Asymmetric Multistage Models of R&D: Technology Adoption, Contracts and Protection

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M.A., B.A.

A Thesis

Submitted for the Qualification of Doctor of Philosophy

Department of Economics

University of Warwick

November 1997

Abstract

This thesis consists of three individual models on technology adoption, contracts and protection. The first model is motivated by the inconsistency between empirical results and theoretical models regarding the firm size effects upon the timing of adoption. By proposing a two-stage, endogenous learning, Stackelberg model, we conclude that in a pure strategy equilibrium, the large firm may or may not tacitly delay its adoption to capture the information advantage, depending on cost and belief parameters. The welfare analysis provides a justification for government interventions in firms' adoption decisions.

The second model is motivated by the fact that although more and more resources have been devoted to R&D activities, there is little theoretical discussion regarding R&D funding issues. Chapter 3 derives the optimal funding contract, which happens to be a cost-plus-fixed-fee contract in the literature. After considering the adverse selection problem, the optimal contract induces no efficiency loss under both discrete and continuous settings and the principal will be more conservative in funding. The optimal auction maintains both allocation and production efficiency, and bidding the principal's reservation price will be a dominant strategy in a second price auction. Neither the revenue equivalence nor the separation property will hold. With symmetric beliefs, the optimal funding length is shorter than that of contractible effort. Under some assumptions, the lock-in effect persists and the principal will prefer short-term contracts to long-term contracts.

The third model decides the optimal protection forms, protection rates and protection lengths under various cost and revenue circumstances. Since the incentive scheme will be affected by the target firm's future profits, we show that in the context of incomplete information, screening protection schemes can sometimes coincide with the efficient schemes. In R&D area, our result suggests that optimal patent length need not necessarily be increasing in firm's investment efficiency.

Contents

Acknowledgements

Firstly and most importantly, I would like to thank my supervisor Jonathan Thomas, under whose supervision, I have learned far more than I planned to. I'm deeply appreciated for his being always patient, encouraging, and helping me to develop every idea that came to my mind. I wouldn't have gone so far without his help. I'm also indebted to advice from Martin Cripps, Aydin Hayri, and Amrita Dhillon. Special thanks to Juan Angel Garcia and Toby Kendall for correcting my English.

I like to thank all my colleagues and friends that shared my joy and sorrow in these four years. Especially my beautiful, friendly and funny officemates: Olga Arratibel, Lorenzo Cappellari, Michele Ca Zori, Marco Delmastro, Roberto de Santis, Juan Angel Garcia, Silvia Marchesi, Guillio Piccirilli, Chiara Rubino and Chris Williams. Guido Ascari is very nice to let me use his desk. I also want to thank Keith Church, Chris Dawkins, Ana Maria Irequi, Cormack Hollingworths, Sushanta Mallick and Oliver Salome. I'll remember all the friends from business school that joined in our badminton games every night in the summer of 1996. Also thanks to Colin Cohare, Wen-Lin Chen, Cheng-Li Huang, Noorazida Mohd Idris, Woan-Yuh Jang, Louis Khoo, Vickie Li, Freya Martin, Stamatoula Matsoukis, Jane Parker, Jonathan Spencer, Yio-Shen Tsai, Marika Tourmi, Julieta, Satomi Shima, Ming-Yu Ho, Leticia Vernete and Megumi Yoshikawa.

The financial support through a scholarship from the Ministry of Education of Taiwan is especially acknowledged.

Finally, I'd like to dedicate this thesis to my parents. They might never know what's going on here, but I'm sure they will be very happy!

Declaration

This is to declare that,

- I am responsible for the work submitted in this thesis.
- This work has been written by me.
- All verbatim extracts have been distinguished and specifically acknowledged.
- This work has not been submitted within a degree program at any other institution.

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1. Introduction

1.1 Motivation and Methodology

Technological change has played an important role in economic growth. The most cited evidence is "Solow's (1957) discovery that only a small fraction of per capita growth (10 percent for the US non-farm sector over the period of 1909-49) was associated with an increase in the ratio of capital to labour"[1]. The significant role of technical progress has led economists to study firms' incentives to create and adopt new technologies. Therefore, apart from competition in prices and quantities, firms' research and development (R&D) activities have been an essential topic in Industrial Economics.

There are usually three stages in R&D activities[2]: The first stage is the invention process, encompassing the generation of new ideas. The basic research or fundamental technological breakthroughs are mainly carried out by universities and government agencies. For example, more than 58% of all Department of Defence basic research funding is spent on university research centres (Becker (1996)). The second stage is the innovation process, encompassing the development of new ideas into marketable products and processes. The third stage is the diffusion stage, in which the new products and processes spread across the potential markets. This thesis consists of three individual models addressing players' behaviour for these three stages in reverse order. That is, we

[1] Tirole (1988, p. 389).
[2] The classification of three stages follows Stoneman (1995).

first talk about firms' adoption decisions in Chapter 2, then the design of R&D funding contracts in Chapter 3, and finally the design of protection scheme in Chapter 4.

