (1-q_I)(w_I - \alpha_b - \beta_b) - 2\gamma_0& \\
\leq q_E(v_E - 2\gamma_g) + (1-q_E)(w_E - 2\gamma_b) - K - \alpha_0 - \beta_0.& \quad \text{(A.12)}
\end{aligned}$$

This optimization problem is yet another LP, and an optimal incentive scheme $W_{(\cdot,\cdot)}$ can thus be found by checking the KKT conditions. As before, the optimal incentive scheme changes structurally as a function of $\Delta\mu$. Table A.2 summarizes the properties of the optimal solution to (A.7)-(A.12) by detailing (a) the optimal incentives, (b) the associated expected profits, and (c) the binding constraints. Last, we note that irrespective of $\Delta\mu$, the firm invests, on expectation, in $n_I = \big(\mathbb{P}(r_3 = g, r_4 = b) + \mathbb{P}(r_3 = b, r_4 = g)\big)\big(1 - \mathbb{P}(r_1 = b, r_2 = b)\big) + \mathbb{P}(r_3 = b, r_4 = b)\big(2\mathbb{P}(r_1 = g, r_2 = g) + \mathbb{P}(r_1 = g, r_2 = b) + \mathbb{P}(r_1 = b, r_2 = g)\big) = 5/8$ internal projects, and $n_E = 2\mathbb{P}(r_3 = g, r_4 = g) + \mathbb{P}(r_3 = g, r_4 = b) + \mathbb{P}(r_3 = b, r_4 = g) = 1$ external projects.

The optimal incentive scheme. We now derive the optimal incentive scheme, as presented in Table 2.1, by comparing the different cases in Tables A.1 and A.2. We begin by noting that $4c < 8q_I\phi_I/5$; hence we can establish the suboptimality of cases (Ea) and (Eb) by showing that those cases are always dominated by case (Ia). In particular, for $\Delta\mu > 8(5-4q_I)\phi_I/5$, $\Pi^{\text{Ia}}_{(\cdot,\cdot)} - \Pi^{\text{Ea}}_{(\cdot,\cdot)} = \Delta\mu - \phi_I > 0$; and for $\Delta\mu \in (8q_I\phi_I/5, 8(5-4q_I)\phi_I/5]$, $\Pi^{\text{Ia}}_{(\cdot,\cdot)} - \Pi^{\text{Eb}}_{(\cdot,\cdot)} > (5+q_I)\phi_I/10 > 0$.

Next, we establish when (and when not) case (Ec) is optimal. First, for $\Delta\mu \geq 4c$, we always have $\Pi^{\text{Ia}}_{(\cdot,\cdot)} - \Pi^{\text{Ec}}_{(\cdot,\cdot)} = 3\Delta\mu/8 + (1-q_I)\phi_I/2 > 0$; case (Ia) is thus optimal for $\Delta\mu \geq 4c$. Second, for $(5q_I-4)\phi_I \leq \Delta\mu < 4c$, $\Pi^{\text{Ib}}_{(\cdot,\cdot)} - \Pi^{\text{Ec}}_{(\cdot,\cdot)} \geq 0$ if and only if $\Delta\mu \geq 4(3q_I-2)\phi_I/7$, which implies that case (Ib) is optimal if $\max\{(5q_I-4)\phi_I, 4(3q_I-2)\phi_I/7\} \leq \Delta\mu < 4c$. Third, for $-3q_I\phi_I \leq \Delta\mu < (5q_I-4)\phi_I$, we have $\Pi^{\text{Ic}}_{(\cdot,\cdot)} - \Pi^{\text{Ec}}_{(\cdot,\cdot)} \geq 0$ if and only if $\Delta\mu \geq (17q_I-12)\phi_I/8$, which implies that case (Ic) is optimal if $\max\{-3q_I\phi_I, (17q_I-12)\phi_I/8\} \leq \Delta\mu < (5q_I-4)\phi_I$. Finally, for $\Delta\mu < -3q_I\phi_I$, it is always true that $\Pi^{\text{Id}}_{(\cdot,\cdot)} - \Pi^{\text{Ec}}_{(\cdot,\cdot)} < 0$, which implies that case (Ec) is optimal for $\Delta\mu < -3q_I\phi_I$. Combining the above conditions yields the case distinctions presented in the proposition and Table 2.1. □

Proof. Proof of Proposition 2.6. The proof proceeds in three steps. We first show that, whenever an (I,E)-policy is the optimal *full commitment* policy (cf. Proposition 2.4), then an $(\cdot,\cdot)$-policy is strictly superior to an (I,E)-policy; that is, an (I,E)-policy is always dominated by (at least) one of the other resource allocation policies, and thus never optimal. We then derive the auxiliary functions $\hat{\mu}$ and $\breve{\mu}$; in the last step, we use those functions to establish the optimal resource allocation policy.

Recall from Proposition 2.4 that an (I,E)-policy is the optimal full commitment policy if and only if $\mu_I > 3\phi_I/2 + d$ and $(\mu_I + 8d)/3 < \mu_E \leq 3\mu_I - 4\phi_I$. It is now straightforward to verify that in this parameter space, and for any value of $\Delta\mu$, we have $\Pi_{(\cdot,\cdot)} - \Pi_{(I,E)} > 0$. To be specific, suppose that $\mu_I > 3\phi_I/2 + d$ and $(\mu_I + 8d)/3 < \mu_E \leq 3\mu_I - 4\phi_I$. Then: (a) if $\Delta\mu \geq 4c$, $\Pi_{(\cdot,\cdot)} - \Pi_{(I,E)} = \mu_I/4 - \mu_E/8 > 0$; (b) if $\max\{(5q_I-4)\phi_I, 4(3q_I-2)\phi_I/7\} \leq \Delta\mu < 4c$, $\Pi_{(\cdot,\cdot)} - \Pi_{(I,E)} = 3\mu_I/4 - 5\mu_E/8 - 2c > 0$; (c) if $(17q_I-12)\phi_I/8 \leq \Delta\mu < (5q_I-4)\phi_I$, $\Pi_{(\cdot,\cdot)} - \Pi_{(I,E)} = 7\mu_I/8 - 3\mu_E/4 - (13q_I-8)\phi_I/8 > 0$; and (d) if $\Delta\mu < \max\{4(3q_I-2)\phi_I/7, (17q_I-12)\phi_I/8\}$, $\Pi_{(\cdot,\cdot)} - \Pi_{(I,E)} = -\mu_I/8 + \mu_E/4 -$

$(1-q_I)\phi_I/2 > 0$. It follows readily that an (I,E)-policy is never optimal.

In a next step, we derive the auxiliary functions $\hat{\mu}$ and $\breve{\mu}$, which have an intuitive interpretation: if $\mu_I \leq \hat{\mu}$ (resp. $\mu_I \leq \breve{\mu}$), then the firm always prefers an (I,I)-policy (resp. (E,E)-policy) over an $(\cdot,\cdot)$-policy with an investment preference for internal (resp. external) projects (cf. Table 2.1). We begin with deriving $\hat{\mu}$, which requires us to investigate three different cases that correspond to cases (i)-(iii) in Table 2.1. First, the firm prefers an (I,I)-policy to case (i) of Table 2.1 if $\Pi_{(I,I)} - \Pi^{i}_{(\cdot,\cdot)} = -5\mu_E/8 + 2d \geq 0$, or equivalently, $\mu_E \leq 16d/5$. By Proposition 2.4(i), this implies that the firm always prefers an (I,I)-policy to case (i) of Table 2.1 if $\mu_I \leq \phi_I + 6d/5 = \hat{\mu}_1$. Second, the firm prefers an (I,I)-policy to case (ii) of Table 2.1 if $\Pi_{(I,I)} - \Pi^{ii}_{(\cdot,\cdot)} = -\mu_I/2 - \mu_E/8 + 2d + 2c \geq 0$, or equivalently, $\mu_E \leq -4\mu_I + 16(c+d)$. By Proposition 2.4(i), this implies that the firm always prefers an (I,I)-policy to case (ii) of Table 2.1 if $\mu_I \leq (8q_I - 3)\phi_I/5 + 14d/5 = \hat{\mu}_2$. Third, the firm prefers an (I,I)-policy to case (iii) of Table 2.1 if $\Pi_{(I,I)} - \Pi^{iii}_{(\cdot,\cdot)} = -5\mu_I/8 + 2d + (13q_I - 8)\phi_I/8 \geq 0$, or equivalently, $\mu_I \leq (13q_I - 8)\phi_I/5 + 16d/5 = \hat{\mu}_3$. Now, the particular structure of cases (i)-(iii) allows us to set $\hat{\mu} = \max\{\hat{\mu}_1, \hat{\mu}_2, \hat{\mu}_3\}$. We now turn to $\breve{\mu}$: the firm prefers an (E,E)-policy to case (iv) of Table 2.1 if $\Pi_{(E,E)} - \Pi^{iv}_{(\cdot,\cdot)} = -5\mu_I/8 + (3-q_I)\phi_I/2 \geq 0$, or equivalently, $\mu_I \leq 4(3-q_I)\phi_I/5 = \breve{\mu}$.

With the help of the auxiliary functions $\hat{\mu}$ and $\breve{\mu}$, we can now construct the exact optimality conditions:

(i) If $\mu_I \leq \min\{\hat{\mu}, \breve{\mu}\}$, then the firm never finds it optimal to implement an $(\cdot,\cdot)$-policy. The optimal resource allocation policy thus follows immediately from Proposition 2.4(i).

(ii) If $\hat{\mu} < \mu_I < \breve{\mu}$, then an $(\cdot,\cdot)$-policy with investment preference for internal projects can be optimal. In particular, $\mathcal{P}^* = (I,I)$ if $\Pi_{(I,I)} - \Pi^{i}_{(\cdot,\cdot)} \geq 0$ or $\Pi_{(I,I)} - \Pi^{ii}_{(\cdot,\cdot)} \geq 0$; $\mathcal{P}^* = (E,E)$ if $\Pi_{(E,E)} - \Pi^{i}_{(\cdot,\cdot)} \geq 0$, $\Pi_{(E,E)} - \Pi^{ii}_{(\cdot,\cdot)} \geq 0$, or $\Pi_{(E,E)} - \Pi^{iii}_{(\cdot,\cdot)} \geq 0$; and $\mathcal{P}^* = (\cdot,\cdot)$ otherwise.

(iii) If $\breve{\mu} < \mu_I < \hat{\mu}$, then an $(\cdot,\cdot)$-policy with investment preference for external projects can be optimal. In particular, $\mathcal{P}^* = (I,I)$ if $\Pi_{(I,I)} - \Pi^{iv}_{(\cdot,\cdot)} \geq 0$; and $\mathcal{P}^* = (\cdot,\cdot)$ otherwise.

(iv) If $\mu_I \geq \max\{\hat{\mu}, \breve{\mu}\}$, then an $(\cdot,\cdot)$-policy with any investment preference can be optimal. In particular, $\mathcal{P}^* = (I, I)$ if $\Pi_{(I,I)} - \Pi^{i}_{(\cdot,\cdot)} \geq 0$ or $\Pi_{(I,I)} - \Pi^{ii}_{(\cdot,\cdot)} \geq 0$; and $\mathcal{P}^* = (\cdot,\cdot)$ otherwise. □

Proof. Proof of Proposition 2.7. The proofs of part (i) and (ii) follow exactly the same steps, namely: We begin each part with a derivation of the firm's incentive design problem under (i) an $(I,\cdot)$-policy and (ii) an $(E,\cdot)$-policy, respectively. Next, we characterize the firm's optimal incentive scheme—and its associated properties—for the different partial commitment policies. Last, we establish when it is optimal for the firm to implement (i) an $(I,\cdot)$-policy or (ii) an $(E,\cdot)$-policy.

(i) Under an $(I,\cdot)$-policy, the firm has both dedicated and unassigned resources. Now, similar to a $(\cdot,\cdot)$-policy, the firm allocates its unassigned resources only to the ex-post most promising project. In particular, the firm selects the project with the highest expected value net of any incentive payments triggered by an investment in that project (see condition (RA')). It follows that the firm's investment preference (i.e., I or E) for its unassigned resources is determined endogenously as an outcome of the firm's incentive design. Hence, to find the firm's optimal incentive scheme, we must solve two separate optimization problems—one for each alternative investment preference—and then compare the optimal profits associated with the different solutions.

Preference for internal projects. Suppose the firm seeks to design an incentive scheme that (a) maximizes its expected profits, but that (b) also guarantees that the firm always prefers internal over external projects when allocating unassigned resources (i.e., condition (RA') holds). In that case, the firm must solve the following optimization problem to obtain an optimal incentive scheme:

$$\max_{W} \ \Pi_{(I,\cdot)}(W) = \mu_I + \frac{9}{16}\mu_E - q_I(\alpha_g + \beta_g) - (1 - q_I)(\alpha_b + \beta_b) - (\alpha_0 + \beta_0)$$

$$- \frac{9}{8}(q_E\gamma_g + (1 - q_E)\gamma_b) - \frac{23}{8}\gamma_0 - 2w_0 - 2d \tag{A.13}$$

$$\text{s.t. } 8(q_I\alpha_g + (1 - q_I)\alpha_b - \alpha_0) \geq 3(q_E\gamma_g + (1 - q_E)\gamma_b - \gamma_0) \tag{A.14}$$

$$8((1 - q_I)\alpha_g + q_I\alpha_b - \alpha_0) \leq 3(q_E\gamma_g + (1 - q_E)\gamma_b - \gamma_0) \tag{A.15}$$

$$(2q_I - 1)(\alpha_g - \alpha_b) \geq 4c \tag{A.16}$$

$$w_i(a^*, \theta) \geq 0 \tag{A.17}$$

$$q_I(v_I - \alpha_g - \beta_g) + (1 - q_I)(w_I - \alpha_b - \beta_b) - 2\gamma_0$$

$$\geq q_E(v_E - 2\gamma_g) + (1 - q_E)(w_E - 2\gamma_b) - K - \alpha_0 - \beta_0. \tag{A.18}$$

Given that this optimization problem is an LP, we can derive its optimal solution from the KKT conditions, which reveal that the optimal incentive scheme changes as a function of $\Delta\mu$. Table A.3 summarizes the properties of the optimal solution to (A.13)-(A.18) by detailing (a) the optimal incentives, (b) the associated expected profits, and (c) the binding constraints. Last, we note that irrespective of $\Delta\mu$, the firm invests, on expectation, in $n_I = 2\mathbb{P}(r_1 = g, r_2 = g) + \mathbb{P}(r_1 = g, r_2 = b) + \mathbb{P}(r_1 = b, r_2 = g) = 1$ internal projects, and $n_E = \big(1 - \mathbb{P}(r_1 = g, r_2 = g)\big)\big(1 - \mathbb{P}(r_3 = b, r_4 = b)\big) = 9/16$ external projects.

Preference for external projects. Now suppose that the firm seeks to design an incentive scheme that (a) maximizes its expected profits, but that (b) guarantees that the firm always prefers external over internal projects when allocating unassigned resources (i.e., condition (RA') is reversed). In that case, the solution to the following optimization problem yields an optimal incentive

Table A.3.: Partial Resource Commitment to Internal Projects and Preference for Internal Projects.

Case	Condition	Incentive Scheme $W_{(I,\cdot)}$	Expected Profits $\Pi_{(I,\cdot)}$	Binding Constraints
(Ia)	$4c \leq \Delta\mu$	$\alpha_g = \phi_I$ $\alpha_0 = (1-q_I)\phi_I$	$\mu_I + 9\mu_E/16 - 2d - \phi_I$	(A.15), (A.16), and five of (A.17)
(Ib)	$(19q_I - 16)\phi_I/3$ $\leq \Delta\mu < 4c$	$\alpha_g = \phi_I$ $\alpha_0 =$ $(3\Delta\mu - (19q_I - 16)\phi_I)/13$ $\gamma_g = \gamma_b =$ $-24(\Delta\mu + 4c)/39$	$\mu_I + 9\mu_E/16 + 6\Delta\mu/13$ $-(12q_I + 7)\phi_I/13 - 2d$	(A.15), (A.16), (A.18), and three of (A.17)
(Ic)	$-13q_I\phi_I/3 \leq \Delta\mu$ $< (19q_I - 16)\phi_I/3$	$\alpha_g = \phi_I$ $\gamma_g = \gamma_b = (q_I\phi_I - \Delta\mu)/2$	$\mu_I + 9\mu_E/16 - 2d$ $-(25q_I\phi_I - 9\Delta\mu)/16$	(A.16), (A.18), and six of (A.17)
(Id)	$\Delta\mu < -13q_I\phi_I/3$	$\alpha_g = -3\Delta\mu/(13q_I)$ $\gamma_b = -8\Delta\mu/(13(1-q_E))$	$\mu_I + 9\mu_E/16 - 2d$ $+12\Delta\mu/13$	(A.14), (A.18), and ten of (A.17)

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

Table A.4.: Partial Resource Commitment to Internal Projects and Preference for External Projects.

Case	Condition	Incentive Scheme $W_{(I,\cdot)}$	Expected Profits $\Pi_{(I,\cdot)}$	Binding Constraints
(Ea)	$16q_I\phi_I/13$ $< \Delta\mu$	$\alpha_g = 16\phi_I/13$ $\alpha_0 = \beta_0 = 8(1-q_I)\phi_I/5$ $\gamma_g = \gamma_b = -\Delta\mu/2$ $+8(18q_I - 13)\phi_I/65$	$13\mu_I/16 + 3\mu_E/4 - \Delta\mu/4$ $-(91 - 46q_I)\phi_I/65 - 2d$	(A.21), (A.22), (A.24), and four of (A.23)
(Eb)	$\Delta\mu$ $\leq 16q_I\phi_I/13$	$\alpha_g = 16\phi_I/13$ $\alpha_0 = \beta_0 = 8(1-q_I)\phi_I/5$ $\gamma_g = \gamma_b = -8(1-q_I)\phi_I/5$	$13\mu_I/16 + 3\mu_E/4$ $-(7 - 2q_I)\phi_I/5 - 2d$	(A.21),(A.22), and eight of (A.23)

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

scheme:

$$
\begin{aligned}
\max_{W} \ \Pi_{(I,\cdot)}(W) &= \frac{13}{16}\mu_I + \frac{3}{4}\mu_E - \frac{13}{16}(q_I(\alpha_g + \beta_g) + (1-q_I)(\alpha_b + \beta_b)) - \frac{19}{16}(\alpha_0 + \beta_0) \\
&\quad - \frac{3}{2}(q_E\gamma_g + (1-q_E)\gamma_b) - \frac{5}{2}\gamma_0 - 2w_0 - 2d && \text{(A.19)} \\
\text{s.t.} \ & 13(q_I\alpha_g + (1-q_I)\alpha_b - \alpha_0) \geq 3(q_I\beta_g + (1-q_I)\beta_b - \beta_0) && \text{(A.20)} \\
& 13((1-q_I\alpha_g + q_I\alpha_b - \alpha_0) \leq 3(q_I\beta_g + (1-q_I)\beta_b - \beta_0) && \text{(A.21)} \\
& 13(2q_I - 1)(\alpha_g - \alpha_b) \geq 64c && \text{(A.22)} \\
& w_i(a^*, \theta) \geq 0 && \text{(A.23)} \\
& q_I(v_I - \alpha_g - \beta_g) + (1-q_I)(w_I - \alpha_b - \beta_b) - 2\gamma_0 \\
& \quad \leq q_E(v_E - 2\gamma_g) + (1-q_E)(w_E - 2\gamma_b) - K - \alpha_0 - \beta_0. && \text{(A.24)}
\end{aligned}
$$

This optimization problem is again an LP, and an optimal incentive scheme $W_{(I,\cdot)}$ can thus be found by checking the KKT conditions. As before, the optimal incentive scheme changes structurally as a function of $\Delta\mu$. Table A.4 summarizes the properties of the optimal solution to (A.19)-(A.24) by detailing (a) the optimal incentives, (b) the associated expected profits, and (c) the binding constraints. Last, we note that irrespective of $\Delta\mu$, the firm invests, on expectation, in $n_I = \mathbb{P}(r_1 = g, r_2 = g)\big(2\mathbb{P}(r_3 = b, r_4 = b) + \big(1 - \mathbb{P}(r_3 = b, r_4 = b)\big)\big) + \mathbb{P}(r_1 = g, r_2 = b) + \mathbb{P}(r_1 = b, r_2 = g) = 13/16$ internal projects, and $n_E = 1 - \mathbb{P}(r_3 = b, r_4 = b) = 3/4$ external projects.

The optimal incentive scheme. We now derive the optimal incentive scheme by comparing the different cases in Tables A.3 and A.4. We begin by noting that $4c < 16q_I\phi_I/13$; hence we can establish the suboptimality of case (Ea) by showing that case (Ia) always dominates case (Ea). In particular, for $16q_I\phi_I/13 < \Delta\mu$, we have $\Pi^{\text{Ia}}_{(I,\cdot)} - \Pi^{\text{Ea}}_{(I,\cdot)} = 7\Delta\mu/16 - (46q_I - 26)\phi_I/65 > 0$.

Next, we establish when (and when not) case (Eb) is optimal. First, for $\Delta\mu \geq 4c$, we always have $\Pi^{\text{Ia}}_{(I,\cdot)} - \Pi^{\text{Eb}}_{(I,\cdot)} = 3\Delta\mu/16 + 2(1-q_I)\phi_I/5 > 0$; case (Ia) is thus optimal for $\Delta\mu \geq 4c$. Second, for $(19q_I - 16)\phi_I/3 \leq \Delta\mu < 4c$, $\Pi^{\text{Ib}}_{(I,\cdot)} - \Pi^{\text{Eb}}_{(I,\cdot)} \geq 0$ if and only if $\Delta\mu \geq 32(43q_I - 28)\phi_I/675$, which implies that

Table A.5.: The Optimal $(I, \cdot)$-Policy.

Case	Condition	Pref.	Incen. Sch. $W_{(I,\cdot)}$	(n_I, n_E)	Expected Profits $\Pi_{(I,\cdot)}$
(i)	$4c \leq \Delta\mu$	I	$\alpha_g = \phi_I$ $\alpha_0 = (1 - q_I)\phi_I$	$(1, 9/16)$	$\mu_I + 9\mu_E/16 - 2d - \phi_I$
(ii)	$\max\{(19q_I - 16)\phi_I/3,$ $32(43q_I - 28)\phi_I/675\}$ $\leq \Delta\mu < 4c$	I	$\alpha_g = \phi_I$ $\alpha_0 = (3\Delta\mu - (19q_I -$ $16)\phi_I)/13$ $\gamma_g = \gamma_b = -24(\Delta\mu$ $+4c)/39$	$(1, 9/16)$	$\mu_I + 9\mu_E/16 + 6\Delta\mu/13$ $-(12q_I + 7)\phi_I/13 - 2d$
(iii)	$(157q_I - 112)\phi_I/60$ $\leq \Delta\mu < (19q_I - 16)\phi_I/3$	I	$\alpha_g = \phi_I$ $\gamma_g = \gamma_b =$ $(q_I\phi_I - \Delta\mu)/2$	$(1, 9/16)$	$\mu_I + 9\mu_E/16 - 2d$ $-(25q_I\phi_I - 9\Delta\mu)/16$
(iv)	$\Delta\mu <$ $\max\{32(43q_I - 28)\phi_I/675,$ $(157q_I - 112)\phi_I/60\}$	E	$\alpha_g = 16\phi_I/13$ $\alpha_0 = \beta_0 =$ $8(1 - q_I)\phi_I/5$ $\gamma_g = \gamma_b =$ $-8(1 - q_I)\phi_I/5$	$(13/16, 3/4)$	$13\mu_I/16 + 3\mu_E/4$ $-(7 - 2q_I)\phi_I/5 - 2d$

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

case (Ib) is optimal if $\max\{(19q_I - 16)\phi_I/3, 32(43q_I - 28)\phi_I/675\} \leq \Delta\mu < 4c$. Third, for $-13q_I\phi_I/3 \leq \Delta\mu < (19q_I - 16)\phi_I/3$, we have $\Pi^{\mathrm{Ic}}_{(I,\cdot)} - \Pi^{\mathrm{Eb}}_{(I,\cdot)} \geq 0$ if and only if $\Delta\mu \geq (157q_I - 112)\phi_I/60$, which implies that case (Ic) is optimal if $(157q_I - 112)\phi_I/60 \leq \Delta\mu < (19q_I - 16)\phi_I/3$. Finally, for $\Delta\mu < -13q_I\phi_I/3$, it is always true that $\Pi^{\mathrm{Id}}_{(I,\cdot)} - \Pi^{\mathrm{Eb}}_{(I,\cdot)} < 0$, which implies that case (Eb) is optimal for $\Delta\mu < -13q_I\phi_I/3$. Combining the above conditions yields the firm's optimal incentive scheme for an $(I,\cdot)$-policy; Table A.5 summarizes the different cases and their associated properties.

Optimality of an $(I,\cdot)$-policy. We establish the optimality conditions for an $(I,\cdot)$-policy in two steps. First, we show that an $(I,\cdot)$-policy with investment preference for internal projects (i.e., cases (i)-(iii) in Table A.5) can never be optimal. We then establish when (and when not) an $(I,\cdot)$-policy with investment preference for external projects (i.e., case (iv) in Table A.5) is optimal.

For case (i) in Table A.5 (i.e., $\Delta\mu \geq 4c$), it is true that $\Pi_{(I,\cdot)} - \Pi_{(\cdot,\cdot)} = -\mu_E/16 < 0$, which implies that this case is always dominated by a $(\cdot,\cdot)$-policy. Next, for $\max\{(5q_I - 4)\phi_I, 4(3q_I - 2)\phi_I/7\} \leq \Delta\mu < 4c$, we have $\Pi_{(I,\cdot)} - \Pi_{(\cdot,\cdot)} = -\mu_I/26 - 5\mu_E/208 + 2c/13 \geq 0$ and $\Pi_{(I,\cdot)} - \Pi_{(E,E)} = 19\mu_I/13 - 187\mu_E/208 - (12q_I + 7)\phi_I/13 \geq 0$ if and only if $\mu_E \leq -128(1 - q_I)/(29(2q_I - 1))$, which is a contradiction. Similarly, for $\max\{(19q_I - 16)\phi_I/3, 32(43q_I - 28)\phi_I/675\} \leq \Delta\mu < (5q_I - 4)\phi_I$, we have $\Pi_{(I,\cdot)} - \Pi_{(\cdot,\cdot)} = -17\mu_I/104 + 21\mu_E/208 + (73q_I - 56)\phi_I/104 \geq 0$ and $\Pi_{(I,\cdot)} - \Pi_{(E,E)} = 19\mu_I/13 - 187\mu_E/208 - (12q_I + 7)\phi_I/13 \geq 0$ if and only if $\mu_I \geq (896q_I - 895)/(2q_I - 1)$, which can never be true in the assumed parameter interval. Together, the last two cases establish the suboptimality of case (ii) in Table A.5. Finally, for $\max\{-13q_I\phi_I/3, (157q_I - 112)\phi_I/60\} \leq \Delta\mu < (19q_I - 16)\phi_I/3$, we have $\Pi_{(I,\cdot)} - \Pi_{(\cdot,\cdot)} = -\mu_I/16 + q_I\phi_I/16 \geq 0$ and $\Pi_{(I,\cdot)} - \Pi_{(E,E)} = 25\mu_I/16 - \mu_E - 25q_I\phi_I/16 \geq 0$ if and only if $\mu_E \leq 0$, which is yet another contradiction that establishes the suboptimality of case (iii) in Table A.5.

We now conclude the proof by establishing when case (iv) in Table A.5 designates the firm's optimal resource allocation policy. In particular, it is straightforward to show that this case can be optimal only if $\Delta\mu < \max\{(5q_I -$

$4)\phi_I, 4(3q_I-2)\phi_I/7\}$ and $\Delta\mu < \max\{32(43q_I-28)\phi_I/675, (157q_I-112)\phi_I/60\}$. Now, assume that those conditions are satisfied. Then, an $(I,\cdot)$-policy is optimal if and only if (I) $\Pi_{(I,\cdot)} - \Pi^{(iii)}_{(\cdot,\cdot)} = -13\mu_I/16 + 3\mu_E/4 + (81q_I-56)\phi_I/40 \geq 0$, (II) $\Pi_{(I,\cdot)} - \Pi^{(iv)}_{(\cdot,\cdot)} = 3\mu_I/16 - \mu_E/4 + (1-q_I)\phi_I/10 \geq 0$, (III) $\Pi_{(I,\cdot)} - \Pi_{(E,E)} = 13\mu_I/16 - \mu_E/4 - (7-2q_I)\phi_I/5 \geq 0$, and (IV) $\Pi_{(I,\cdot)} - \Pi_{(I,I)} = -3\mu_I/16 + 3\mu_E/4 - 2(1-q_I)\phi_I/5 - 2d \geq 0$. Combining our parameter assumptions with conditions (I), (II), and (III) yields conditions (b) and (c) in the proposition. Moreover, for condition (b) to be non-empty, we need $q_I \geq 68/77$, which leads to condition (a) in the proposition. Last, condition (d) is an immediate consequence of condition (IV).

(ii) Akin to an $(I,\cdot)$-policy, when the firm employs an $(E,\cdot)$-policy, it allocates its unassigned resources only to the ex-post most promising project. The firm's investment preference (i.e., I or E) for its unassigned resources is thus again determined endogenously as an outcome of the firm's incentive design. Hence, to find the firm's optimal incentive scheme, we must solve two separate optimization problems—one for each alternative investment preference—and then compare the optimal profits associated with the different solutions.

Preference for internal projects. Suppose the firm seeks to design an incentive scheme that (a) maximizes its expected profits, but that (b) also guarantees that the firm always prefers internal over external projects when allocating unassigned resources (i.e., condition (RA') holds). In that case, the firm must solve the following optimization problem to arrive at an optimal incentive scheme:

$$\begin{aligned}
\max_{W} \ \Pi_{(E,\cdot)}(W) = \frac{3}{4}\mu_I + \frac{13}{16}\mu_E - \frac{3}{4}(q_I(\alpha_g + \beta_g) + (1-q_I)(\alpha_b + \beta_b)) \\
- \frac{5}{4}(\alpha_0 + \beta_0) \ - \frac{13}{8}(q_E\gamma_g + (1-q_E)\gamma_b) - \frac{19}{8}\gamma_0 - 2w_0 - 2d \qquad \text{(A.25)} \\
\text{s.t. } 6(q_I\alpha_g + (1-q_I)\alpha_b - \alpha_0) \geq \\
2(q_I\beta_g + (1-q_I)\beta_b - \beta_0) + (q_E\gamma_g + (1-q_E)\gamma_b - \gamma_0) \qquad \text{(A.26)} \\
6((1-q_I)\alpha_g + q_I\alpha_b - \alpha_0) \leq \\
2(q_I\beta_g + (1-q_I)\beta_b - \beta_0) + (q_E\gamma_g + (1-q_E)\gamma_b - \gamma_0) \qquad \text{(A.27)} \\
6(2q_I - 1)(\alpha_g - \alpha_b) \geq 32c \qquad \text{(A.28)} \\
w_i(a^*, \theta) \geq 0 \qquad \text{(A.29)} \\
q_I(v_I - \alpha_g - \beta_g) + (1-q_I)(w_I - \alpha_b - \beta_b) - 2\gamma_0 \\
\geq q_E(v_E - 2\gamma_g) + (1-q_E)(w_E - 2\gamma_b) - K - \alpha_0 - \beta_0. \qquad \text{(A.30)}
\end{aligned}$$

Given that this optimization problem is an LP, we can derive the optimal solution from the KKT conditions, which reveal that the optimal incentive scheme changes as a function of $\Delta\mu$. Table A.6 summarizes the properties of the optimal solution to (A.25)-(A.30) by detailing (a) the optimal incentives, (b) the associated expected profits, and (c) the binding constraints. Last, we note that irrespective of $\Delta\mu$, the firm invests, on expectation, in $n_I = 1-\mathbb{P}(r_1 = b, r_2 = b) = 3/4$ internal projects, and $n_E = \mathbb{P}(r_3 = g, r_4 = g)\big(2\mathbb{P}(r_1 = b, r_2 = b) + \big(1 - \mathbb{P}(r_1 = b, r_2 = b)\big)\big) + \mathbb{P}(r_3 = g, r_4 = b) + \mathbb{P}(r_3 = b, r_4 = g) = 13/16$ external projects.

Preference for external projects. Now suppose that the firm seeks to design an incentive scheme that (a) maximizes its expected profits, but that (b) guarantees that the firm always prefers external over internal projects when allocating unassigned resources (i.e., condition (RA') is reversed). In that case, the solution to the following optimization problem gives the firm's optimal

Table A.6.: Partial Resource Commitment to External Projects and Preference for Internal Projects.

Case	Condition	Incentive Scheme $W_{(E,\cdot)}$	Expected Profits $\Pi_{(E,\cdot)}$	Binding Constraints
(Ia)	$4(4q_I - 3)\phi_I/3$ $\leq \Delta\mu$	$\alpha_g = 4\phi_I/3$ $\alpha_0 = 2(1 - q_I)\phi_I$ $\beta_g = \beta_b = -2(1 - q_I)\phi_I$	$3\mu_I/4 + 13\mu_E/16$ $-2d - \phi_I$	(A.27), (A.28), and nine of (A.29)
(Ib)	$-8q_I\phi_I/3 \leq \Delta\mu$ $< 4(4q_I - 3)\phi_I/3$	$\alpha_g = 4\phi_I/3$ $\alpha_0 = -\Delta\mu/2 + 2q_I\phi_I/3$ $\beta_g = \beta_b = \Delta\mu/2 - 2q_I\phi_I/3$	$3\mu_I/4 + 13\mu_E/16 - 2d$ $+\Delta\mu/4 - 4q_I\phi_I/3$	(A.28), (A.30), and nine of (A.29)
(Ic)	$\Delta\mu < -8q_I\phi_I/3$	$\alpha_g = -\Delta\mu/(2q_I)$ $\alpha_0 = -3\Delta\mu/4$ $\beta_g = \beta_b = 3\Delta\mu/4$	$3\mu_I/4 + 13\mu_E/16 - 2d$ $+3\Delta\mu/4$	(A.26), (A.30), and nine of (A.29)

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

Table A.7.: Partial Resource Commitment to External Projects and Preference for External Projects.