Chapter 2 analyses firms' adoption decisions under an asymmetric market structure, and it aims to solve a missing point in the existing literature, which is shown as follows. The main theme of the adoption literature has been the "timing of adoption", which is basically guided by the empirical observation that firms adopt a certain new technology at different times. More specifically, the path of the diffusion process is frequently depicted by an S-shaped (or sigmoid) curve. Following Stoneman (1986), we can classify the theoretical diffusion literature as "probit" and "game-theoretic" models, where the latter takes into account the interactions among firms. Of the various issues, the effect of current monopoly power upon firms' adoption decisions is of primary interest. Empirical studies of technology adoption show inconsistent results regarding the firm size impact upon firms' adoption time, but theoretical models seldom conclude that small firms can possibly lead in adoption. This inconsistency between empirical results and theoretical models is hence the motivation for the first model of this thesis.

To be more specific, although the majority of the empirical literature reports large firms' leadership in adoption, there are some cases where small firms adopt earlier. For example, Mansfield (1967) examines 14 innovations and concludes that larger firms tend to adopt sooner than smaller firms. On the contrary, in his study of intra-firm diffusion of diesel locomotive usage, Mansfield shows that smaller railroad companies replaced their machines more rapidly than larger ones. Another example can be found in Nabseth and Ray (1974) who conclude from a study covering ten innovations in six European countries that no evidence supports large firms' leadership in adoption. In the studies of the basic oxygen furnace among steel companies, Adams and Birlam (1966), Oster (1982) and Sumrall (1982) all conclude that large firms tend to delay diffusion.

Unlike the empirical controversy, theoretically, the "probit" (or rank) models (where firms' adoption strategy present the "simple reservation property") all assert that large firms lead in adoption. Examples can be found in David (1969, 1975), Davies (1979) and Nooteboom (1993). After introducing imperfect information, Jesen (1982, 1988) and McCardle (1985) assume heterogeneity of firms' beliefs about the innovation's profitability and conclude a similar "critical belief" in adoption decisions. Another branch of theoretical models - the game theoretic approach, seldom addresses the impact of current monopoly power on firms' adoption decisions (e.g., Reinganum (1981, 1983), Fudenberg and Tirole (1985), Hendricks (1992)). An exception can be found in Sadanand (1989), who analyses the firm size effect by assuming one large firm facing a nonatomic continuum of small firms. He concludes that the large firm will adopt first as a Stackelberg leader and all the small firms will adopt in the second stage as followers. Overall, the small firm's possible leadership in adoption seems to be a missing point in the existing literature. Hence, the first model of this thesis is trying to build a model to explain this point. The main result supports two possible outcomes, that is, the large firm may or may not adopt earlier than the small firm, depending on the levels of the prior belief and current production cost.

Chapter 3 discusses the optimal contracts for funding R&D projects. Each year, there are more and more resources (including money and researchers) devoted to the creation of innovation. For example, "Japanese government spending on science and technology has increased about 5% annually over the last decade"[3]. Freemantle (1997)

[3] From East Asian Executive Reports (1996).

reports that "between 1981 and 1992, the total funding of R&D in Germany climbed steadily from about $24 billion to over $48 billion a year". Yet, there is little theoretical literature[4] specifically addressing R&D funding issues. The aim of the second model is therefore to design the optimal funding contracts for long-term R&D projects confronted with opportunism problems.

R&D projects are different from others, such as construction projects, in that the performance of the contractor's effort is difficult to observe or monitor. The monitoring or progress-checking devices that we usually find in other contracts are not really applicable to R&D projects, and hence the moral hazard problems in R&D projects are more severe than in other contracts. In addition, as the invention processing is time consuming, for example, the search for AIDS remedy, most R&D contracts take the form of long-term contracts. These two features of R&D contracts make them to be an interesting topic to study. Corresponding to two settings about the timing of innovation in the R&D literature: the deterministic and stochastic settings (see Reinganum (1989) for discussion of the literature), Chapter 3 discusses the optimal funding contracts for these two different settings of innovation time. But essentially, the discussion of optimal contracts belongs to the subject of information economics.

Information economics is a broad subject with many variations. There are mainly two types of problems: the first is the moral hazard (hidden action or opportunism) problem, where "one party to a transaction may undertake certain actions that affect the other party's valuation of the transaction, but that the second party cannot monitor/enforce perfectly"[5]. The second is the adverse selection (hidden information)

[4] The only exception is Aghion and Tirole (1994), which will be explained in chapter 3 to be different from our setting.
[5] The definitions of moral hazard and adverse selection follow Kreps (1990).

problem, where "one party to a transaction knows things pertaining to the transaction that are relevant to but unknown by the second party".

Most discussion of moral hazard and adverse selection problems uses the principal and agent framework. Our derivation of optimal funding contracts in Chapter 3 adopts this framework, and assumes that there is a self-interested principal who wishes to assign an agent to undertake a time-consuming R&D project. The assumption of a "self-interested" principal is in contrast to the assumption of a "benevolent" principal, who makes her decision to maximise the sum of all players' expected utilities. The latter setting will be applied in Chapter 4, where a government agency wishes to design a protection scheme for the protected firm to undertake a welfare improving investment. Apart from this, there is another structure difference between Chapter 3 and Chapter 4 concerning the agent's valuation from the mechanisms. That is, in Chapter 3, it is assumed that the project value is irrelevant to the agent, for example, one can think of the case of employed researchers whose research outcomes belong to their employers. However, in Chapter 4, the agent's (protected firms) future profits will be affected by whether protection succeeds in motivating the investment. The different assumptions about the agent's valuation will affect the determination of compensation scheme, as we will discuss in details later.