Case	Condition	Incentive Scheme $W_{(E,\cdot)}$	Expected Profits $\Pi_{(E,\cdot)}$	Binding Constraints
(Ea)	$16(3 - 2q_I)\phi_I/9$ $< \Delta\mu$	$\alpha_g = 16\phi_I/9$ $\beta_g = (\Delta\mu - 16q_I\phi_I/9)/q_I$	$9\mu_I/16 + \mu_E$ $-9\Delta\mu/16 - 2d$	(A.34), (A.36), and eleven of (A.35)
(Eb)	$16q_I\phi_I/9 < \Delta\mu$ $\leq 16(3 - 2q_I)\phi_I/9$	$\alpha_g = 16\phi_I/9$ $\alpha_0 = \beta_0 = -\Delta\mu/2$ $+8(3 - 2q_I)\phi_I/9$ $\gamma_g = \gamma_b = \Delta\mu/2$ $-8(3 - 2q_I)\phi_I/9$ $\beta_g = \Delta\mu/q_I + 16\phi_I/9$	$9\mu_I/16 + \mu_E - \Delta\mu/8$ $-7(3 - 2q_I)\phi_I/9 - 2d$	(A.33),(A.34), (A.36), and six of (A.35)
(Ec)	$\Delta\mu \leq 16q_I\phi_I/9$	$\alpha_g = 16\phi_I/9$ $\alpha_0 = \beta_0 = 8(1 - q_I)\phi_I/3$ $\gamma_g = \gamma_b = -8(1 - q_I)\phi_I/3$	$9\mu_I/16 + \mu_E$ $-(7 - 4q_I)\phi_I/3 - 2d$	(A.33),(A.34), and eight of (A.35)

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

incentive scheme:

$$\max_W \ \Pi_{(E,\cdot)}(W) = \frac{9}{16}\mu_I + \mu_E - \frac{9}{16}(q_I(\alpha_g+\beta_g)+(1-q_I)(\alpha_b+\beta_b)) - \frac{23}{16}(\alpha_0+\beta_0)$$
$$-2(q_E\gamma_g+(1-q_E)\gamma_b) - 2\gamma_0 - 2w_0 - 2d \tag{A.31}$$
$$\text{s.t. } 3(q_I\alpha_g+(1-q_I)\alpha_b-\alpha_0) \geq q_I\beta_g+(1-q_I)\beta_b-\beta_0 \tag{A.32}$$
$$3((1-q_I)\alpha_g+q_I\alpha_b-\alpha_0) \leq q_I\beta_g+(1-q_I)\beta_b-\beta_0 \tag{A.33}$$
$$9(2q_I-1)(\alpha_g-\alpha_b) \geq 64c \tag{A.34}$$
$$w_i(a^*,\theta) \geq 0 \tag{A.35}$$
$$q_I(v_I-\alpha_g-\beta_g)+(1-q_I)(w_I-\alpha_b-\beta_b)-2\gamma_0$$
$$\leq q_E(v_E-2\gamma_g)+(1-q_E)(w_E-2\gamma_b)-K-\alpha_0-\beta_0 \tag{A.36}$$

This optimization problem is again an LP, and an optimal incentive scheme $W_{(E,\cdot)}$ can thus be found by checking the KKT conditions. As before, the optimal incentive scheme changes structurally as a function of $\Delta\mu$. Table A.7 summarizes the properties of the optimal solution to (A.31)-(A.36) by detailing (a) the optimal incentives, (b) the associated expected profits, and (c) the binding constraints. Last, we note that irrespective of $\Delta\mu$, the firm invests, on expectation, in $n_I = \big(1-\mathbb{P}(r_3=g,r_4=g)\big)\big(1-\mathbb{P}(r_1=b,r_2=b)\big) = 9/16$ internal projects, and $n_E = 2\mathbb{P}(r_3=g,r_4=g)+\mathbb{P}(r_3=g,r_4=b)+\mathbb{P}(r_3=b,r_4=g) = 1$ external projects.

The optimal incentive scheme. We now derive the optimal incentive scheme by comparing the different cases in Tables A.6 and A.7. We begin by noting that $4(4q_I-3)\phi_I/3 < 16q_I\phi_I/9$; hence we can establish the suboptimality of cases (Ea) and (Eb) by showing that case (Ia) always dominates cases (Ea) and (Eb). In particular, for $\Delta\mu > 16(3-2q_I)\phi_I/9$, we have $\Pi^{\text{Ia}}_{(E,\cdot)} - \Pi^{\text{Ea}}_{(E,\cdot)} = 3\Delta\mu/4 - \phi_I > 0$; and for $16q_I\phi_I/9 < \Delta\mu \leq 16(3-2q_I)\phi_I/9$, we have $\Pi^{\text{Ia}}_{(E,\cdot)} - \Pi^{\text{Eb}}_{(E,\cdot)} = 5\Delta\mu/16 + 2(6-7q_I)\phi_I/9 > 0$.

Next, we establish when (and when not) case (Ec) is optimal. First, for $\Delta\mu \geq 4(4q_I-3)\phi_I/3$, we have $\Pi^{\text{Ia}}_{(E,\cdot)} - \Pi^{\text{Ec}}_{(E,\cdot)} = 3\Delta\mu/16 + 4(1-q_I)\phi_I/3 > 0$,

Table A.8.: The Optimal $(E,\cdot)$-Policy.

Case	Condition	Pref.	Incen. Sch. $W_{(E,\cdot)}$	(n_I, n_E)	Expected Profits $\Pi_{(E,\cdot)}$
(i)	$4(4q_I - 3)\phi_I/3 \leq \Delta\mu$	I	$\alpha_g = 4\phi_I/3$ $\alpha_0 = 2(1-q_I)\phi_I$ $\beta_g = \beta_b = -2(1-q_I)\phi_I$	$(3/4, 13/16)$	$3\mu_I/4 + 13\mu_E/16$ $-2d - \phi_I$
(ii)	$\max\{-8q_I\phi_I/3,$ $16(8q_I - 7)\phi_I/21\}$ $\leq \Delta\mu < 4(4q_I - 3)\phi_I/3$	I	$\alpha_g = 4\phi_I/3$ $\alpha_0 = -\Delta\mu/2 + 2q_I\phi_I/3$ $\beta_g = \beta_b = \Delta\mu/2-$ $2q_I\phi_I/3$	$(3/4, 13/16)$	$3\mu_I/4 + 13\mu_E/16 - 2d$ $+\Delta\mu/4 - 4q_I\phi_I/3$
(iii)	$-16(7 - 4q_I)\phi_I/45$ $\leq \Delta\mu < -8q_I\phi_I/3$	I	$\alpha_g = -\Delta\mu/(2q_I)$ $\alpha_0 = -3\Delta\mu/4$ $\beta_g = \beta_b = 3\Delta\mu/4$	$(3/4, 13/16)$	$3\mu_I/4 + 13\mu_E/16 - 2d$ $+3\Delta\mu/4$
(iv)	$\Delta\mu <$ $\max\{16(8q_I - 7)\phi_I/21,$ $-16(7 - 4q_I)\phi_I/45\}$	E	$\alpha_g = 16\phi_I/9$ $\alpha_0 = \beta_0 =$ $8(1-q_I)\phi_I/3$ $\gamma_g = \gamma_b =$ $-8(1-q_I)\phi_I/3$	$(9/16, 1)$	$9\mu_I/16 + \mu_E$ $-(7 - 4q_I)\phi_I/3 - 2d$

Notes. For each case, any incentive payments that are not displayed in the table have an optimal value of zero.

and thus case (Ia) is optimal. Second, for $-8q_I\phi_I/3 \leq \Delta\mu < 4(4q_I-3)\phi_I/3$, $\Pi^{\text{Ib}}_{(E,\cdot)} - \Pi^{\text{Ec}}_{(E,\cdot)} \geq 0$ holds if and only if $\Delta\mu \geq 16(8q_I-7)\phi_I/21$, which implies that case (Ib) is optimal if $\max\{-8q_I\phi_I/3, 16(8q_I-7)\phi_I/21\} \leq \Delta\mu < 4(4q_I-3)\phi_I/3$. Third, for $\Delta\mu < -8q_I\phi_I/3$, $\Pi^{\text{Ic}}_{(E,\cdot)} - \Pi^{\text{Ec}}_{(E,\cdot)} \geq 0$ if and only if $\Delta\mu \geq -16(7-4q_I)\phi_I/45$, which implies that case (Ic) is optimal if $-16(7-4q_I)\phi_I/45 \leq \Delta\mu < -8q_I\phi_I/3$. Combining the above conditions yields the firm's optimal incentive scheme for an $(E,\cdot)$-policy; Table A.8 summarizes the different cases and their associated properties.

Optimality of an $(E,\cdot)$*-policy.* We establish the optimality conditions for an $(E,\cdot)$-policy in three steps. First, we show that an $(E,\cdot)$-policy with investment preference for external projects (i.e., case (iv) in Table A.8) can never be optimal. Next, we proceed to exclude case (iii) in Table A.8 as an optimal resource allocation policy. We then establish when (and when not) cases (i) and (ii) in Table A.8 are optimal.

To exclude case (iv) in Table A.8, suppose initially that $(17q_I-12)\phi_I/8 \leq \Delta\mu < \max\{16(8q_I-7)\phi_I/21, -16(7-4q_I)\phi_I/45\}$. Then we have $\Pi_{(E,\cdot)} - \Pi_{(\cdot,\cdot)} = -17\mu_I/16 + \mu_E + (71q_I-56)\phi_I/24 < 0$. Now suppose that $\Delta\mu < \max\{4(3q_I-2)\phi_I/7, (17q_I-12)\phi_I/8\}$; in this case, it holds that $\Pi_{(E,\cdot)} - \Pi_{(\cdot,\cdot)} = -\mu_I/16 - 5(1-q_I)\phi_I/6 < 0$. It follows immediately that case (iv) is always strictly dominated by a $(\cdot,\cdot)$-policy.

We now turn to case (iii) in Table A.8: if $-16(7-4q_I)\phi_I/45 \leq \Delta\mu < -8q_I\phi_I/3$, then $\Pi_{(E,\cdot)} - \Pi_{(\cdot,\cdot)} = 14\mu_I/16 - 15\mu_E/16 + (3-q_I)\phi_I/2 < 0$, which implies that case (iii) is never optimal.

We now conclude the proof by establishing when cases (i) and (ii) in Table A.8 present the firm's optimal resource allocation policy. We begin our argument with case (ii). First, suppose that $(17q_I-12)\phi_I/8 \leq \Delta\mu < (5q_I-4)\phi_I$. In that case, we have $\Pi_{(E,\cdot)} - \Pi^{(iii)}_{(\cdot,\cdot)} = -5\mu_I/8 + 9\mu_E/16 + 7q_I\phi_I/24 \geq 0$ and $\Pi_{(E,\cdot)} - \Pi_{(E,E)} = \mu_I - 7\mu_E/16 - 4q_I\phi_I/3 \geq 0$ if and only if $\mu_I \leq (324-327q_I)\phi_I/24$, which is impossible. In any other case, for case (ii) to be optimal, we require that $\Pi_{(E,\cdot)} - \Pi^{(ii)}_{(\cdot,\cdot)} = -\mu_I/2 + 7\mu_E/16 + (3-2q_I)\phi_I/6 \geq 0$, $\Pi_{(E,\cdot)} - \Pi^{(iv)}_{(\cdot,\cdot)} = 3\mu_I/8 - 7\mu_E/16 - (11q_I-9)\phi_I/6 \geq 0$, and $\Pi_{(E,\cdot)} - \Pi_{(E,E)} = \mu_I - 7\mu_E/16 -$

$4q_I\phi_I/3 \geq 0$. From those conditions, it follows that case (ii) is optimal only if (I) $8\mu_I/7 - 8(3-2q_I)\phi_I/21 \leq \mu_E \leq \min\{6\mu_I/7 - 8(11q_I-9)\phi_I/21, 16\mu_I/7 - 64q_I\phi_I/21\}$ and (II) $(10q_I-3)\phi_I/3 \leq \mu_I \leq 4(12-13q_I)\phi_I/3$. Moreover, these inequalities can only hold if $q_I \leq 51/62$, thus yielding condition (a) in the proposition.

Next, consider case (i). This case can never be optimal if $\Delta\mu \geq 4c$, because $\Pi_{(E,\cdot)} - \Pi^{(i)}_{(\cdot,\cdot)} = -\mu_I/4 + 3\mu_E/16 < 0$. In any other case, we need $\Pi_{(E,\cdot)} - \Pi^{(ii)}_{(\cdot,\cdot)} = -3\mu_I/4 + 11\mu_E/16 + 2c \geq 0$, $\Pi_{(E,\cdot)} - \Pi^{(iv)}_{(\cdot,\cdot)} = \mu_I/8 - 3\mu_E/16 + (1-q_I)\phi_I/2 \geq 0$, and $\Pi_{(E,\cdot)} - \Pi_{(E,E)} = 3\mu_I/4 - 3\mu_E/16 - \phi_I \geq 0$ for an optimality of case (i). This is equivalent to asking that (III) $12(\mu_I - 32c)/11 \leq \mu_E \leq \min\{4\mu_I - 16\phi_I/3, 2\mu_I/3 + 8(1-q_I)\phi_I/3\}$ and (IV) $(25-6q_I)\phi_I/12 \leq \mu_I \leq 4(8-5q_I)\phi_I/7$. Combining all of the above conditions yields conditions (a)-(c) in the proposition.

Finally, for $\Pi_{(E,\cdot)} - \Pi_{(I,I)} \geq 0$, we must have $d \leq \max\{13\mu_E/32 - \mu_I/8, 9\mu_E/32 - (4q_I-3)\phi_I/6\}$, which gives condition (d) in the proposition. □

Appendix B

Proofs of Chapter III

Proof. Proof of proposition 3.1: First, we derive the optimization problem corresponding with this strategy, and then we characterize its optimal solution:

The optimizaion problem for the N strategy: The firm maximizes its expected profits, $\pi_N = p \cdot \{Pr(s_E = g)[q_E(v_E^h - \gamma^h) + (1 - q_E)(w_E - \gamma^l) - \alpha^n] + Pr(s_E = b)[Pr(s_I = g)(q_I(v_I - \alpha^h) + (1 - q_I)(w_I - \alpha^l) - \gamma^n) + Pr(s_I = b)(-\alpha^n - \gamma^n)]\} + (1 - p) \cdot \{Pr(s_I = g)[q_I(v_I - \alpha^h) + (1 - q_I)(w_I - \alpha^l) - \gamma^n] + Pr(s_I = b)[Pr(s_E = g)(q_E(v_E^l - \gamma^h) + (1 - q_E)(w_E - \gamma^l) - \alpha^n) + Pr(s_E = b)(-\alpha^n - \gamma^n)]\} - \delta$. We now derive the explicit form of constraints; to ensure preference for internal when $v_E = v_E^l$ we need (Pref.) constraint $q_I(v_I - \alpha^h) + (1 - q_I)(w_I - \alpha^l) - \gamma^n \geq q_E(v_E^l - \gamma^h) + (1 - q_E)(w_E - \gamma^l) - k - \alpha^n$. for truth-telling constraints (IC-g) and (IC-b) the required utilities are derived as follows $\mathcal{U}(m_I = g|s_I = g, e = h, \mathcal{P} = N) = p \cdot \{Pr(s_E = g)[q_E\gamma^h + (1 - q_E)\gamma^l + \alpha^n] + Pr(s_E = b)[q_I\alpha^h + (1 - q_I)\alpha^l + \gamma^n]\} + (1 - p) \cdot \{q_I\alpha^h + (1 - q_I)\alpha^l + \gamma^n\} + \delta \geq \mathcal{U}(m_I = b|s_I = g, e = h, \mathcal{P} = N) = Pr(s_E = g)[q_E\gamma^h + (1 - q_E)\gamma^l + \alpha^n] + Pr(s_E = b)[\alpha^n + \gamma^n] + \delta$, similarly $\mathcal{U}(m_I = b|s_I = b, e = h, \mathcal{P} = N) = Pr(s_E = g)[q_E\gamma^h + (1 - q_E)\gamma^l + \alpha^n] + Pr(s_E = b)[\alpha^n + \gamma^n] + \delta \geq \mathcal{U}(m_I = g|s_I = b, e = h, \mathcal{P} = N) = p \cdot \{Pr(s_E = g)[q_E\gamma^h + (1 - q_E)\gamma^l + \alpha^n] + Pr(s_E = b)[(1 - q_I)\alpha^h + q_I\alpha^l + \gamma^n]\} + (1 - p) \cdot \{(1 - q_I)\alpha^h + q_I\alpha^l + \gamma^n\} + \delta$. Canceling out identical terms gives the desired constraints. Next, we derive the constraint (IC-e), the required utilities are derived as follows: $\mathcal{U}(e = h, m = s, \mathcal{P} = N) = P(s_I = g)\mathcal{U}(m_I = g|s_I = g, e = h, \mathcal{P} = N) + P(s_I = b)\mathcal{U}(m_I = b|s_I =$

$b, e = h, \mathcal{P} = N) - c \geq \mathcal{U}(e = l, m = s, \mathcal{P} = N) = P(s_I = g)\mathcal{U}(m_I = g|s_I = g, e = l, \mathcal{P} = N) + P(s_I = b)\mathcal{U}(m_I = b|s_I = b, e = l, \mathcal{P} = N)$. for *limited liability* (LL) we must make sure any possible final payment is non-zero, $\delta+\alpha^h+\gamma^n \geq 0, \delta+\alpha^l+\gamma^n \geq 0, \delta+\alpha^n+\gamma^n \geq 0, \delta+\alpha^n+\gamma^h \geq 0, \delta+\alpha^n+\gamma^l \geq 0$.

The optimal contract under the N strategy: Since the objective function and constraints are linear, the KKT implies that the feasibility of the corresponding primal and dual solutions, and complementary slackness conditions are *necessary* and *sufficient* for optimality (Ruszczynski 2011). For $8q_I c/((2q_I - 1)(2-p)) \leq \mu_I - \mu_E^l$: $\alpha^{h*} = 4\phi/(2-p)$, $\alpha^{n*} = 4(1-q_I)\phi$, $\gamma^{h*} = \gamma^{l*} = -4(1-q_I)\phi$ the rest of variables equal to zero, and $\Pi_N^* = \frac{2-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l - \phi$; constraints (IC-b), (IC-e), the second and the last two (LL) constraints are binding. For $8((1-p)q_I - (2-p)(1-q_I))c/(((1-p)(2-p)(2q_I-1)) \leq \mu_I - \mu_E^l < 8q_I c/((2q_I-1)(2-p))$: $\alpha^{h*} = 4\phi/(2-p)$, $\alpha^{n*} = -4(-2pq_I + p + 3q_I - 2)\phi/(2-p) + (1-p)(\mu_I - \mu_E^l)$, $\gamma^{h*} = \gamma^{l*} = 8c - (2-p)(\mu_I - \mu_E^l)$ the rest of variables equal to zero, and $\Pi_N^* = \frac{2-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l - (\frac{(p(2q_I-1)+2)\phi}{2-p} - \frac{p(\mu_i - \mu_e^l)}{2})$; constraints (Pref.), (IC-b), (IC-e), and the second (LL) constraint are binding. For $-8q_I c/((1-p)(2-p)(2q_I-1)) \leq \mu_I - \mu_E^l < 8((1-p)q_I - (2-p)(1-q_I))c/((1-p)(2-p)(2q_I-1))$: $\alpha^{h*} = 4\phi/(2-p)$, $\gamma^{h*} = \gamma^{l*} = -(\mu_I - \mu_E^l) + 4q_I\phi/(2-p)$ the rest of variables equal to zero, and $\Pi_N^* = \frac{2-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l - (\frac{3q_I\phi}{2-p} - \frac{(1+p)(\mu_I - \mu_E^l)}{4})$; constraints (Pref.), (IC-e), and the second and third (LL) constraints are binding. For $\mu_I - \mu_E^l < -8qc/((1-p)(2-p)(2q_I-1))$: $\alpha^{h*} = -(1-p)(\mu_I - \mu_E^l) + 4(1-q_I)\phi/(2-p)$, $\alpha^{l*} = -(\mu_I - \mu_E^l)(1-p) - 4q_I\phi/(2-p)$, $\gamma^{h*} = \gamma^{l*} = -(\mu_I - \mu_E^l)(2-p)$ the rest of variables equal to zero, and $\Pi_N^* = \frac{2-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l - (\frac{-(2-p)(\mu_I - \mu_E^l)}{2})$; constraints (Pref.), (IC-g), (IC-e), and the third (LL) constraint are binding. □

Proof. Proof of proposition 3.2: First, we derive the optimization problem corresponding with this strategy, and then we characterize its optimal solution:

The optimizaion problem for the R strategy: $\pi_R = p \cdot \{Pr(s_E = g)[q_E(v_E^h - \gamma^h) + (1-q_E)(w_E - \gamma^l) - \alpha^n] + Pr(s_E = b)[-\alpha^n - \gamma_n]\} + (1-p) \cdot \{Pr(s_I = g)[q_I(v_I - \alpha^h) + (1-q_I)(w_I - \alpha^l) - \gamma^n] + Pr(s_I = b)[Pr(s_E = g)(q_E(v_E^l - \gamma^h) +$

$(1-q_E)(w_E-\gamma^l)-\alpha^n)+Pr(s_E=b)(-\alpha^n-\gamma^n)]\}-\delta$. We now derive the explicit form of constraints; to ensure preference for internal when $v_E=v_E^l$ we need (Pref.) constraint $q_I(v_I-\alpha^h)+(1-q_I)(w_I-\alpha^l)-\gamma^n\geq q_E(v_E^l-\gamma^h)+(1-q_E)(w_E-\gamma^l)-k-\alpha^n$. for truth-telling constraints (IC-g) and (IC-b) the required utilities are derived as follows $\mathcal{U}(m_I=g|s_I=g,e=h,\mathcal{P}=R)=p\cdot\{Pr(s_E=g)[q_E\gamma^h+(1-q_E)\gamma^l+\alpha^n]+Pr(s_E=b)[q_I\alpha^h+(1-q_I)\alpha^l+\gamma^n]\}+(1-p)\cdot\{q_I\alpha^h+(1-q_I)\alpha^l+\gamma^n\}+\delta\geq\mathcal{U}(m_I=b|s_I=g,e=h,\mathcal{P}=R)=Pr(s_E=g)[q_E\gamma^h+(1-q_E)\gamma^l+\alpha^n]+Pr(s_E=b)[\alpha^n+\gamma^n]+\delta$, similarly $\mathcal{U}(m_I=b|s_I=b,e=h,\mathcal{P}=R)=Pr(s_E=g)[q_E\gamma^h+(1-q_E)\gamma^l+\alpha^n]+Pr(s_E=b)[\alpha^n+\gamma^n]+\delta\geq\mathcal{U}(m_I=g|s_I=b,e=h,\mathcal{P}=R)=p\cdot\{Pr(s_E=g)[q_E\gamma^h+(1-q_E)\gamma^l+\alpha^n]+Pr(s_E=b)[\alpha^n+\gamma^n]\}+(1-p)\cdot\{(1-q_I)\alpha^h+q_I\alpha^l+\gamma^n\}+\delta$. Canceling out identical terms gives the desired constraints. Next, we derive the constraint (IC-e), the required utilities are derived as follows: $\mathcal{U}(e=h,m=s,\mathcal{P}=R)=P(s_I=g)\mathcal{U}(m_I=g|s_I=g,e=h,\mathcal{P}=R)+P(s_I=b)\mathcal{U}(m_I=b|s_I=b,e=h,\mathcal{P}=R)-c\geq\mathcal{U}(e=l,m=s,\mathcal{P}=R)=P(s_I=g)\mathcal{U}(m_I=g|s_I=g,e=l,\mathcal{P}=R)+P(s_I=b)\mathcal{U}(m_I=b|s_I=b,e=l,\mathcal{P}=R)$. for *limited liability* (LL) we must make sure any possible final payment is non-zero, $\delta+\alpha^h+\gamma^n\geq0,\delta+\alpha^l+\gamma^n\geq0,\delta+\alpha^n+\gamma^n\geq0,\delta+\alpha^n+\gamma^h\geq0,\delta+\alpha^n+\gamma^l\geq0$.

The optimal contract under the R strategy: Since the objective function and constraints are linear, the KKT implies that the feasibility of the corresponding primal and dual solutions, and complementary slackness conditions are *necessary* and *sufficient* for optimality (Ruszczynski 2011). For $4q_Ic/(2q_I-1)\leq\mu_I-\mu_E^l$: $\alpha^{h*}=2\phi$, $\alpha^{n*}=4(1-q_I)\phi$, $\gamma^{h*}=\gamma^{l*}=-4(1-q_I)\phi$ the rest of variables equal to zero, and $\Pi_R^*=\frac{1-p}{4}\mu_I+\frac{p}{2}\mu_E^h+\frac{1-p}{4}\mu_E^l-(1+p-2pq_I)\phi$; constraints (IC-b), (IC-e), the second and the last two (LL) constraints are binding. For $4(3q_I-2)c/(2q_I-1)\leq\mu_I-\mu_E^l<4q_Ic/(2q_I-1)$: $\alpha^{h*}=2\phi$, $\alpha^{n*}=-2(3q_I-2)\phi+(\mu_I-\mu_E^l)$, $\gamma^{h*}=\gamma^{l*}=8c-2(\mu_I-\mu_E^l)$ the rest of variables equal to zero, and $\Pi_R^*=\frac{1-p}{4}\mu_I+\frac{p}{2}\mu_E^h+\frac{1-p}{4}\mu_E^l-(1+p-2pq_I)\phi$; constraints (Pref.), (IC-b), (IC-e), and the second (LL) constraint are binding. For $-4q_Ic/(2q_I-1)\leq\mu_I-\mu_E^l<4(3q_I-2)c/(2q_I-1)$: $\alpha^{h*}=2\phi$, $\gamma^{h*}=\gamma^{l*}=-(\mu_I-\mu_E^l)+2q_I\phi$ the rest of variables equal to zero, and

$\Pi_R^* = \frac{1-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l - (q_I(3-p)\phi/2 - (1+p)(\mu_I - \mu_E^l)/4)$; constraints (Pref.), (IC-e), and the second and third (LL) constraints are binding. For $\mu_I - \mu_E^l < -4q_I c/(2q_I - 1)$: $\alpha^{h*} = -(\mu_I - \mu_E^l) + 2(1-q_I)\phi$, $\alpha^{l*} = -(\mu_I - \mu_E^l) - 2q_I\phi$, $\gamma^{h*} = \gamma^{l*} = -2(\mu_I - \mu_E^l)$ the rest of variables equal to zero, and $\Pi_R^* = \frac{1-p}{4}\mu_I + \frac{p}{2}\mu_E^h + \frac{1-p}{4}\mu_E^l + (\mu_I - \mu_E^l)$; constraints (Pref.), (IC-g), (IC-e), and the third (LL) constraint are binding. □

Proof. Proof of proposition 3.3: To derive the conditions under which the decision to reveal or not to reveal is relevant, we compare the optimal solution of both strategies against the optimal solutions of strong preference for internal and strong preference external cases. As such, this proof consists of three parts. First, we derive the optimal solution of strong preference cases. Second, we compare the two revealing and not revealing strategies with strong preference for external and determine when weak preference yields higher objective value. Third, we compare the two strategies now with strong preference for internal and determine when weak preference yields higher objective value. The combination of second and third parts would give the universal conditions under which the decision is relevant.

The optimal contract under the strong preference: The respective optimization problems of two strong preference cases have the same structure as the problems under the two strategies discussed extensively in the proofs of propositions 3.1 and 3.2. The major differences are that under strong preference for external the (Pref.) constraint is $q_I(v_I - \alpha^h) + (1-q_I)(w_I - \alpha^l) - \gamma^n \leq q_E(v_E^l - \gamma^h) + (1-q_E)(w_E - \gamma^l) - k - \alpha^n$, ensuring preference for external project even if $v_E = v_E^l$, and under strong preference for internal the (Pref.) constraint is $q_I(v_I - \alpha^h) + (1-q_I)(w_I - \alpha^l) - \gamma^n \geq q_E(v_E^h - \gamma^h) + (1-q_E)(w_E - \gamma^l) - k - \alpha^n$, ensuring preference for internal project even if $v_E = v_E^h$. We omit the extensive derivation of the optimization problems. The optimal solution to the case of strong preference for internal is: For $\mu_I - \mu_E^h \geq 4q_I c/(2q_I - 1)$, $\pi_{SI}^* = \mu_I/2 + p\mu_E^h/4 + (1-p)\mu_E^l/4 - 2c/(2q_I - 1)$. For $4(3q_I - 2)c/(2q_I - 1) \leq \mu_I - \mu_E^h < 4q_I c/(2q_I - 1)$, $\pi_{SI}^* = \mu_I/2 + p\mu_E^h/4 + (1-p)\mu_E^l/4 - 2c/(2q_I - 1)$.

For $-4q_Ic/(2q_I-1) \le \mu_I - \mu_E^h < 4(3q_I-2)c/(2q_I-1)$, $\pi_{SI}^* = \mu_I/2 + p\mu_E^h/4 + (1-p)\mu_E^l/4 - (3q_Ic/(2q_I-1) - (\mu_I - \mu_E^h)/4)$. For $\mu_I - \mu_E^h < -4q_Ic/(2q_I-1)$, $\pi_{SI}^* = \mu_I/2 + p\mu_E^h/4 + (1-p)\mu_E^l/4 + (\mu_I - \mu_E^h)$. The optimal solution to the case of strong preference for external is: For $\mu_I - \mu_E^l \le 8q_Ic/(2q_I-1)$, $\pi_{SE}^* = \mu_I/4 + p\mu_E^h/2 + (1-p)\mu_E^l/2 - 2c/(2q_I-1)$. For $8q_Ic/(2q_I-1) < \mu_I - \mu_e^l$, $\pi_{SE}^* = \mu_I/4 + p\mu_E^h/2 + (1-p)\mu_E^l/2 - (\mu_I - \mu_E^l)/(4q_I)$.

Weak preference vs. strong preference for external: By comparing the optimal solutions of two weak preference strategies against the optimal solution of strong preference for external, we get the conditions under which senior management does not have a strong preference for the external project: Suppose that $\frac{8q_Ic}{(2-p)(2q_I-1)} \le \mu_I - \mu_E^l$, the firm would always have a weak preference for an internal project. Suppose that $\max\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{4(3q_I-2)c}{2q_I-1}\} \le \mu_I - \mu_E^l < \frac{8q_Ic}{(2-p)(2q_I-1)}$, the firm would have a weak preference if $\mu_E^l \le \max\{\frac{1-2p}{1-p}\mu_I + \frac{8pc}{1-p}, \mu_I - \frac{16pq_Ic}{(1+p)(2-p)(2q_I-1)}\}$. Suppose that $\frac{4(3q_I-2)c}{2q_I-1} \le \mu_I - \mu_E^l < \frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}$, the firm would have a weak preference if $\mu_E^l \le \max\{\frac{1-2p}{1-p}\mu_I + \frac{8pc}{1-p}, \mu_I - \frac{4(3q_I+p-2)c}{(2-p)(2q_I-1)}\}$. Suppose that $\max\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{-4q_Ic}{2q_I-1}\} \le \mu_I - \mu_E^l < \frac{4(3q_I-2)c}{2q_I-1}$, the firm would have a weak preference if $\mu_E^l \le \max\{\frac{2-p}{2}\mu_I + \frac{2(pq_I-3q_I+2)c}{2q_I-1}, \mu_I - \frac{16pq_Ic}{(1+p)(2-p)(2q_I-1)}\}$. Suppose that $\frac{-4q_Ic}{2q_I-1} \le \mu_I - \mu_E^l < \min\{\frac{8((1-p)q_I-(2-p)(1}{(1-p)(2-p)(2q_I}$ the firm would have a weak preference if $\mu_E^l \le \max\{\frac{2-p}{2}\mu_I + \frac{2(pq_I-3q_I+2)c}{2q_I-1}, \mu_I - \frac{4(3q_I+p-2)c}{(2-p)(2q_I-1)}\}$. Suppose that $\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)} \le \mu_I - \mu_E^l < \frac{-4q_Ic}{2q_I-1}$, the firm would have a weak preference if $\mu_E^l \le \mu_I - \frac{16pq_Ic}{(1+p)(2-p)(2q_I-1)}$. Suppose that $\frac{-8q_Ic}{(1-p)(2-p)(2q_I-1)} \le \mu_I - \mu_E^l < \min\{\frac{-4q_Ic}{2q_I-1}, \frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}\}$, the firm would have a weak preference if $\mu_E^l \le \mu_I - \frac{4(3q_I+p-2)c}{(2-p)(2q_I-1)}$. Suppose that $\mu_I - \mu_E^l < \frac{-8q_Ic}{(1-p)(2-p)(2q_I-1)}$, the firm would always have a strong preference for an external project. The conditions imply that for the decision to be relevant, μ_E^l needs to be sufficiently small relative to μ_I.

Weak preference vs. strong preference for internal: By comparing the optimal solutions of two weak preference strategies against the optimal solution of strong preference for internal, we get the conditions under which senior management does not have a strong preference for the internal project: Suppose that $\frac{4(3q_I-2)c}{2q_I-1} \le \mu_I - \mu_E^h$, if $\frac{8q_Ic}{(2-p)(2q_I-1)} \le \mu_I - \mu_E^l$, the firm would always have a strong preference for an internal project, if $\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)} \leq \mu_I - \mu_E^l < \frac{8q_Ic}{(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq -\mu_I + 2\mu_E^l + \frac{16q_Ic}{(2-p)(2q_I-1)}$, if $\mu_I - \mu_E^l < \frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq -\frac{1}{p}\mu_I + \frac{1+p}{p}\mu_E^l + \frac{8(3q_I+p-2)c}{p(2-p)(2q_I-1)}$. Suppose that $\frac{-4q_Ic}{2q_I-1} \leq \mu_I - \mu_E^h < \frac{4(3q_I-2)c}{2q_I-1}$, if $\frac{8q_Ic}{(2-p)(2q_I-1)} \leq \mu_I - \mu_E^l$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\mu_I - \frac{4(3q_I-2)c}{(1+p)(2q_I-1)}, \frac{2p+1}{p+1}\mu_I + \frac{4(2+2p-3q_I-4pq_I)c}{(1+p)(2q_I-1)}\}$. if $\max\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{4(3q_I-2)c}{2q_I-1}\} \leq \mu_I - \mu_E^l < \frac{8q_Ic}{(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{1-p}{1+p}\mu_I + \frac{2p}{1+p}\mu_E^l + \frac{4(4-2p-6q_I+7pq_I)c}{(1+p)(2-p)(2q_I-1)}, \frac{2p+1}{p+1}\mu_I + \frac{4(2+2p-3q_I-4pq_I)c}{(1+p)(2q_I-1)}\}$. if $\frac{4(3q_I-2)c}{2q_I-1} \leq \mu_I - \mu_E^l < \frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\mu_E^l + \frac{12pq_Ic}{(1+p)(2-p)(2q_I-1)}, \frac{2p+1}{p+1}\mu_I + \frac{4(2+2p-3q_I-4pq_I)c}{(1+p)(2q_I-1)}\}$. if $\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)} \leq \mu_I - \mu_E^l < \frac{4(3q_I-2)c}{2q_I-1}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{1-p}{1+p}\mu_I + \frac{2p}{1+p}\mu_E^l + \frac{4(4-2p-6q_I+7pq_I)c}{(1+p)(2-p)(2q_I-1)}, \frac{p}{1+p}\mu_I + \mu_E^l - \frac{4pq_Ic}{(1+p)(2q_I-1)}\}$. if $\mu_I - \mu_E^l < \min\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{4(3q_I-2)c}{2q_I-1}\}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\mu_E^l + \frac{12pq_Ic}{(1+p)(2-p)(2q_I-1)}, \frac{p}{1+p}\mu_I + \mu_E^l - \frac{4pq_Ic}{(1+p)(2q_I-1)}\}$. Suppose that $\mu_I - \mu_E^h < \frac{-4q_Ic}{2q_I-1}$, if $\frac{8q_Ic}{(2-p)(2q_I-1)} \leq \mu_I - \mu_E^l$, the firm would always have a weak preference for an internal project. if $\max\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{4(3q_I-2)c}{2q_I-1}\} \leq \mu_I - \mu_E^l < \frac{8q_Ic}{(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{4-p}{4+p}\mu_I + \frac{2p}{4+p}\mu_E^l + \frac{8(2pq_I-p+2)c}{(4+p)(2-p)(2q_I-1)}, \frac{2p+4}{p+4}\mu_I + \frac{8(1+p-2pq_I)c}{(p+4)(2q_I-1)}\}$. if $\frac{4(3q_I-2)c}{2q_I-1} \leq \mu_I - \mu_E^l < \frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{3}{4+p}\mu_I + \frac{1+p}{4+p}\mu_E^l + \frac{24q_Ic}{(4+p)(2-p)(2q_I-1)}, \frac{2p+4}{p+4}\mu_I + \frac{8(1+p-2pq_I)c}{(p+4)(2q_I-1)}\}$. if $\max\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{-4q_Ic}{2q_I-1}\} \leq \mu_I - \mu_E^l < \frac{4(3q_I-2)c}{2q_I-1}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{4-p}{4+p}\mu_I + \frac{2p}{4+p}\mu_E^l + \frac{8(2pq_I-p+2)c}{(4+p)(2-p)(2q_I-1)}, \frac{3+p}{4+p}\mu_I + \frac{1+p}{4+p}\mu_E^l + \frac{4q_I(3-p)c}{(4+p)(2q_I-1)}\}$. if $\frac{-4q_Ic}{2q_I-1} \leq \mu_I - \mu_E^l < \min\{\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}, \frac{4(3q_I-2)c}{2q_I-1}\}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{3}{4+p}\mu_I + \frac{1+p}{4+p}\mu_E^l + \frac{24q_Ic}{(4+p)(2-p)(2q_I-1)}, \frac{3+p}{4+p}\mu_I + \frac{1+p}{4+p}\mu_E^l + \frac{4q_I(3-p)c}{(4+p)(2q_I-1)}\}$. if $\frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)} \leq \mu_I - \mu_E^l < \frac{-4q_Ic}{2q_I-1}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{4-p}{4+p}\mu_I + \frac{2p}{4+p}\mu_E^l + \frac{8(2pq_I-p+2)c}{(4+p)(2-p)(2q_I-1)}, \frac{2p}{4+p}\mu_I + \frac{4}{4+p}\mu_E^l\}$. if $\frac{-8q_Ic}{(1-p)(2-p)(2q_I-1)} \leq \mu_I - \mu_E^l < \min\{\frac{-4q_Ic}{2q_I-1}, \frac{8((1-p)q_I-(2-p)(1-q_I))c}{(1-p)(2-p)(2q_I-1)}\}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{3}{4+p}\mu_I + \frac{1+p}{4+p}\mu_E^l +$