Chapter 3 starts with a deterministic setting for the timing of innovation, and discusses firstly the case with only a moral hazard problem as a benchmark of comparison. Later, by assuming the agent has private information about the innovation time, we discuss both the moral hazard and adverse selection problems in the contexts of discrete and continuous settings. The terms "discrete" and "continuous" refer to the principal's anticipation about how the information that is better known by the agent is distributed. The discussion of the optimal contract with an adverse selection problem mainly relies on applying the revelation principle (Gibbard (1973), Green and Laffont (1977), Dasgupta et al. (1979) and Myerson (1979)).

When there is incomplete information, the contract (mechanism) design is typically studied as a three-step game. "In step 1, the principal designs a mechanism, or contract, or incentive scheme. A mechanism is a game in which the agents send costless messages, and an allocation that depends on the realised messages.... In step 2, the agents simultaneously accept or reject the mechanism.... In step 3, the agents who accept the mechanism play the game specified by the mechanism"[6]. The revelation principle says that "to obtain her highest expected payoff, the principal can restrict attention to mechanisms that are accepted by all agents at step 2 and in which at step 3 all agents simultaneously and truthfully reveal their types". Since this principle plays a major role in the discussion of the optimal funding contract in Chapter 3 and the optimal protection scheme in Chapter 4, we present the formal statement[7] of the revelation principle as follows.

The revelation principle says that any efficient outcome of any Bayesian game can be represented by a truth-telling direct mechanism. The following will describe the forms of a general mechanism, equilibrium and a truth-telling direct mechanism, then explain the principle. Suppose there is a principal and i agents ($i=1,...I$) with types $\Delta = (\Delta^1, \dots, \Delta^I)$ from set D. The object of the mechanism is to determine an allocation $c = \{x, r\}$, where the vector $x \in X \subset \Re^n$ is the decision of the principal and $r = (r^1, \dots, r^I)$ is a vector of money transfers from the principal to each agent. A

[6] Definitions of mechanism design and the revelation principle are quoted from Fudenberg and Tirole (1991).
[7] The formal statement of the principle is again adopted from Fudenberg and Tirole, however, in order to use notations consistent with the remaining chapters, the notation has been changed.

mechanism m defines a message space U^i for each agent i, a game form to announce the messages, and $\mu = (\mu^1, \dots, \mu^I)$ to be the vector of all messages sent by the agents in the game form. The allocation depends on the agents' messages: $c_m : \mu \rightarrow C = X \times \Re^I$. Assume that there is a pure strategy equilibrium $\mu^{i*}(\Delta^i)$.

Now consider a new message space D^i (type space) for each i, so that each agent announces a type $\hat{\Delta}^i$. Denote $\hat{\Delta} = (\hat{\Delta}^1, \dots, \hat{\Delta}^I)$ and the new location rule as $\bar{c}: D \rightarrow C$ by $\bar{c}(\hat{\Delta}) = c_m(\mu^*(\hat{\Delta}))$, where $\mu^*(\hat{\Delta})$ is the vector of the equilibrium strategies.

Theorem (*the revelation principle*)[8]

Suppose that a mechanism with message spaces U^i and allocation function c_m has a Bayesian equilibrium $\mu^*(\cdot) = \{\mu^{i*}(\Delta^i)\}_{i=1,\dots,I,\ \Delta^i \in D^i}$. Then there exists a direct-revelation mechanism $(\bar{c})$ such that the message spaces are the type spaces $(\bar{U}^i = D^i)$, and such that there exists a Bayesian equilibrium in which all agents accept the mechanism and announce their true types.

Another interesting issue in Chapter 3 is the design of the optimal auctioning contract, since in most cases an agent will be selected from several other competitors. There are some interesting results in auction theory, including the revenue equivalence theorem (Vickrey (1961)) and the separation property (Laffont and Tirole (1993)). By comparing the results from the optimal auction and a second-price auction, we can see how the opportunism problem in R&D contracts changes these commonly agreed conclusions. The last section of Chapter 3 talks about the stochastic setting of innovation time (see Lee and Wilde (1980), Reinganum (1982), Harris and Vickers (1987)). With both incomplete and imperfect information, the design of the optimal contract becomes

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[8] When applying this theorem, chapter 3 and chapter 4 concentrate on a truth telling direct mechanism and refer to the allocation function in this theorem as the "contract" itself, and the decision x as the "allocation rule". The notational changes, although a bit confusing, are to cope specifically with the topic of contract design and the discussion of auction.

more interesting. The choice between long term and short term contracts is also discussed here.