$\frac{24q_I c}{(4+p)(2-p)(2q_I-1)}, \frac{2p}{4+p}\mu_I + \frac{4}{4+p}\mu_E^l\}$. if $\mu_I - \mu_E^l < \frac{-8q_I c}{(1-p)(2-p)(2q_I-1)}$, the firm would have a weak preference iff $\mu_E^h \geq \min\{\frac{3p}{4+p}\mu_I + \frac{4-2p}{4+p}\mu_E^l, \frac{2p}{4+p}\mu_I + \frac{4}{4+p}\mu_E^l\}$. The conditions imply that for the decision to be relevant, μ_E^h needs to be sufficiently large relative to μ_I. □

Proof. Proof of proposition 3.4: To find out the optimal strategy, we need to compare the optimal revealing strategy against the not revealing. To this end, we compare the optimal values of the objective functions corresponding with each case in proposition 3.1 with the ones from proposition 3.2. This would derive the conditions in this proposition. □

Appendix C

Proofs of Chapter IV

Proof. Proof of Lemma 4.1: We show in next two parts of this proof, the existence of a pure-strategy (subgame) PBE in second-round (part a) and then in the first round (part b). Given that effort spaces are nonempty convex subsets of $\mathbb{R}$ and that utility functions are continuous in all players' actions, we follow this procedure: In both parts, we first prove that there is at least one solution to the first-order optimality condition. And then prove the concavity of each player's utility function in his own action. This would be sufficient to prove the existence of pure-strategy equilibria (Fudenberg and Tirole 1991).

part (a): There exists pure-strategy Perfect Bayesian Nash equilibrium for contestant i's second-round effort.

After observing the signal realization s, the contestant i updates his belief on first-round performance shocks and chooses his second-round effort e_{i2} to maximize his expected second-round utility u_{i2}.

$$\begin{aligned} u_{i2} = & A\mathbb{E}_{\mu_s}[G_{\omega_{j2}-\omega_{i2}}(v_{i1} + \alpha_i r_2(e_{i2}) - v_{j1} - \alpha_j r_2(e_{j2}))] - c_2(e_{i2}), \\ & \forall i, j \in \{a, b\} : i \neq j. \end{aligned} \tag{C.1}$$

The first-order optimality condition for e_{i2} is:

$$\frac{du_{i2}}{de_{i2}} = \alpha_i r_2'(e_{i2}) A \mathbb{E}_{\mu_s}[g_{\omega_{j2}-\omega_{i2}}(v_{i1} + \alpha_i r_2(e_{i2}) - v_{j1} - \alpha_j r_2(e_{j2}))] - c_2'(e_{i2}) = 0 \quad \forall i, j \in \{a, b\} : i \neq j. \tag{C.2}$$

Given that $r_2'(0) > 0$, $c_t'(0) = 0$, and $c_t'(\bar{e})/r_t'(\bar{e}) > A \sup g_{\omega_{bt}-\omega_{at}}$, there exists at least one point $e^* \in E$ such that $h_2'(e^*) = c_2'(e^*)$.
Now, the sufficient condition for existence of *equilibrium* second-round effort, is the *strict* concavity (*quasicavity*) of u_{i2} in e_{i2}. That is:

$$\alpha_i r_2''(e_{i2}) A \mathbb{E}_{\mu_s}[g_{\omega_{j2}-\omega_{i2}}(v_{i2} - v_{j2})] + \alpha_i^2 r_2'(e_{i2})^2 A \mathbb{E}_{\mu_s}[g'_{\omega_{j2}-\omega_{i2}}(v_{i2} - v_{j2})] < c_2''(e_{i2}), \forall e_{i2} \in E, \forall i, j \in \{a, b\} : i \neq j \tag{C.3}$$

Remember that $e_{it} \in [0, \bar{e}]$. Let us denote $\underline{g}_{\omega_{b2}-\omega_{a2}} = \inf_x g_{\omega_{j2}-\omega_{i2}}(x)$. Then the following provides the sufficient condition for the above to hold:

$$\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)| < \inf_{e \in [0,\bar{e}]} (c_2''(e) - \alpha r_2''(e) A \underline{g}_{\omega_{b2}-\omega_{a2}}) / (A(\alpha r_2'(e))^2) \tag{C.4}$$

The above inequality depends on the shape of $g_{\omega_{b2}-\omega_{a2}}$. Roughly speaking, the second-order conditions will be satisfied if the distribution of $\omega_{b2} - \omega_{a2}$ is sufficiently dispersed and/or the marginal cost of effort rises sufficiently rapidly (this is in accordance with the literature; see Meyer 1992).

Then $e_{i2|s}$ denotes the second-round equilibrium effort of player i and is a real implicit function. Since $\partial u_{i2}'/\partial e_{i2} \neq 0$, according to *implicit function* theorem, it is a differentiable function of first-round efforts and the posterior belief:

$$e_{i2|s} = \arg\max_{e_{i2} \in E} u_{i2}(e \mid e_{j2} = e_{j2|s}), \quad \forall i, j \in \{a, b\} : i \neq j \tag{C.5}$$

Part (b): There exists pure-strategy Perfect Bayesian Nash equilibrium for contestant i's first-round effort.

After observing the feedback policy P chosen by the contest holder, the contestant i chooses his first-round effort e_{i1} to maximize his expected first-round utility u_{i1}.

$$\begin{aligned}u_{i1} =& A\mathbb{E}_{\tau,\mu_s}[G_{\omega_{j2}-\omega_{i2}}(\sigma_i + \alpha_i r_1(e_{i1}) + \omega_{i1} + \alpha_i r_2(e_{i2|s}) - \sigma_j - \alpha_j r_1(e_{j1}) \\ &- \omega_{j1} - \alpha_j r_2(e_{j2|s}))] - c_1(e_{i1}) - \mathbb{E}_{\tau,\mu_s}[c_2(e_{i2|s})], \quad \forall i,j \in \{a,b\} : i \neq j.\end{aligned} \tag{C.6}$$

Assuming $\Delta v_2 = \sigma_a + \alpha r_1(e_{a1}) + \omega_{a1} + \alpha r_2(e_{a2|s}) - \sigma_b - r_1(e_{b1}) - \omega_{b1} - r_2(e_{b2|s})$, the first-order optimality condition for e_{i1} is: (remember that $g_{\omega_{b2}-\omega_{a2}}(z) = g_{\omega_{a2}-\omega_{b2}}(-z)$ for all z)

$$\begin{aligned}\frac{du_{i1}}{de_{i1}} =& A\mathbb{E}_{\tau,\mu_s}[\big(\alpha_i r_1'(e_{i1}) + \alpha_i r_2'(e_{i2|s})de_{i2|s}/de_{i1} - \alpha_j r_2'(e_{j2|s})de_{j2|s}/de_{i1}\big) \\ g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] &- c_1'(e_{i1}) - \mathbb{E}_{\tau,\mu_s}[c_2'(e_{i2|s})de_{i2|s}/de_{i1}] = 0, \quad \forall i,j \in \{a,b\} : i \neq j.\end{aligned} \tag{C.7}$$

Reminder: From the first-order optimality conditions for second-round effort, we have $c_2'(e_{i2|s}) = \alpha_i r_2'(e_{i2|s})A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)]$. So, based on the *law of iterated expectations* and *envelope theorem*, we can simplify the above equation:

$$\begin{aligned}\frac{du_{i1}}{de_{i1}} = A\mathbb{E}_{\tau,\mu_s}[\big(\alpha_i r_1'(e_{i1}) - \alpha_j r_2'(e_{j2|s})de_{j2|s}/de_{i1}\big)\, g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] - c_1'(e_{i1}) = 0, \\ \forall i,j \in \{a,b\} : i \neq j.\end{aligned} \tag{C.8}$$

From C.2, we know that $c_2'(e_{i2|s}) = \alpha_i r_2'(e_{i2|s})A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(v_{a2} - v_{b2})]$ and $\eta_2(e_{b2|s}) = A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(v_{a2} - v_{b2})]$, and we define $\Delta e_1 = \alpha \cdot r_1(e_{a1}) - r_1(e_{b1})$, then we can rewrite C.8 as follows:

$$\begin{aligned} \frac{du_{a1}}{de_{a1}} =& \alpha r_1'(e_{a1})\mathbb{E}_\tau[\eta_2(e_{b2|s}) - dc_2(e_{b2|s})/d\Delta e_1] - c_1'(e_{a1}) \\ \frac{du_{b1}}{de_{b1}} =& r_1'(e_{b1})\mathbb{E}_\tau[\eta_2(e_{b2|s}) + n \cdot dc_2(e_{b2|s})/d\Delta e_1] - c_1'(e_{b1}) \end{aligned} \tag{C.9}$$

Given that $r_2'(0) > 0$, $c_t'(0) = 0$, and $c_t'(\bar{e})/r_t'(\bar{e}) > A \sup g_{\omega_{bt}-\omega_{at}}$, if it can be shown that $\eta_2(e_{b2|s}) - dc_2(e_{b2|s})/d\Delta e_1 > 0$ and $\eta_2(e_{b2|s}) + n \cdot dc_2(e_{b2|s})/d\Delta e_1 > 0$, then there exists at least one point $e_{i1} = e_i^*$ such that $\frac{du_{i1}}{de_{i1}} = 0$. A sufficient condition for both to hold is:

$$|de_{b2|s}/d\Delta e_1| < \eta_2(e_{b2|s})/(n \cdot c_2'(e_{b2|s})) \tag{C.10}$$

Since $e_{b2|s}$ is a differentiable function of Δe_1, according to implicit function theorem, we can derive the following from C.2:

$$\left(\frac{du_{i2}'}{d\Delta e_1} = \frac{\partial u_{i2}'}{\partial \Delta e_1} + \frac{\partial u_{i2}'}{\partial e_{b2|s}}\frac{de_{b2|s}}{d\Delta e_1} + \frac{\partial u_{i2}'}{\partial \mu^1}\frac{d\mu^1}{d\Delta e_1} = 0 \rightarrow \frac{de_{b2|s}}{d\Delta e_1} = \frac{-\frac{\partial u_{i2}'}{\partial \Delta e_1}}{\frac{\partial u_{i2}'}{\partial e_{b2|s}}}\right)$$

$$de_{b2|s}/d\Delta e_1 = \frac{A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}'(\Delta v_2)]}{\eta_2'(e_{b2|s}) - (\alpha m - 1)r_2'(e_{b2|s})A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}'(\Delta v_2)]} \tag{C.11}$$

Then a more sufficient condition is:

$$\sup_x |g_{\omega_{b2}-\omega_{a2}}'(x)| < \inf_{e \in [0,\bar{e}]} \eta_2'(e)/(A(2n-1)r_2'(e)) \tag{C.12}$$

so under the above condition there exists at least one point $e_{i1} = e_i^*$ such that $\frac{du_{i1}}{de_{i1}} = 0$. As such the set of player i's optimal first-round effort (*response function*), under the above condition, is non-empty. To prove the existence of equilibrium, we need now to show that u_{i1} is strictly concave (*quasiconcave*) in e_{i1}.

$$
\begin{aligned}
\frac{d^2u_{a1}}{de_{a1}^2} =& \alpha r_1''(e_{a1})\mathbb{E}_\tau[\eta_2(e_{b2|s}) - dc_2(e_{b2|s})/d\Delta e_1] \\
&+ (\alpha r_1'(e_{a1}))^2\mathbb{E}_\tau[\eta_2'(e_{b2|s}) \cdot de_{b2|s}/d\Delta e_1 - d^2c_2(e_{b2|s})/d\Delta e_1^2] - c_1''(e_{a1}) \\
\frac{d^2u_{b1}}{de_{b1}^2} =& r_1''(e_{b1})\mathbb{E}_\tau[\eta_2(e_{b2|s}) + n \cdot dc_2(e_{b2|s})/d\Delta e_1] \\
&- (r_1'(e_{b1}))^2\mathbb{E}_\tau[\eta_2'(e_{b2|s}) \cdot de_{b2|s}/d\Delta e_1 + n \cdot d^2c_2(e_{b2|s})/d\Delta e_1^2] - c_1''(e_{b1})
\end{aligned} \tag{C.13}
$$

The most general conditions required for the concavitiy of first-round utility functions in own action are as follows:

$$
\begin{aligned}
\mathbb{E}_\tau[d^2c_2(e_{b2|s})/d\Delta e_1^2] > \mathbb{E}_\tau[\eta_2'(e_{b2|s}) \cdot de_{b2|s}/d\Delta e_1 \\
-(c_1''(e_{a1}) - \alpha r_1''(e_{a1})(\eta_2(e_{b2|s}) - dc_2(e_{b2|s})/d\Delta e_1))/(\alpha r_1'(e_{a1}))^2] \\
n\mathbb{E}_\tau[d^2c_2(e_{b2|s})/d\Delta e_1^2] > \mathbb{E}_\tau[-\eta_2'(e_{b2|s}) \cdot de_{b2|s}/d\Delta e_1 \\
-(c_1''(e_{b1}) - r_1''(e_{b1})(\eta_2(e_{b2|s}) + n \cdot dc_2(e_{b2|s})/d\Delta e_1))/(r_1'(e_{b1}))^2]
\end{aligned} \tag{C.14}
$$

Let us assume:

$$
\begin{aligned}
h_{a0} &= (c_1''(e_{a1}) - \alpha r_1''(e_{a1})(\eta_2(e_{b2|s}) - dc_2(e_{b2|s})/d\Delta e_1))/(\alpha r_1'(e_{a1}))^2 \\
h_{b0} &= (c_1''(e_{b1}) - r_1''(e_{b1})(\eta_2(e_{b2|s}) + n \cdot dc_2(e_{b2|s})/d\Delta e_1))/(r_1'(e_{b1}))^2
\end{aligned}
$$

Keep in mind that $h_{a0}, h_{b0} > 0$. Let $e_{b2|s}' = de_{b2|s}/d\Delta e_1$. Further from chain rule we have:

$$
d^2c_2(e_{b2|s})/d\Delta e_1^2 = c_2''(e_{b2|s})(de_{b2|s}/d\Delta e_1)^2 + c_2'(e_{b2|s})d^2e_{b2|s}/d\Delta e_1^2
$$

The inequality C.4 gives lower and upper bounds on $g'_{\omega_{b2}-\omega_{a2}}$. Then $\overline{|e_{b2|s}'|} = A\overline{g'_{\omega_{b2}-\omega_{a2}}}/(\eta_2'(e_{b2|s}) - (\alpha m - 1)r_2'(e_{b2|s})A\overline{g'_{\omega_{b2}-\omega_{a2}}})$ and $\underline{|e_{b2|s}'|} = A\underline{g'_{\omega_{b2}-\omega_{a2}}}/(\eta_2'(e_{b2|s}) - (\alpha m - 1)r_2'(e_{b2|s})A\underline{g'_{\omega_{b2}-\omega_{a2}}})$. Then a sufficient condition for C.14 to hold is:

$$\begin{aligned}
&c_2'(e_{b2|s})d^2 e_{b2|s}/d\Delta e_1^2 > \\
&\eta_2'(e_{b2|s}) \cdot \overline{|e_{b2|s}'|} - c_2''(e_{b2|s})\underline{|e_{b2|s}'|}^2 - \inf_{e_{i1}\in(0,\overline{e}]} \min\{h_{a0}, (1/n)h_{b0}\} \\
&\forall e_{b2|s} \in (0, \overline{e}]
\end{aligned} \tag{C.15}$$

Let $h_{11}(e_{b2|s})$ denote the right-hand-side of the above inequality. For the left-hand-side we have:

$$\begin{aligned}
&d^2 e_{b2|s}/d\Delta e_1^2 = \\
&(A\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_2)]\eta_2'(e_{b2|s})^2 \\
&-(A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)])^2(\eta_2''(e_{b2|s}) - (n-1)r_2''(e_{b2|s})A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]))/ \\
&(\eta_2'(e_{b2|s}) - (n-1)r_2'(e_{b2|s})A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)])^3
\end{aligned} \tag{C.16}$$

Let:

$$\begin{aligned}
h_{21}(e_{b2|s}) &= (\eta_2'(e_{b2|s}) - (n-1)r_2'(e_{b2|s})\underline{g'_{\omega_{b2}-\omega_{a2}}})^3 \\
h_{22}(e_{b2|s}) &= \overline{(Ag'_{\omega_{b2}-\omega_{a2}})^2}(\eta_2''(e_{b2|s}) - (n-1)r_2''(e_{b2|s})\overline{Ag'_{\omega_{b2}-\omega_{a2}}}) \\
\overline{h_3} &= \sup_{e_{b2|s}\in(0,\overline{e}]} (h_{11}(e_{b2|s}) \cdot h_{21}(e_{b2|s})/c_2'(e_{b2|s}) + h_{22}(e_{b2|s}))/(A\eta_2(e_{b2|s})^2)
\end{aligned}$$

We can now make the condition more explicit:

$$\inf_x \mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(x)] > \overline{h_3} \tag{C.17}$$

Then $e_{i1|P}$ denotes the first-round equilibrium effort of player i and is a real implicit function. According to *implicit function* theorem it is a differentiable function of the contest-holders chosen policy:

$$e_{i1|P} = \arg\max_{e_{i1}\in E} u_{i1}(e \,|e_{j1} = e_{j1|P}), \quad \forall i,j \in \{a,b\} : i \neq j \tag{C.18}$$

□

Proof. Proof of Proposition 4.1:

Given that $\partial u'_{i2}/\partial e_{i2} \neq 0$, by *implicit function* theorem, equations 4.4 imply the second-round equilibrium efforts of both contestants, which are implicit, real, differentiable functions of first-round efforts and the posterior belief. □

Proof. Proof of Corollary 4.1:

Let $\eta_2(x) = c'_2(x)/r'_2(x)$ which is an increasing function. From equation 4.4 we know that $\eta_2(e_{a2|s}) = \alpha \cdot \eta_2(e_{b2|s})$. Thus, there exists a constant k such that $e_{a2|s} = k \cdot e_{b2|s} = k \cdot e^*_2$. Then, since $r_t(x)$ is a strictly increasing (and concave) function in x, there exists a constant m such that $r_2(e_{a2|s}) = m \cdot r_2(e_{b2|s})$. And similarly, since $c_t(x)$ is an increasing (and strictly convex) function in x, there exists a constant n such that $c_2(e_{a2|s}) = n \cdot c_2(e_{b2|s})$. ($\alpha = n/m$ and $n \geq k \geq m > 1$) □

Proof. Proof of Proposition 4.2: Given that $\partial u'_{i1}/\partial e_{i1} \neq 0$, by *implicit function* theorem, equations 4.9 imply the second-round equilibrium efforts of both contestants, which are implicit, real, differentiable functions of the given feedback policy. □

Proof. Proof of Lemma 4.2: If, $\forall i, j \in \{a, b\} : j \neq i$, (1) the first-round game is supermodular for each τ in e_{i1} and e_{j1}, and (2) u_{i1} has increasing differences in (e_{i1}, τ) for each e_{j1}, then $e_{i1|P} = \gamma_{i1}(\tau)$ would be increasing in τ (Milgrom and Roberts 1990).

For the first-round game to be supermodular for each τ, given that the effort spaces are compact sets, u_{i1} needs to have increasing differences in own effort and in rival's effort. Since u_{i1} is twice continuously differentiable, increasing differences is equivalent to $\frac{\partial^2 u_{i1}}{\partial e_{i1} \partial e_{j1}} \geq 0$ for all i and $j \neq i$ (Amir 2005).

$$\begin{aligned} u_{i1}(e_{a1}, e_{b1}, \tau) = & A\mathbb{E}_{\tau,\mu_s}[G_{\omega_{j2}-\omega_{i2}}(\alpha_i r_1(e_{i1}) + \omega_{i1} + \alpha_i r_2(e_{i2|s}) - \alpha_j r_1(e_{j1}) \\ & - \omega_{j1} - \alpha_j r_2(e_{j2|s}))] - c_1(e_{i1}) - \mathbb{E}_{\tau,\mu_s}[c_2(e_{i2|s})] \end{aligned} \tag{C.19}$$

First condition:

$$\begin{aligned}
\frac{\partial^2 u_{a1}}{\partial e_{a1}\partial e_{b1}} =& \alpha r_1'(e_{a1})r_1'(e_{b1})A\mathbb{E}_\tau[-\eta_2'(e_{b2|s})\cdot \partial e_{b2|s}/\partial\Delta e_1 + \partial^2 c_2(e_{b2|s})/\partial\Delta^2 e_1]\\
\frac{\partial^2 u_{b1}}{\partial e_{b1}\partial e_{a1}} =& \alpha r_1'(e_{a1})r_1'(e_{b1})A\mathbb{E}_\tau[\eta_2'(e_{b2|s})\cdot \partial e_{b2|s}/\partial\Delta e_1 + n\cdot\partial^2 c_2(e_{b2|s})/\partial\Delta^2 e_1]
\end{aligned} \tag{C.20}$$

For the above two cross derivatives to be non-negative, the following needs to hold:

$$\begin{aligned}
&c_2'(e_{b2|s})\cdot\partial^2 e_{b2|s}/\partial\Delta^2 e_1 \geq \eta_2'(e_{b2|s})\cdot\partial e_{b2|s}/\partial\Delta e_1 - c_2''(e_{b2|s})\cdot(\partial e_{b2|s}/\partial\Delta e_1)^2\\
&c_2'(e_{b2|s})\cdot\partial^2 e_{b2|s}/\partial\Delta^2 e_1 \geq -(1/n)\eta_2'(e_{b2|s})\cdot\partial e_{b2|s}/\partial\Delta e_1 - c_2''(e_{b2|s})\cdot(\partial e_{b2|s}/\partial\Delta e_1)^2
\end{aligned} \tag{C.21}$$

These are very similar to conditions in C.14 but stricter. This means that supermodularity implies the existence of equilibrium, which is in line with the literature (Amir 2005). A sufficient condition for the above to hold is:

$$c_2'(e_{b2|s})\cdot\partial^2 e_{b2|s}/\partial\Delta^2 e_1 \geq \eta_2'(e_{b2|s})\cdot|e_{b2|s}'| - c_2''(e_{b2|s})\cdot(e_{b2|s}')^2, \quad \forall e_{b2|s}\in(0,\overline{e}] \tag{C.22}$$

Let h_{12} denote the right-hand-side of the above inequality. Similar to C.17, we can construct a sufficient condition for the above the to hold:

$$\inf_x g''_{\omega_{b2}-\omega_{a2}}(x) > \overline{h_4} \tag{C.23}$$

In which $\overline{h_4} = \sup_{e_{b2|s}\in(0,\overline{e}]}(h_{12}(e_{b2|s})\cdot h_{21}(e_{b2|s})/c_2'(e_{b2|s}) + h_{22}(e_{b2|s}))/(A\eta_2(e_{b2|s})^2)$.

Second condition:

From C.9 we have:

$$\begin{aligned}
\frac{du_{a1}}{de_{a1}} =& \alpha r_1'(e_{a1})A\mathbb{E}_\tau[\eta_2(e_{b2|s}) - \partial c_2(e_{b2|s})/\partial\Delta e_1] - c_1'(e_{a1})\\
\frac{du_{b1}}{de_{b1}} =& r_1'(e_{b1})A\mathbb{E}_\tau[\eta_2(e_{b2|s}) + n\cdot\partial c_2(e_{b2|s})/\partial\Delta e_1] - c_1'(e_{b1})
\end{aligned}$$

By definition, for u_{a1} and u_{b1} to have increasing differences in own action and τ, the above two need to be increasing in τ.

Keeping Δe_1 fixed (partial derivative logic), let $\psi_a(e_{b2|s}) = \eta_2(e_{b2|s}) - \partial c_2(e_{b2|s})/\partial\Delta e_1$ and $\psi_b(e_{b2|s}) = \eta_2(e_{b2|s}) + n \cdot \partial c_2(e_{b2|s})/\partial\Delta e_1$. Remember that $e_{b2|s} = \gamma_{b2}(\mu_s)$. We can define $\Psi_i(\mu_s) = (\psi_i \circ \gamma_{b2})(\mu_s)$. Based on Jensesn's inequality we know if $\Psi_i(\mu_s)$ is convex in μ_s then:

$$\begin{aligned} &\mathbb{E}_s[\Psi_i(\mu_s)|\tau^u] = \Psi_i(\mathbb{E}[\mu_s]) \\ <&\mathbb{E}_s[\Psi_i(\mu_s)|\tau^m] \\ <&\mathbb{E}_s[\Psi_i(\mu_s)|\tau^i] = \mathbb{E}[\Psi_i(\mu_1)] \end{aligned} \tag{C.24}$$

which is equivalent of the function $\frac{du_{i1}}{de_{i1}}$ being increasing in τ. For $\Psi_i(\mu_s)$ to be convex in μ_s, the following should hold:

$$\frac{d^2\Psi_i(\mu_s)}{d\mu_s^2} = \frac{\partial^2\psi_i(e_{i2|s})}{\partial e_{i2|s}^2} \cdot (\frac{d\gamma_{b2}}{d\mu_s})^2 + \frac{\partial\psi_i(e_{i2|s})}{\partial e_{i2|s}} \cdot \frac{d^2\gamma_{b2}}{d\mu_s^2} \geq 0 \tag{C.25}$$

Thus, a sufficient condition for $\Psi_i(\mu_s)$ to be convex, is that γ_{b2} is convex in μ_s, and $\psi_i(e_{i2|s})$ is increasing and convex in $e_{i2|s}$.

For $\psi_i(e_{i2|s})$ to be increasing in $e_{i2|s}$:

$$-\eta_2'(e_{b2|s})/(n \cdot c_2''(e_{b2|s})) \leq e_{i2|s}' \leq \eta_2'(e_{b2|s})/c_2''(e_{b2|s}) \tag{C.26}$$

A sufficient condition for the above to hold is:

$$\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)| \leq \underline{h_5} = \inf_{e_{b2|s}\in(0,\bar{e}]} \frac{\eta_2(e_{b2|s})'^2}{A(n \cdot c_2(e_{b2|s})'' + (n-1)r_2(e_{b2|s})'\eta_2(e_{b2|s})')} \tag{C.27}$$

For $\psi_i(e_{i2|s})$ to be convex in $e_{i2|s}$:

$$-\eta_2''(e_{b2|s})/n \leq c_2'''(e_{b2|s}) \cdot e_{i2|s}' \leq \eta_2''(e_{b2|s}) \tag{C.28}$$

A sufficient condition for the above to hold is:

$$\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)| \leq \underline{h_6} = \inf_{e_{b2|s}\in(0,\bar{e}]} \frac{\eta_2(e_{b2|s})'' \cdot \eta_2(e_{b2|s})'}{A(n\cdot|c_2(e_{b2|s})'''| + (n-1)r_2(e_{b2|s})'\eta_2(e_{b2|s})'')} \tag{C.29}$$

This inequality can be satisfied only if $(\eta_2 \circ \gamma_{b2})$ is convex.

And if $\Psi_i(\Delta e_1, \mu_s)$ is concave in μ_s the order in C.24 reverses; meaning the function $\frac{du_{i1}}{de_{i1}}$ being decreasing in τ. For $\Psi_i(\mu_s)$ to be concave in μ_s, the following should hold:

$$\frac{d^2\Psi_i(\mu_s)}{d\mu_s^2} = \frac{\partial^2\psi_i(e_{i2|s})}{\partial e_{i2|s}^2}\cdot(\frac{d\gamma_{i2}}{d\mu_s})^2 + \frac{\partial\psi_i(e_{i2|s})}{\partial e_{i2|s}}\cdot\frac{d^2\gamma_{i2}}{d\mu_s^2} \leq 0 \tag{C.30}$$

Thus, a sufficient condition for $\Psi_i(\mu_s)$ to be concave, is that γ_{b2} is concave in μ_s, and $\psi_i(e_{i2|s})$ is increasing and concave in $e_{i2|s}$.

For $\psi_i(e_{i2|s})$ to be concave in $e_{i2|s}$:

$$\eta_2''(e_{b2|s}) \leq c_2'''(e_{b2|s})\cdot e'_{i2|s} \leq -\eta_2''(e_{b2|s})/n \tag{C.31}$$

A sufficient condition for the above to hold is:

$$\sup_x |g'_{\omega_{b2}-\omega_{a2}}(x)| \leq \underline{h_7} = \inf_{e_{b2|s}\in(0,\bar{e}]} \frac{-\eta_2(e_{b2|s})'' \cdot \eta_2(e_{b2|s})'}{A(n\cdot|c_2(e_{b2|s})'''| + (n-1)r_2(e_{b2|s})'\eta_2(e_{b2|s})'')} \tag{C.32}$$

This inequality can be satisfied only if $(\eta_2 \circ \gamma_{b2})$ is concave. □

Proof. Proof of lemma 4.3: We first show that if $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)] = 0$, then Δe_1 is increasing in τ given that first-round efforts are increasing, and then show that this holds true also if $|\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]|$ is sufficiently small.

Remember the first order optimality conditions:

$$\begin{aligned}
\eta_1(e_{a1|P}) =& \alpha A\mathbb{E}_\tau[\eta_2(e_{b2|s}) - c_2'(e_{b2|s})\partial e_{b2|s}/\partial\Delta e_1]\\
\eta_1(e_{b1|P}) =& A\mathbb{E}_\tau[\eta_2(e_{b2|s}) + n\cdot c_2'(e_{b2|s})\partial e_{b2|s}/\partial\Delta e_1]\\
de_{b2|s}/d\Delta e_1 =& \frac{A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]}{\eta_2'(e_{b2|s}) - (\alpha m-1)r_2'(e_{b2|s})A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]}
\end{aligned} \tag{C.33}$$

It is clear if $\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(v_2)] = 0$, then $de_{b2|s}/d\Delta e_1 = 0$ which leads to $\eta_1(e_{a1|P}) = \alpha\eta_1(e_{b1|P})$. As such, there exists a constant $m_1 > 1$ as $r_1(e_{a1|P}) = m_1 r_1(e_{b1|P})$. Therefore for any $\tau \succeq \tau'$:

$$\begin{aligned} \alpha(r_1(\gamma_{a1}(\tau)) - r_1(\gamma_{a1}(\tau'))) &= \alpha m_1(r_1(\gamma_{b1}(\tau)) - r_1(\gamma_{b1}(\tau'))) \\ &> r_1(\gamma_{b1}(\tau)) - r_1(\gamma_{b1}(\tau')) \end{aligned} \tag{C.34}$$

After rearranging we would have:

$$\alpha r_1(\gamma_{a1}(\tau)) - r_1(\gamma_{b1}(\tau)) > \alpha r_1(\gamma_{a1}(\tau')) - r_1(\gamma_{b1}(\tau')) \tag{C.35}$$

Which is the definition of Δe_1 being *strictly* increasing in τ.

Now, since equations in C.33 are continuous in $\mathbb{E}_{\omega_1}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]$, intermediate value theorem (Landau 2001) asserts that there exists a constant $\varphi \in \mathbb{R}^+$ such that $-\varphi \leq \mathbb{E}_{\omega_1}[g'_{\omega_{b2}-\omega_{a2}}(v_2)] \leq \varphi$ for which $\alpha r_1(\gamma_{a1}(\tau)) - r_1(\gamma_{b1}(\tau)) \geq \alpha r_1(\gamma_{a1}(\tau')) - r_1(\gamma_{b1}(\tau'))$. Then, by definition, if $|\mathbb{E}_{\omega_1}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]| \leq \varphi$ then Δe_1 is increasing in τ.

If first-round efforts are decreasing, by changing the inequality signs in the proof above, it is proved that if $|\mathbb{E}_{\omega_1}[g'_{\omega_{b2}-\omega_{a2}}(v_2)]| \leq \varphi$ then Δe_1 is decreasing in τ.