Finally, the third model is motivated by the observation that government interventions (protection) of various forms are still used by many developed and developing countries, and the empirical results do not always support the positive effect of protection. Chapter 4 builds up a general protection model, where "protection" is a general term for government interventions and could take the form of, for example, an export or import tax or subsidy, a voluntary export restraint, or a patent. When the public good property of innovation causes some difficulty in the appropriability of R&D activities. Patents are the most commonly used instruments to adjust this market failure. However, there are other government interventions with the names of regulation and protection; for example, the protection or subsidies granted due to the infant industry argument in developing countries (e.g., Krugman and Smith (1994)), or due to the injured industry argument in developed countries (e.g., Miyagiwa and Ohno (1995)), and the preparation allowance periods before the launch of severe environmental laws. A common feature of the various interventions is: protection is granted on the grounds that the protected firms can undertake a welfare-improving investment in order to adopt new equipment for international competition, to update machinery, to install anti-pollution equipment, or to invest in creating a new product or production process. The difference is that the preparation allowance period and the infant or injured industry protection put emphasis on protection *during the investment*, but patents are granted *after the success of the investment*. This observation of these two different forms of protection gives the motivation for the discussion of optimal protection schemes in Chapter 4.

We derive the optimal protection scheme through mechanism design. As noted earlier, in this chapter, the principal will maximise the social surplus, and the investment outcome will also affect the agent's future profits. Taking into account the agent's future profits makes the discussion more complicated, as different future profits indicate different incentive compensations. The main result shows that only a few cases justify protection, and the optimal protection form could involve no protection, one-part or two-part protection. One-part protection refers to the use of only during- or post- investment protection, and two-part protection means using both protection forms. There are many empirical studies testing the protection effects, some of which agree with the positive effects (e.g., Baldwin and Krugman (1988)) and some disagree (e.g., Krueger and Tuncer (1982), Luzio and Greenstein (1995)). Chapter 4 says that not all cases fit into the same protection form, and the protection scheme will be in vain if a wrong form has been used. The second part of Chapter 4 discuss the setting of protection scheme in the context of incomplete information, and we gain some implications regarding the patent policy.

1.2 Outline of the Thesis

Since the existing literature cannot explain small firms' leadership in adoption, Chapter 2 builds a two stage, endogenous learning, Stackelberg model in order to explain this missing point. After considering each firm's reaction, it is not easy to discuss the market structure effect. Therefore, we follow the reasoning by Varian (1987) and use a Stackelberg setting to depict the market structure with different firm sizes. We have noted that the leader and follower structure alone cannot solve our problem. Furthermore, when raising funds, due to higher profits the dominant firms have relatively more internal funding resources. Even with external funding, the dominant firms are seen as more reliable by banks and generally can raise funds at lower interest costs. The positive relation between discount rate and interest rate suggests that the dominant firms will put higher weights on their future profits than small firms. Considering the two effects from internal and external funding, we assume in this two stage game that the follower is more myopic than the leader, and to make this extreme, that the follower lives only for one stage[9]. To exclude other heterogeneous factors, we assume that both the leading and following firms have identical initial beliefs about the cost uncertainty and the same current production cost. This cost uncertainty can be resolved through learning from the experience of earlier adoption.

The main issue of this model is: *Which firm will adopt first: the LR[10] firm or the SR firm?* Our result supports two possibilities, that is, the large firm may or may not adopt earlier than the small firm, depending on the levels of the prior belief and the current production cost (both of which are common to the two firms). The intuition is as follows: with the assumptions of different life spans and uncertain profitability, the leading firm may delay its adoption in order to grasp the information benefit of learning from earlier adopters, but the short-lived firm can only react myopically. In making adoption decisions, both players will adopt cut-off strategies, and there will be a gap between two players' cut-off points. This gap explains the possibility that the small firm might adopt earlier than the large firm. Section 2.2 also provides the comparative statics about the equilibrium. Section 2.3 discusses the welfare effect by assuming a benevolent central planner. The result justifies the situation when government intervention is needed to

[9] As will be shown later, an asymmetric setting with the same life span will not explain the missing aspect.
[10] LR refers to the large firm which lives for two stage; SR refers to the small firm which lives for one stage. Refer to Chapter 2 for details.

encourage firms to adopt a new technology. This central planner adopts a cut-off strategy similar to those of the firms, and the gap between the leading firm's critical point and the central planner's cut-off point provides the justification for government intervention.

The second model is motivated by the fact that although more and more resources (personnel and money) have been devoted to R&D activities, there is little theoretical discussion regarding R&D funding issues. Chapter 3 provides a guideline to a rich class of funding contracts, especially for time-consuming projects confronted with moral hazard problems. To emphasise the opportunism problem and to set a benchmark of efficiency, the basic model in Chapter 3 firstly supposes that the total time needed to complete a project is deterministic and known by both the principal and the agent. With a further assumption of no initial wealth for the agent (so penalty is impossible and there is a moral hazard problem), Section 3.2 derives the optimal contract form from a general compensation scheme, which implements the agent's full effort in the context of complete information. The optimal contract describes a funding period and an end-of-contract reward, which happens to be a multi-stage version of the "Cost-Plus-Fixed-Fee" (CPFF) contract in the literature.