□

Proof. Proof of Lemma 4.4: In order to determine the functional properties, including the convexity (concavity), of the equilibrium second-round efforts, $\gamma_{i2}(\Delta e_1, \mu_s)$, in μ_s, we use the implicit function theorem. From the first-optimality condition of the second-round efforts (remember C.2):

$$\begin{aligned} \frac{du_{i2}}{de_{i2}} =& \alpha_i r'_2(e_{i2}) A \mathbb{E}_{\mu_s}[g_{\omega_{j2}-\omega_{i2}}(v_{i1} + \alpha_i r_2(e_{i2}) - v_{j1} - \alpha_j r_2(e_{j2}))] - c'_2(e_{i2}) = 0 \\ & \forall i, j \in \{a, b\} : i \neq j. \end{aligned}$$

By setting $r_2(e_{a2|s}) = m \cdot r_2(e_{b2|s})$ (see corollary 4.1), we can combine the above two equations into the following:

$$F(e_2^*, \Delta e_1, \mu_s) = A\mathbb{E}_{\mu_s}[g_{\omega_{b2}-\omega_{a2}}(v_{a1} + (n-1)r_2(e_2^*) - v_{b1})] - \eta_2(e_2^*) = 0 \tag{C.36}$$

Now, we can apply implicit function theorem to calculate the first and second derivative of $e_2^* = \gamma_{b2}(\Delta e_1, \mu_s)$ with respect to μ_s. Let F_e and F_μ be the partial derivatives of function F with respect to $e_{b2|s}$ and μ_s, respectively, and F_{xx} second order derivatives.

$$\frac{de_2^*}{d\mu_s} = \frac{-F_\mu}{F_e} \tag{C.37}$$

$$\frac{d^2 e_2^*}{d\mu_s^2} = \frac{-F_{ee} \cdot F_\mu^2 / F_e + 2F_\mu \cdot F_{e\mu} - F_{\mu\mu} \cdot F_e}{F_e^2} \tag{C.38}$$

From the second-order optimality conditions (C.4) for equilibrium second-round efforts, it can be easily verified that $F_e < 0$. Furthermore, F can be written as:

$$F = A \int_{\omega_1 \in \Omega} g_{\omega_{b2}-\omega_{a2}}(\Delta v_2)\mu_s(\omega_1)d\omega_1 - \eta_2(e_2^*) \tag{C.39}$$

From above, it is clear that F is linear in μ_s (other variables held constant); so, $F_{\mu\mu} = 0$. And for any distribution of the second-round shocks that $\lim_{x\to\pm\infty} g_{\omega_{b2}-\omega_{a2}}(x) = 0$, we would have $F_\mu = A$ and $F_{e\mu} = 0$. As a result if $F_{ee} > 0$ then $\gamma_{i2}(\Delta e_1, \mu_s)$ is convex in μ_s, and if $F_{ee} < 0$ then $\gamma_{i2}(\Delta e_1, \mu_s)$ is concave for $\forall i \in \{a, b\}$.

$$\begin{aligned} F_e =& (n-1)r_2'(e_2^*)A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] - \eta_2'(e_2^*) \\ F_{ee} =& (n-1)r_2''(e_2^*)A\mathbb{E}_{\mu_s}[g'_{\omega_{b2}-\omega_{a2}}(\Delta v_2)] + \{(n-1)r_2'(e_2^*)\}^2 A\mathbb{E}_{\mu_s}[g''_{\omega_{b2}-\omega_{a2}}(v_2)] \\ & - \eta_2''(e_2^*) \end{aligned} \tag{C.40}$$

□

Proof. Proof of Theorem 4.1: Let's first check the case of $\beta = 1$: $\Pi = \mathbb{E}[(v_{a2} + v_{b2})/2]$.

$$\begin{aligned}\Pi &= \mathbb{E}_{\tau,\omega}[\sum_t (\alpha \cdot r_t(e_{at}) + \omega_{at} + r_t(e_{bt}) + \omega_{bt})/2] \\ &= (1/2) \cdot \mathbb{E}_\tau[\sum_t \sum_i \alpha_i \cdot r_t(e_{it})] + (1/2) \cdot \mathbb{E}_\omega[\sum_t \sum_i \omega_{it}]\end{aligned} \tag{C.41}$$

It is clear from the above equation that the optimal feedback policy is the one that maximizes the first term.

$$\begin{aligned}\mathbb{E}_\tau[\sum_t \sum_i \alpha_i \cdot r(e_i)] &= \sum_i \alpha_i \cdot r_1(e_{i1|P}) + \mathbb{E}_\tau[\sum_i \alpha_i \cdot r_2(e_{i2|1})] \\ &= \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau)) + \mathbb{E}_\tau[\sum_i \alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1(\tau), \mu_s))]\end{aligned} \tag{C.42}$$

We now evaluate this expression for different classes of feedback policies:

$$\begin{aligned}P \in \mathcal{P}_I: &\quad \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau^I)) + \mathbb{E}_{\omega_1}[\sum_i \alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1^I, \mu_1))] \\ P \in \mathcal{P} \backslash \{\mathcal{P}_I \cup \mathcal{P}_U\}: &\quad \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau^P)) + \mathbb{E}_\tau[\sum_i \alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1^P, \mu_s))] \\ P \in \mathcal{P}_U: &\quad \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau^U)) + \sum_i \alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1^U, \mu_0))\end{aligned} \tag{C.43}$$

We know that $r_1(\cdot)$ is increasing; if lemma 1 (a) holds then $\gamma_{i1}(\tau)$ is increasing for all i. As such, it is clear that $\sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau^I)) \geq \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau^P)) \geq \sum_i \alpha_i \cdot r_1(\gamma_{i1}(\tau^U))$.

As for the second term let

$$l_2 : (E^2, \Delta(\Omega^2)) \to \mathbb{R} \text{ be } l_{i2}(\Delta e_1, x) = (r_2 \circ \gamma_2)(\Delta e_1, x).$$

If we keep the first argument of γ_{i2} fixed we would have:

$$P \in \mathcal{P}_U : \alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1, \mu_0)) = \alpha_i \cdot l_{i2}(\Delta e_1, \mu_0)$$
$$P \in \mathcal{P}_I : \mathbb{E}_{\omega_1}[\alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1, \mu_1))] = \alpha_i \cdot \mathbb{E}_{\omega_1}[l_2(\Delta e_1, \mu_1)]$$
$$P \in \mathcal{P} \backslash \{\mathcal{P}_I \cup \mathcal{P}_U\} : \mathbb{E}_\tau[\alpha_i \cdot r_2(\gamma_{i2}(\Delta e_1^P, \mu_s))] = \alpha_i \cdot \mathbb{E}_\tau[l_2(\Delta e_1, \mu_s)]$$

Since $\mathbb{E}_\tau[\mu_s] = \mu_0$, from Jensen's inequality we know **if** $l_2(\Delta e_1, \mu_s)$ is convex in μ_s then we always have:

$$\mathbb{E}_{\omega_1}[l_2(\Delta e_1, \mu_1)] \geq \mathbb{E}_\tau[l_2(\Delta e_1, \mu_s)] \geq l_{i2}(\Delta e_1, \mu_0)$$

And if $l_2(\Delta e_1, \mu_s)$ is concave in μ_s, the above inequalities reverse.

Now we evaluate the impact of Δe_1 on this term:

$$\Pi(P \in \mathcal{P}_U) = l_2(\Delta e_1^U, \mu_0)$$
$$\Pi(P \in \mathcal{P}_I) = \mathbb{E}_{\omega_1}[l_2(\Delta e_1^I, \mu_1)]$$
$$\Pi(P \in \mathcal{P} \backslash \{\mathcal{P}_I \cup \mathcal{P}_U\}) = \mathbb{E}_\tau[l_2(\Delta e_1^P, \mu_s)]$$

Now given that lemmas 4.2 (i), 4.3, and 4.5 hold, and as we know that r_2 is increasing, we would have the following for any i:

$$\mathbb{E}_{\omega_1}[l_2(\Delta e_1^I, \mu_1)] \geq \mathbb{E}_s[l_2(\Delta e_1^P, \mu_s)] \geq l_{i2}(\Delta e_1^U, \mu_0)$$

Now combining both, proves the theorem (the reverse is proved similarly).

$\square$

Proof. Proof of Theorem 4.2: Now we can check the case of $\beta = 0$: $\Pi = \mathbb{E}[max\{v_{a2}, v_{b2}\}]$.

Let:

$$p_i = G_{\omega_{j1}+\omega_{j2}-\omega_{i1}-\omega_{i2}}(\alpha_i \cdot r_1(e_{i1}) + \alpha_i \cdot r_2(e_{i2}) - \alpha_j \cdot r_1(e_{j1}) - \alpha_j \cdot r_2(e_{j2})))$$

$$p_a + p_b = 1$$

Now considering the law of iterated expectations, we can write the expected profits as:

$$
\begin{aligned}
\Pi =&\mathbb{E}_{\tau,\omega}[max\{v_{a2}, v_{b2}\}] \\
=&\mathbb{E}_{\tau,\omega}[\mathbb{1}_{\{\sum_t(\alpha \cdot r_t(e_{at})+\omega_{at})>\sum_t(r_t(e_{bt})+\omega_{bt})\}} \cdot v_{a2} \\
&+ \mathbb{1}_{\{\sum_t(\alpha \cdot r_t(e_{at})+\omega_{at})<\sum_t(r_t(e_{bt})+\omega_{bt})\}} \cdot v_{b2}] \\
=&\mathbb{E}_{\tau,\omega}[\mathbb{1}_{\{v_{a2}>v_{b2}\}} \cdot \sum_t \alpha \cdot r_t(e_{at}) + \mathbb{1}_{\{v_{a2}>v_{b2}\}} \cdot \sum_t \omega_{at} + \mathbb{1}_{\{v_{a2}<v_{b2}\}} \cdot \sum_t \cdot r_t(e_{bt}) \\
&+ \mathbb{1}_{\{v_{a2}<v_{b2}\}} \cdot \sum_t \omega_{bt}] \\
=&\mathbb{E}_{\tau}[p_a \cdot \sum_t \alpha \cdot r_t(e_{at}) + (1-p_a) \cdot \sum_t r_t(e_{bt})] \\
&+ \mathbb{E}_{\tau}[\mathbb{E}_{\omega}[\mathbb{1}_{\{v_{a2}>v_{b2}\}} \cdot \sum_t \omega_{at} + (1-\mathbb{1}_{\{v_{a2}>v_{b2}\}}) \cdot \sum_t \omega_{bt}|\mu_s]]
\end{aligned}
\tag{C.44}
$$

Assuming $\omega = \sum_t(\omega_{at} - \omega_{bt})$, the last expectation of the above equation can be re-written:

$$
\begin{aligned}
&\mathbb{E}_{\tau}[\mathbb{E}_{\omega}[\mathbb{1}_{\{v_{a2}>v_{b2}\}} \cdot \omega|\mu_s]] + \mathbb{E}_{\omega}[\sum_t \omega_{bt}] \\
&= \mathbb{E}_{\tau}\left[\mathbb{E}_{\omega}[\omega|\omega > \sum_t(r_t(e_{bt}) - \alpha \cdot r_t(e_{at}))]\right] + \mathbb{E}_{\omega}[\sum_t \omega_{bt}]
\end{aligned}
\tag{C.45}
$$

We can define $\lambda_{\omega}(x) = \mathbb{E}_{\omega}[\omega|\omega > x]$ as the conditional expectation function of the aggregate shock difference and for C.44 have:

$$\begin{aligned}\Pi &= \mathbb{E}_{\tau,\omega}[max\{v_{a2}, v_{b2}\}] \\ &= \mathbb{E}_{\tau}[p_a \cdot \sum_t \alpha \cdot r_t(e_{at}) + (1-p_a) \cdot \sum_t r_t(e_{bt})] + \mathbb{E}_{\tau}[\lambda_\omega(\sum_t (r_t(e_{bt}) - \alpha \cdot r_t(e_{at})))] \\ &+ \mathbb{E}_{\omega}[\sum_t \omega_{bt}]\end{aligned} \tag{C.46}$$

It is clear from the above equation that the optimal feedback policy is the one that maximizes the first two terms.

$$\begin{aligned}&\mathbb{E}_{\tau}[p_a \cdot \sum_t \alpha \cdot r_t(e_{at}) + (1-p_a) \cdot \sum_t r_t(e_{bt}) + \lambda_\omega(\sum_t (r_t(e_{bt}) - \alpha \cdot r_t(e_{at})))] \\ &= \sum_i \alpha_i \mathbb{E}_{\tau}[p_i] r_1(\gamma_{i1}(\tau)) + \sum_i \mathbb{E}_{\tau}[\alpha_i \cdot p_i \cdot r_2(\gamma_{i2}(\Delta e_1, \mu_s))] + \mathbb{E}_{\tau}[\lambda_\omega(\tau, \mu_s)]\end{aligned} \tag{C.47}$$

We now evaluate these expressions for different classes of feedback policies:

$$\begin{aligned}&P \in \mathcal{P}_I : \\ &\sum_i \alpha_i \mathbb{E}_{\omega}[p_i] r_1(\gamma_{i1}(\tau^I)) + \sum_i \mathbb{E}_{\omega}[\alpha_i \cdot p_i \cdot r_2(\gamma_{i2}(\Delta e_1^I, \mu_1))] + \mathbb{E}_{\omega}[\lambda_\omega(\tau^I, \mu_1)] \\ &P \in \mathcal{P} \backslash \{\mathcal{P}_I \cup \mathcal{P}_U\} : \\ &\sum_i \alpha_i \mathbb{E}_{\tau}[p_i] r_1(\gamma_{i1}(\tau^P)) + \sum_i \mathbb{E}_{\tau}[\alpha_i \cdot p_i \cdot r_2(\gamma_{i2}(\Delta e_1^P, \mu_s))] + \mathbb{E}_{s}[\lambda_\omega(\tau^P, \mu_s)] \\ &P \in \mathcal{P}_U : \\ &\sum_i \alpha_i p_i r_1(\gamma_{i1}(\tau^U)) + \sum_i \alpha_i \cdot p_i \cdot r_2(\gamma_{i2}(\Delta e_1^U, \mu_0)) + \lambda_\omega(\tau^U, \mu_0)\end{aligned} \tag{C.48}$$

Assume $\tilde{\Pi}_{\beta=0} = \sum_i \alpha_i p_i r_1(\gamma_{i1}(\tau)) + \sum_i \alpha_i \cdot p_i \cdot r_2(\gamma_{i2}(\Delta e_1, \mu_s)) + \lambda_\omega(\tau, \mu_s)$.

We can break the analysis in two parts corresponding with two rounds. Regarding the first-round, given that $\gamma_{i1}(\tau)$ is increasing (lemma 4.2 (i) holds), $\tilde{\Pi}_{\beta=0}$ needs to be increasing in first-round efforts for fully informative policy to be optimal. (We know that $r_1(\cdot)$ and p_i are increasing in γ_{i1}; so if $\lambda_\omega()$ does not create problems, this condition is easily satisfied!)

Regarding the second-round, first we need $\tilde{\Pi}_{\beta=0}$ to be increasing in second-round efforts and then, according to Jensen's inequality, we need it to be convex in μ_s for fully informative policy to be optimal. Further if lemmas 4.3, and 4.5 hold second-round efforts are also positively impacted by the first-round efforts, given a fully informative policy.

If all the above-mentioned conditions hold the fully informative policy would be optimal (the reverse is proved similarly).

□

Bibliography

Adner, R. (2007). Real options and resource reallocation processes. In Reuer, J. and Tong, T., editors, *Real Options Theory (Advances in Strategic Management, Vol. 24)*, pages 363–372. Emerald Publishing, Bingley, UK.

Ales, L., Cho, S.-H., and Körpeoğlu, E. (2017). Optimal award scheme in innovation tournaments. *Operations Research*, 65(3):693–702.

Ales, L., Cho, S.-H., and Körpeoğlu, E. (2021). Innovation tournaments with multiple contributors. *Production and Operations Management*, 30(6):1772–1784.

Ali, A., Kalwani, M., and Kovenock, D. (1993). Selecting product development projects: Pioneering versus incremental innovation strategies. *Management Science*, 39(3):255–274.

Amir, R. (2005). Supermodularity and complementarity in economics: An elementary survey. *Southern Economic Journal*, pages 636–660.

Aoyagi, M. (2010). Information feedback in a dynamic tournament. *Games and Economic Behavior*, 70(2):242–260.

Arora, A., Belenzon, S., and Suh, J. (2022). Science and the market for technology. *Management Science*, page forthcoming.

Arora, A. and Fosfuri, A. (2003). Licensing the market for technology. *Journal of Economic Behavior and Organization*, 52(2):277–295.

Arora, A. and Gambardella, A. (2010). The market for technology. In Hall, B. and Rosenberg, N., editors, *Handbook of the Economics of Innovation*, chapter 15, pages 641–678. Elsevier, Amsterdam, The Netherlands.

Balakrishnan, R. (1991). Information acquisition and resource allocation decisions. *The Accounting Review*, 60(1):120–139.

Bhaskaran, S. and Krishnan, V. (2009). Effort, revenue, and cost sharing mechanisms for collaborative new product development. *Management Science*, 55(7):1152–1169.

Bhaskaran, S. and Ramachandran, K. (2011). Managing technology selection an development risk in competitive environments. *Production and Operations Management*, 20(4):541–555.

Bhattacharya, S., Gaba, V., and Hasija, S. (2015). A comparison of milestone-based and buyout options contracts for coordinating R&D partnerships. *Management Science*, 61(5):963–978.

Birkinshaw, J. (2001). Strategies for managing internal competition. *California Management Review*, 44(1):21–38.

Boudreau, K. and Lakhani, K. (2009). How to manage outside innovation: Competitive markets or collaborative communities? *MIT Sloan Management Review*, 50(4):69–75.

Bower, J. (1970). *Managing the Resource Allocation Process*. Harvard Business School Press, Cambridge, MA.

Brown, S., Goetzmann, W., Liang, B., and Schwarz, C. (2012). Trust and delegation. *Journal of Financial Economics*, 103(2):221–234.

Burkill, H. (1984). Monotonic functions on partially ordered sets. *Journal of Combinatorial Theory, Series A*, 37(3):248–256.

Cabral, L., Cozzi, G., Denicolò, V., Spagnolo, G., and Zanza, M. (2006). Procuring innovations. In Dimitri, N., Piga, G., and Spagnolo, G., editors, *Handbook of Procurement*, chapter 19, pages 483–529. Cambridge University Press, Cambridge, UK.

Caskey, J., Nagar, V., and Petacchi, P. (2010). Reporting bias with an audit committee. *The Accounting Review*, 85(2):447–481.

Cassiman, B. and Veugelers, R. (2006). In search of complementarity in innovation strategy: Internal R&D and external knowledge acquisition. *Management Science*, 52(1):68–82.