Next, we consider the case where the agent has better information about the time needed for completion (due to experience or expertise). Following the literature, we denote the value that is better known by the agent as a "type". Sections 3.3 and 3.4 hence determine the optimal contracts with both moral hazard and adverse selection problems for cases when the principal thinks the agent's type is discretely distributed and when it is continuously distributed. The discussion of both discrete and continuous settings serves two aims: (1) to see if the optimal contract will vary with the setting of type; (2) to provide a basic structure for the discussion of optimal auction design. The solution says that when there are only two types (a simplified discrete type setting), the optimal contract will not induce efficiency loss to either type, but instead pays an extra information rent to the efficient type. The intuition is: any shortage in funding will result in the failure of R&D, hence the principal would rather pay more rent than lose the whole project value. When the type is continuously distributed, the principal will adopt a cut-off strategy in funding, that is, to stop funding for types greater than some critical value. It is concluded that the agent's production efficiency remains for efficient types (types smaller than the cut-off point), and the principal will take a more conservative attitude in funding, since the inefficient types will definitely take the contract and shirk.

Section 3.5 derives the optimal auctioning contract in a discrete type setting, as it provides a clearer idea about how an auction works in our model. In the optimal auction, both allocation and production efficiency persist, that is, the project will be assigned to the bidder with the lowest cost and the winner(s) always finishes the project efficiently. The principal can benefit from the agents' competition in two ways. First, the project is more likely to be completed by an efficient type under an auction. Second, competition reduces the incentive rent for the efficient type as he is less likely to mimic the inefficient type who might have less chance to win. However, this rent reduction varies with the difference between the two types, that is, when the inefficient type is not sufficiently greater than the efficient type, the former might be better off shirking under the efficient type's contract (which gives him a higher winning probability). Hence, to motivate the inefficient type (and therefore the efficient type) to choose his own contract, the principal has to reward more than when there is a big difference between the two types.

Finally, we relax the assumption of private information in Section 3.6, and assume that both parties have identical beliefs about the time needed for completion. This setting corresponds to the stochastic nature in the R&D literature. Section 3.6 firstly discusses how opportunism affects the agent's shirking decisions under symmetric beliefs. The optimal contract is derived and we show that the principal's optimal funding length with an opportunism problem is no longer than the contract without an opportunism problem. Later, we introduce the possibility of contract renewal and show that under some constraints, the lock-in effect persists and the principal will prefer a sequence of short-term contracts to a long-term contract. The intuition is because the former provides both parties opportunities to update their beliefs in this symmetric setting.

The third model is motivated by the observation that various government interventions (protection) are still used by many developed and developing countries, but the empirical results do not always support the positive effect of protection. The purpose of Chapter 4 is to provide a positive guideline to various government interventions, and especially to address two important but usually ignored dimensions: the protection form and the protection length. The basic model of Chapter 4 firstly analyses the case with complete information but confronted with a moral hazard problem. Since the investment outcome will also affect the target firm's future profits, the incentive scheme has to consider different cost and revenue environments in order to give the target firm right motivation. Various cases are classified according to the target firm's investment ability and investment willingness. The investment ability refers to whether the target firm can afford the investment cost under its current profit, and the investment willingness refers to the target firm's future profits after the completion of the investment. Hence depending on parameters, the optimal protection could involve no protection, *one-part protection* or *two-part protection*. One-part protection refers to using only during- or post-investment protection, and two-part protection involves both during- and post-investment protection.

This result gives a significant policy implication, that is, as empirical evidences show different conclusions about protection effects: some are positive (e.g., Baldwin and Krugman (1988)) and some are negative (e.g., Krueger and Tuncer (1982), Luzio and Greenstein (1995)), our result suggests that using a correct protection form will be critical for the success of investment and not all cases fit in the same protection form.

Furthermore, we conclude that whether the during-investment protection rate is increasing, decreasing or constant will not affect the investment efficiency, which is in contrast to the prevalent argument that decreasing protection rates can mitigate the protected firms' pain when adjusting towards liberalisation. Finally, after considering the target firm's private information about the time needed to complete the investment, our results show that: (1) The screening protection scheme could possibly coincide with the efficient scheme when only the inefficient type is lacking in investment willingness, or when there are only liquidity problems; (2) The screening scheme is strictly better than the pooled scheme of the efficient type; however, whether it is better than the pooled scheme of the inefficient type is dependent on parameter values; (3) Whenever there is a liquidity problem, the efficient type's post-investment protection will be longer than that of the inefficient type; otherwise, the reverse result applies. In terms of patents, this means that a more efficient firm does not necessarily need a longer patent life span to keep incentive compatibility. The intuition is: when the target firm's future profits are also connected to the success of the investment, the incentive rent (patent life) will vary with the cost and revenue environments.

2. Does the Leader Always Move First? Issues on Technology Adoption

2.1 Introduction

We all believe that in reality market structure is seldom symmetric. For example, "A commonly observed pattern of behaviour is for smaller firms in the computer industry to wait for IBM's announcement of new products, and then adjust their own product decisions accordingly" (Varian (1987), p. 458). For this kind of asymmetric circumstance, the literature uses the Stackelberg model to describe industries in which there is a dominant firm or a natural leader. Hence, although assuming symmetry among firms can provide very useful (sometimes easier to manage) benchmarks for analysis, it cannot cover every aspect in reality. We present a "missing aspect" from the existing technology adoption models, and propose an asymmetric model in the hope that it can provide more comprehensive interpretation for this case.

The "missing aspect" is about the relation between firm size and the timing of technology adoption. This issue has been examined by extensive empirical studies, but their results do not always support the same answer. That is, ***large firms may or may not adopt earlier than small firms***. For example[12], Mansfield (1967) examines 14 innovations

[12] Examples are mainly cited from Baldwin and Scott (1987, Ch 4). Also see Reinganum (1989) and Stoneman (1995) for further surveys of technology diffusion studies.

and concludes that larger firms tend to adopt sooner than smaller firms, but the result from his logistic model does not entirely support this conclusion. On the contrary, in the study of intra-firm diffusion of diesel locomotive usage, Mansfield shows that smaller railroad companies replaced their machine more rapidly than the larger ones. In Nabseth (1973)'s study on the adoption of six process innovations in Sweden, only two cases have significant size effects. Nabseth and Ray (1974) conclude from a study covering ten innovations in six European countries that no evidence supports large firms' leadership in adoption. In the studies of the basic oxygen furnace among steel companies, Adams and Dirlam (1966), Oster (1982) and Sumrall (1982) all conclude that large firms tend to delay diffusion. More recent work, for example Daugherty, Germain and Dorge (1995), show by their logistic regression results that firm size has positive impact on the adoption of electronic data interchange (EDI).

Two characteristics are common in the evidence: first, using the term from the adoption literature, "diffusion" occurs, meaning that firms adopt a certain technology at different times. Second, it is ambiguous whether firm size has a positive or negative effect on the timing of adoption. There have been substantial theoretical models[13] examining this evidence. The pioneering work is David (1969, 1975), who uses a "probit approach"[14] where each firm with a size bigger than the critical firm size will adopt the innovation, and this critical value is determined by the equality of adoption benefit from labour saving and adoption cost. However, as noted by Davies (1979), this critical firm size will disappear if both return and cost functions are proportional to firm size. Davies proposes a model where both the expected and critical payoff periods are functions of firm size, and he concludes that a firm will adopt a new technology if its expected payoff

[13] Refer to Nooteboom (1993) for early adoption theories.
[14] Stoneman (1983) refers the "critical firm size" models as probit approach.

period is less than the critical one. Nooteboom (1993) assumes the expected return to be proportional to firm size and the risk of failed implantation to be independent of firm size. He concludes that large firms adopt earlier than small firms. Although this "critical firm size approach" supports large firms' leadership in adoption, it fails to explain the other possibility, that is, small firms may adopt earlier as well. Moreover, the interaction among firms has not been considered in the above literature.

Another strand of diffusion models assumes imperfect information about the new technology. The intuition is to assume that there is uncertainty regarding the profitability (revenue or cost) of an innovation. We can further distinguish the literature according to whether the uncertainty is to be resolved through time (e.g., Reinganum (1981,1989), Fudenberg and Tirole (1985), Hendricks (1992), Sadanand (1989)), or to be gained by external searching (e.g., Jesen (1982, 1988), McCardle (1985), Toivanen et al. (1995)), or by learning from experience (e.g., Kapur (1992)). Except for Jesen and McCardle, all the other examples fit into another classification: the game-theoretic approach, in which the interaction among firms has been considered.

In Jensen's (1982) model, the uncertainty decreases as the external information about profitability accumulates. Each firm's adoption decision is therefore characterised by an optimal stopping rule. By assuming heterogeneous prior beliefs across firms, his model depicts the traditional S-shaped diffusion curve. Jesen (1988) extends this model by considering firms' information capacity and shows an ambiguous result, that is, greater information capacity will increase learning and hence shorten the expected delay before adoption, but on the other hand, it will also induce a more stringent adoption criterion and thus lengthen the expected delay. McCardle (1985) presents a more general case by considering the information cost. All these models assume the information to be external, for example from "industry trade journals" (Jesen (1982)). Following the same line and adding the interaction among firms, Toivanen et al. (1995) examine firms' adoption decisions when they can defer adoption and invest in a search for external information. They first derive the conditions for which a monopolist will adopt immediately, search or not adopt at all. Then, in a two-stage symmetric duopoly, they derive the conditions for a diffusion equilibrium where one firm adopts the innovation and the other searches for external information. This kind of diffusion equilibrium is firstly shown by Reinganum (1981) by using what is called the game-theoretic approach.

Assuming the adoption cost to be decreasing through time, Reinganum (1981) shows that neither imperfect information about profitability nor heterogeneity across firms is necessary for the diffusion outcome. By letting firms commit to their adoption dates, Reinganum shows that the interaction between firms alone can cause them to adopt at different times. However, as pointed out by Fudenberg and Tirole (1985), "precommitment strategies are equivalent to infinite information lags", that is, these strategies ignore any subsequent information regarding the rival's decision. Alternatively, they assume that firms can respond immediately and show in a duopoly case that the threat of pre-emption makes equalised the rents from adoption, but if the pre-emption gain is sufficiently small, both firms delay and simultaneously adopt the innovation. Hendricks (1992) cites this model and further assumes that there is private information about the rival firm's innovation capacity. He shows that the reputation effect will delay the early adoption and hence rent dissipation will not occur. In another paper, Reinganum (1983) uses a static model incorporating both imperfect profitability and the rival's reaction, and shows that "if initial costs are sufficiently dissimilar, then it is the high cost firm which adopts the new technology, while the low cost firm eschews the adoption".