Chao, R. and Kavadias, S. (2008). A theoretical framework for managing the new product development portfolio: When and how to use strategic buckets. *Management Science*, 54(5):907–921.

Chao, R., Kavadias, S., and Gaimon, C. (2009). Revenue driven resource allocation: Funding authority, incentives, and new product development portfolio management. *Management Science*, 55(9):1556–1569.

Chao, R., Lichtendahl Jr., K., and Grushka-Cockayne, Y. (2014). Incentives in a stage-gate-process. *Production and Operations Management*, 23(8):1286–1298.

Che, Y.-K. and Gale, I. (2003). Optimal design of research contests. *American Economic Review*, 93(3):646–671.

Chesbrough, H. (2003). *Open innovation: The New Imperative for Creating and Profiting from Technology*. Harvard Business School Press, Cambridge, MA.

Clark, K. and Fujimoto, T. (1991). Product development performance. *Harvard Business School Press, Boston, MA*.

Coff, R. (1999). How buyers cope with uncertainty when acquiring firms in knowledge-intensive industries: Caveat emptor. *Organization Science*, 10(2):144–161.

Cohen, W. and Levinthal, D. (1989). Innovation and learning: The two faces of R&D. *Economic Journal*, 99(397):569–596.

Cooper, R., Edgett, S., and Kleinschmidt, E. (2001). *Portfolio Management for New Products*. 2nd ed., Perseus Books, New York, NY.

Crama, P., De Reyck, B., and Degraeve, Z. (2008). Milestone payments or royalties? Contract design for R&D licensing. *Operations Research*, 56(6):1539–1552.

Crama, P., De Reyck, B., and Taneri, N. (2017). Licensing contracts: Control rights, options, and timing. *Management Science*, 63(4):1131–1149.

Crawford, V. and Sobel, J. (1982). Strategic information transmission. *Econometrica: Journal of the Econometric Society*, pages 1431–1451.

Davey, B. and Priestley, H. (2002). *Introduction to lattices and order*. Cambridge university press.

Ding, M. and Eliashberg, J. (2002). Structuring the new product development pipeline. *Management Science*, 48(3):343–363.

Drakeman, D., Drakeman, L., and Oraiopoulos, N. (2022). *From Breakthrough to Blockbuster*. Oxford University Press, New York, NY.

Drakeman, D. and Oraiopoulos, N. (2020). The risk of de-risking innovation: Optimal R&D strategies in ambiguous environments. *California Management Review*, 62(3):42–63.

Ederer, F. (2010). Feedback and motivation in dynamic tournaments. *Journal of Economics & Management Strategy*, 19(3):733–769.

Ederer, F. and Manso, G. (2013). Is pay for performance detrimental to innovation? *Management Science*, 59(7):1496–1513.

Farrell, J. and Rabin, M. (1996). Cheap talk. *Journal of Economic perspectives*, 10(3):103–118.

Freeman, C. (1982). *The economics of industrial innovation. 2d ed.* Cambridge: MIT Press.

Friebel, G. and Raith, M. (2009). Resource allocation and organizational form. *American Economic Journal: Microeconomics*, 2(2):1–33.

Fudenberg, D. and Tirole, J. (1991). *Game theory.* MIT press.

Fullerton, R. and McAfee, P. (1999). Auctionin entry into tournaments. *Journal of Political Economy*, 107(3):573–605.

Gao, P., Fan, X., Huang, Y., and Chen, Y.-J. (2022). Resource allocation among competing innovators. *Management Science*, 68(8):6059–6074.

Gavious, A., Moldovanu, B., and Sela, A. (2002). Bid costs and endogenous bid caps. *RAND Journal of Economics*, pages 709–722.

Gaynor, M. (1989). Competition within the firm: Theory plus some evidence from medical group practice. *The RAND Journal of Economics*, 20(1):59–76.

Gerardi, D. and Maestri, L. (2012). A principal-agent model of sequential testing. *Theoretical Economics*, 7(3):425–463.

Gershkov, A. and Perry, M. (2009). Tournaments with midterm reviews. *Games and Economic Behavior*, 66(1):162–190.

Gershkov, A. and Perry, M. (2012). Dynamic contracts with moral hazard and adverse selection. *The Review of Economic Studies*, 79(1):268–306.

Girotra, K., Terwiesch, C., and Ulrich, K. (2007). Valuing R&D projects in a portfolio: Evidence from the pharmaceutical industry. *Management Science*, 53(9):1452–1466.

Goltsman, M. and Mukherjee, A. (2011). Interim performance feedback in multistage tournaments: The optimality of partial disclosure. *Journal of Labor Economics*, 29(2):229–265.

Gomes, R., Gottlieb, D., and Maestri, L. (2016). Experimentation and project selection: Screening and learning. *Games and Economic Behavior*, 96:145–169.

Green, J. and Stokey, N. (1983). A comparison of tournaments and contracts. *Journal of Political Economy*, 91(3):349–364.

Gürtler, O., Münster, J., and Nieken, P. (2013). Information policy in tournaments with sabotage. *The Scandinavian Journal of Economics*, 115(3):932–966.

Ha, A. and Porteus, E. (1995). Optimal timing of reviews in concurrent design for manufacturability. *Management Science*, 41(9):1431–1447.

Hasija, S. and Bhattacharya, S. (2017). Contracting for new product development. In Ha, A. and Tang, C., editors, *Handbook of Information Exchange in Supply Chain Management*, chapter 7, pages 123–144. Springer, Switzerland.

Hauser, J., Tellis, G. J., and Griffin, A. (2006). Research on innovation: A review and agenda for marketing science. *Marketing science*, 25(6):687–717.

Hörner, J. and Samuelson, L. (2013). Incentives for experimenting agents. *The RAND Journal of Economics*, 44(4):632–663.

Howe, J. (2009). *Crowdsourcing: Why the Power of the Crowd is Driving the Future of Business*. Random House, NY.

Huchzermeier, A. and Loch, C. (2001). Project management under risk: Using the real options approach to evaluate flexibility in R&D. *Management Science*, 47(1):85–101.

Hutchison-Krupat, J. (2018). Communication, incentives, and the execution of a strategic initiative. *Management Science*, 64(7):3380–3399.

Hutchison-Krupat, J. and Kavadias, S. (2015). Strategic resource allocation: Top-down, bottom-up, and the value of strategic buckets. *Management Science*, 61(2):391–412.

Hutchison-Krupat, J. and Kavadias, S. (2018). Organizational enablers for NPD portfolio selection. *IEEE Transactions on Engineering Management*, 65(1):59–71.

Jeppesen, L. and Lakhani, K. (2010). Marginality and problem-solving effectiveness in broadcast search. *Organization Science*, 21(5):1016–1033.

Jiang, Z., Huang, Y., and Beil, D. R. (2021). The role of feedback in dynamic crowdsourcing contests: A structural empirical analysis. *Management Science*.

Kamenica, E. and Gentzkow, M. (2011). Bayesian persuasion. *American Economic Review*, 101(6):2590–2615.

Katz, M. and Shapiro, C. (1986). How to license intangible property. *The Quarterly Journal of Economics*, 101(3):567–589.

Kavadias, S. and Chao, R. (2007). Resource allocation and new product development portfolio management. In *Handbook of new product development management*, pages 151–180. Routledge.

Kavadias, S. and Hutchison-Krupat, J. (2020). A framework for managing innovation. *INFORMS TutORials in Operations Research*, pages 202–228.

Kavadias, S. and Loch, C. (2003). Optimal project sequencing with recourse at a scarce resource. *Production and Operations Management*, 12(4):433–444.

Kessler, E., Bierly, P., and Gopalakrishnan, S. (2000). Internal vs. external learning in new product development: Effects on speed, costs and competitive advantage. *R&D Management*, 30(3):213–224.

Klingebiel, R. (2022). Motivating innovation: Tunnels vs. funnels. *Strategy Science*, page forthcoming.

Klingebiel, R. and Adner, R. (2015). Real options logic revisited: The performance effects of alternative resource allocation regimes. *Academy of Management Journal*, 58(1):221–241.

Klingebiel, R. and Rammer, C. (2014). Resource allocation strategy for innovation portfolio management. *Strategic Management Journal*, 35(2):246–268.

Konrad, K. and Kovenock, D. (2009). Multi-battle contests. *Games and Economic Behavior*, 66(1):256–274.

Körpeoğlu, E. and Cho, S.-H. (2018). Incentives in contests with heterogeneous solvers. *Management Science*, 64(6):2709–2715.

Krishnan, V., Eppinger, S., and Whitney, D. (1997). A model-based framework to overlap product development activities. *Management science*, 43(4):437–451.

Krishnan, V. and Ulrich, K. (2001). Product development decisions: A review of the literature. *Management Science*, 47(1):1–21.

Lambert, R. (1986). Executive effort and selection of risky projects. *The RAND Journal of Economics*, 17(1):77–88.

Landau, E. (2001). *Foundations of analysis*. Number 79. American Mathematical Soc.

Lazear, E. and Rosen, S. (1981). Rank-order tournaments as optimum labor contracts. *Journal of political Economy*, 89(5):841–864.

Lefley, F. (2006). Can a project champion bias project selection and, if so, how can we avoid it? *Management Research News*, 29(4):174–183.

Levinthal, D. (2017). Resource allocation and firm boundaries. *Journal of Management*, 43(8):2580–2587.

Levitt, S. and Snyder, C. (1997). Is no news bad news? Information transmission and the role of "early warning" in the principal-agent model. *The RAND Journal of Economics*, 28(4):641–661.

Loch, C. (2008). Mobilizing an r&d organization through strategy cascading. *Research-Technology Management*, 51(5):18–26.

Loch, C. and Kavadias, S. (2008). *Handbook of New Product Development Management*. Routledge, London, UK.

Loch, C. and Terwiesch, C. (1998). Communication and uncertainty in concurrent engineering. *Management Science*, 44(8):1032–1048.

Lombardino, J. and Lowe, J. (2004). The role of the medicinal chemist in drug discovery–Then and now. *Nature Reviews Drug Discovery*, 3(10):853–862.

Manso, G. (2011). Motivating innovation. *The Journal of Finance*, 66(5):1823–1860.

Marinovic, I. (2015). The credibility of performance feedback in tournaments. *Journal of Economics & Management Strategy*, 24(1):165–188.

Markou, P., Kavadias, S., and Oraiopoulos, N. (2021). Rival signals and project selection: Insights from the drug discovery process. *Working Paper*.

Meyer, M. (1992). Biased contests and moral hazard: Implications for career profiles. *Annales d'Economie et de Statistique*, pages 165–187.

Mihm, J. (2010). Incentives in new product development projects and the role of target costing. *Management Science*, 56(8):1324–1344.

Mihm, J. and Schlapp, J. (2019). Sourcing innovation: On feedback in contests. *Management science*, 65(2):559–576.

Milgrom, P. and Roberts, J. (1990). Rationalizability, learning, and equilibrium in games with strategic complementarities. *Econometrica: Journal of the Econometric Society*, pages 1255–1277.

Moeller, S. and Brady, C. (2014). *Intelligent M&A: Navigating the Mergers and Acquisitions Minefield.* 2nd ed., John Wiley & Sons, Chichester, UK.

Moldovanu, B. and Sela, A. (2001). The optimal allocation of prizes in contests. *American Economic Review*, 91(3):542–558.

Moldovanu, B. and Sela, A. (2006). Contest architecture. *Journal of Economic Theory*, 126(1):70–96.

Nalebuff, B. and Stiglitz, J. (1983). Prizes and incentives: towards a general theory of compensation and competition. *The Bell Journal of Economics*, pages 21–43.

Nelson, R. (1961). Uncertainty, learning, and the economics of parallel research and development efforts. *The Review of Economics and Statistics*, 43(4):351–364.

Nikpayam, H., Fleischmann, M., and Schlapp, J. (2022). How to compose innovation portfolios: Commitment or flexibility? *working paper*.

O Reilly, C. A. and Tushman, M. L. (2004). The ambidextrous organization. *Harvard business review*, 82(4):74–83.

Oraiopoulos, N. and Kavadias, S. (2014). The path-dependent nature of R&D search: Implications for (and from) competition. *Production and Operations Management*, 23(8):1450–1461.

Oraiopoulos, N. and Kavadias, S. (2020). Is diversity (un-)biased? Project selection decisions in executive committees. *Manufacturing & Service Operations Management*, 22(5):906–924.

Petrova, E. (2014). Innovation in the pharmaceutical industry: The process of drug discovery and development. In Ding, M., Eliashberg, J., and Stremersch, S., editors, *Innovation and Marketing in the Pharmaceutical Industry*, pages 19–81. Springer, New York, NY.

Pinto, J. and Patanakul, P. (2015). When narcissism drives project champions: A review and research agenda. *International Journal of Project Management*, 33(5):1180–1190.

Rahmani, M. and Ramachandran, K. (2021). Delegating innovation projects with deadline: Committed vs. flexible stopping. *Management Science*, 67(10):6317–6332.

Reuer, J. and Sakhartov, A. (2021). Economies of scope and optimal due diligence in corporate acquisitions. *Organization Science*, 32(4):1100–1119.

Rohrbeck, R. (2010). Harnessing a network of experts for competitive advantage: Technology scouting in the ICT industry. *R&D Management*, 40(2):169–180.

Rotemberg, J. and Saloner, G. (1994). Benefits of narrow business strategies. *The American Economic Review*, 85(5):1330–1349.

Ruszczynski, A. (2011). *Nonlinear optimization.* Princeton university press.

Santiago, L. and Vakili, P. (2005). On the value of flexibility in R&D projects. *Management Science*, 51(8):1206–1218.

Schilling, M. (2017). *Strategic Management of Technological Innovation.* 5th ed., McGraw-Hill, New York, NY.

Schlapp, J., Oraiopoulos, N., and Mak, V. (2015). Resource allocation decisions under imperfect evaluation and organizational dynamics. *Management Science*, 61(9):2139–2159.

Schlapp, J. and Schumacher, G. (2022). Delegated concept testing in new product development. *Operations Research*, page forthcoming.

Schlickel, M., Huchzermeier, A., Loch, C., and Sting, F. (2013). Alignment in strategy cascading: A case study across manufacturing firms. *Otto Beisheim School of Management Working Paper.*

Schmidt, R. and Freeland, J. (1992). Recent progress in modeling R&D project-selection processes. *IEEE Transactions on Engineering Management*, 39(2):189–201.

Sengul, M., Almeida Costa, A., and Gimeno, J. (2019). The allocation of capital within firms: A review and integration toward a research revival. *Academy of Management Annals*, 13(1):43–83.

Shane, S. and Ulrich, K. (2004). Technological innovation, product development, and entrepreneurship in Management Science. *Management Science*, 50(2):133–144.

Sharpe, P. and Keelin, T. (1998). How SmithKline Beecham makes better resource-allocation decisions. *Harvard Business Review*, 76(2):45–53.

Siegel, R. (2009). All-pay contests. *Econometrica*, 77(1):71–92.

Siegel, R. (2010). Asymmetric contests with conditional investments. *American Economic Review*, 100(5):2230–60.

Siemsen, E. (2008). The hidden perils of career concerns in r&d organizations. *Management Science*, 54(5):863–877.

Simon, H. (1969). *The Sciences of the Artificial.* 3rd ed., 1996, MIT Press, Cambridge, MA.

Sommer, S. and Loch, C. (2004). Selectionism and learning in projects with complexity and unforeseeable uncertainty. *Management Science*, 50(10):1334–1347.

Stein, J. (1997). Internal capital markets and the competition for corporate resources. *The Journal of Finance*, 52(1):111–133.

Stein, J. (2002). Information production and capital allocation: Decentralized versus hierarchical firms. *The Journal of Finance*, 57(5):1891–1921.

Taneri, N. and Crama, P. (2021). Turning the tables in research and development licensing contracts. *Management Science*, 67(9):5838–5856.

Taylor, C. (1995). Digging for golden carrots: An analysis of research tournaments. *The American Economic Review*, pages 872–890.

Terwiesch, C. and Xu, Y. (2008). Innovation contests, open innovation, and multiagent problem solving. *Management science*, 54(9):1529–1543.

Thomke, S. (1995). *The economics of experimentation in the design of new products and processes.* PhD thesis, Massachusetts Institute of Technology.

Tufféry, P. (2015). Accessing external innovation in drug discovery and development. *Expert Opinion on Drug Discovery*, 10(6):579–589.

Van Nieuwerburgh, S. and Veldkamp, L. (2010). Information acquisition and under-diversification. *The Review of Economic Studies*, 77(2):779–805.

West, J. and Bogers, M. (2014). Leveraging external sources of innovation: A review of research on open innovation. *Journal of Product Innovation Management*, 31(4):814–831.

Wheelwright, S. and Clark, K. (1992). *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality*. Simon and Schuster, New York, NY.

Yildirim, H. (2005). Contests with multiple rounds. *Games and Economic Behavior*, 51(1):213–227.

Zschoke, M., Mantin, B., and Jewkes, E. (2014). The effect of competition on R&D portfolio investments. *Production and Operations Management*, 23(8):1439–1449.

Curriculum Vitae

Hossein Nikpayam

Professional Experience

2018 - 2022	Research Assistant Chair of Logistics and Supply Chain Management, University of Mannheim, Mannheim, Germany
2015 - 2017	Research Assistant Niroo Research Institute, Iran
2015 - 2017	Business Analyst Haseb System Consultancy Co., Iran

Education

2017 - 2022	Doctoral Studies in Business Administration (Dr. rer. pol.) University of Mannheim, Mannheim, Germany
2014 - 2016	Master of Science in Industrial Engineering Sharif University of Technology, Tehran, Iran
2009 - 2014	Bachelor of Science in Industrial Engineering Kharazmi University, Tehran, Iran