Sadanand (1989) also derives the conditions for diffusion to occur, by using a two-stage symmetric duopoly model and assuming the uncertainty to be resolved at the end of the first stage. More relevant to the present model, he also analyses the firm size effect by assuming one large firm facing a nonatomic continuum of small firms. He concludes that the large firm will adopt first as a Stackelberg leader and all the small firms adopt in the second stage as followers. As mentioned earlier, these results support only one of the observed outcomes.

Finally, Kapur (1992) models an endogenous learning process in which firms can only learn from the experience of other adopting firms. Learning is through observing the signals sent by previous adopters. Those non-adopting firms can observe these signals and update their priors according to some subjective beliefs on these signals. He concludes that diffusion is the result of a sequential waiting game and the path of a mixed strategy equilibrium depicts the S-shaped diffusion curve.

The present model characterises the asymmetry among firms by assuming an ex-ante[15] Stackelberg framework. To cope with the firm size issue, we adopt the reasoning mentioned by Varian, that is, the Stackelberg model is often used to describe industries in which there is a dominant firm or a natural leader, and further assume that the large firm is the leading firm and the small firm is the following firm. An interesting question to ask is whether this leader-follower setting *alone* can explain the missing aspect of the adoption literature. To check, for example, in Reinganum, Fudenberg and Tirole type models where both firms have infinite life spans, if we replace the symmetric assumption by a Stackelberg setting, it can be seen that since the leader has the priority in decision making, there will be a pure strategy equilibrium where the leader pre-empts the

[15] That is, before the adoption of the new technology.

adoption. Likewise, in Kapur's model, there will be no pure strategy equilibrium that supports diffusion. In other words, the leader-follower structure or endogenous learning alone can not explain the puzzle mentioned earlier.

The present paper proposes a two-stage, endogenous learning, Stackelberg model to analyse firms' adoption decisions for an uncertain profitability innovation. We have noted that the leader and follower structure alone cannot solve our problem. Furthermore, when raising funds, due to higher profits the dominant firms have relatively more internal funding resources. Even with external funding, the dominant firms are seen as more reliable by banks and generally can raise funds at lower interest costs. The positive relation between discount rate and interest rate suggests that the dominant firms will put higher weights on their future profits than small firms. Considering the two effects from internal and external funding, we assume in this two stage game that the follower is more myopic than the leader, and to make this extreme, that the follower lives only for one stage. To exclude other heterogeneous factors, we assume that both the leading and following firms have an identical initial belief about the cost uncertainty and the same current production cost. This cost uncertainty can be resolved through learning from the experience of earlier adoption. The main issue of this model is: *Which firm will adopt first: the LR firm or the SR firm*[16]*?* Our result supports two possible outcomes, that is, the large firm may or may not adopt earlier than the small firm, depending on the levels of the prior belief and the current production cost (both of which are common to the two firms). The intuition is as follows: with the assumptions of different life spans and uncertain profitability, the leading firm may delay its adoption in order to grasp the intertemporal benefit of learning from earlier adopters, but the short-lived firm can only

[16] In the following, LR denotes the large firm who lives for two stages and SR denotes the small firm who lives for only one stage.

react myopically. In making adoption decisions, both players will adopt cut-off strategies, and there will be a gap between the two players' cut-off points. This gap explains the possibility that small firm might adopt earlier than large firm.

In the comparative statics of the equilibrium, we show that the realised market concentration for LR adopting earlier is very likely to fall below the pre-adoption level. This is in contrast to some other studies, for example Hannan and McDowell (1990). One reason for the disadvantage from early adoption is because of the perfect learning assumption, which indicates the high spillover or imitation effect. Later in the welfare analysis, a central planner is assumed to decide which firm should adopt earlier from the welfare point of view. Similar to firms' decisions, this central planner also adopts a cut-off strategy, and the gap between the leading firm's critical point and the central planner's cut-off point provides the justification for government intervention (e.g., Green et al. (1996)).

In the rest of this chapter, section 2.2 presents the model, the main result and the comparative statics. Section 2.3 is the welfare analysis. Section 2.4 concludes this model and discusses further research. All proofs are put in Appendices 2.1 and 2.2.

2.2 The Model[17]

Consider an industry where both the leader and follower are producing a homogeneous good. The production lasts for two stages. Due to the effects from internal and external funding, it is assumed that the leader has a discount rate of 1 and the follower's discount rate is 0. That is, the leader (denoted by LR) lives for two stages, and shares the market

[17] We consider "inter-firm" rather than "intra-firm" adoption.

with different short run followers (denoted by SR) in each stage. The market demand is described by a linear inverse demand function with a constant term A and slope 1. Linearity is assumed to get unambiguous implications and more general demand functions would not change the nature of the analysis. Furthermore, it is assumed that both LR and SR are using the same production technology before adopting the innovation and have the same current production cost $\bar{c}$, where $A > \bar{c}$.

Suppose that both firms simultaneously confront a *non-drastic* process[18] innovation. It is assumed that there is no adoption cost and the adoption decision is irreversible[19], however, the adoption effect is uncertain: it is publicly known[20] that both LR and SR have the initial assessment $p \in [0,1]$ that this innovation will decrease the production cost to c_1 and $(1-p)$ that the production cost will increase to c_2, where $c_1 < \bar{c} < c_2$ and $A > c_2$. If any firm adopts earlier, the rival firm can observe the performance[21] of the adopting firm and update its prior. To avoid complication, perfect learning is assumed, that is, when each firm observes a successful adoption from the other firm, it will update its prior to $p = 1$; similarly, if failure is observed, the prior will be adjusted to 0. An

[18] There is usually a classification between product and process innovations. The former refers to new goods or new services, and the latter means better ways of producing the existing products. However, the line between these two types is vague in reality, as a product innovation might become the input for another product. Following most of the adoption literature, we discusses firms' decisions towards a process innovation.

[19] The alternative assumption of irreversibility is to assume an adoption cost.

[20] We did not assume *common knowledge* in belief in order to allow the central planner having an variant belief in the analysis of welfare effect.

[21] The term 'performance' refers to the realised cost change from the adoption. It is assumed that the observation of the performance is through an informal information approach, for example, word of mouth from the manager or labours of the adopting firm, rather than from observing output or price. This reason is because the output of an early adopter is actually set ex-ante before the realisation of market price (see the output decisions below), and hence reveals no information about the uncertainty. However, during the production process, the involved individuals can somehow tell whether the innovation is really saving cost. Equivalently, it is assumed that separating equilibrium of the signalling game exists, and there is no concealing. Hence, before the realisation of the market price, the rival firm can obtain information about the adoption.

interpretation for this perfect learning setting is the presence of a highly spillover or imitation effect.

Since the leader-follower setting is basically a sequential game, the whole model consists of four stages. The timing of the firms' adoption and production decisions is described as follows.

```
                                        t = 1                                       t = 2
I---------------------------------------I-------------------------------------------I
                    ↓                   ↓                     ↓                     ↓
                   (A)                 (B)                   (C)                   (D)
```

(A) At $t = 1$, LR makes the decision whether to adopt now or to wait for SR to adopt first, and then sets its optimal output according to its adoption decision. *(B)* Two cases are considered according to LR's adoption decision at $t = 1$: (i) if LR has decided to adopt first, SR can observe the performance from LR's adoption, update its belief (to 1 if the adoption is successful and to 0 otherwise), and make its adoption decision accordingly; (ii) if LR has decided to wait at $t = 1$, SR now has to decide whether to adopt under uncertainty and sets its optimal output accordingly. *(C)* At $t = 2$, there are three cases: (i) if LR has decided to adopt at $t = 1$, it now has to set the optimal output according to the result from its own adoption at $t = 1$, since the adoption is irreversible; (ii) if LR has decided to wait for SR and SR actually adopts at $t = 1$, it now has to observe the performance from SR's adoption, update its belief and set the optimal output accordingly; (iii) if LR has decided to wait for SR but SR does not adopt at $t = 1$, then again it has to decide whether to adopt the innovation and sets its output accordingly. *(D)* The decision for SR at $t = 2$ is the same as SR at $t = 1$.

The whole process is solved backwards through time. We firstly describe SR's output and adoption decisions, then LR's decisions.

2.2.1 SR's decision

Since both SR firms at $t = 1$ and $t = 2$ react static optimally to LR's action, the following decision rule will apply to both SR firms. Denote q_{SR} and q_{LR} as SR and LR's outputs. Each SR makes its output decision by taking LR's output as given. For a given belief p (could be prior or posterior), SR's expected profit for ***deciding to adopt*** the technology is:

$$\pi^{a}_{SR} = \max_{q_{SR}}\left\{p((A - q_{LR} - q_{SR})q_{SR} - c_1 q_{SR}) + (1-p)((A - q_{LR} - q_{SR})q_{SR} - c_2 q_{SR})\right\}. \qquad (2.1)$$

The superscript "a" denotes "adopting". To generalise SRs' decisions in both stages, we keep the notation of the prior p[22], and note that SRs' expected profit is the maximisation over the weighted values, instead of a weighted sum of maximised values. The reason is: since SR's output decision is made given the prior belief[23], SR needs to set an optimal output to minimise the possible loss from this uncertainty. The same situation will apply to LR's adoption if it decides to adopt the innovation under uncertainty. Denote SR's optimal output and profit by $q^{a}_{SR}(q_{LR}, p)$ and $\pi^{*a}_{SR}(q_{LR}, p)$, where "*" denotes the optimal value.

$$q^{a}_{SR}(q_{LR}, p) = \tfrac{1}{2}(A - q_{LR} - (pc_1 + (1-p)c_2))$$

and

[22] If LR adopts earlier, p could be 1 or 0 depending on the observation.
[23] Note that the innovation is a process innovation. Before it is actually put into the production process, the adopting firm has to invest in other production capacity or order components, etc. Hence the output decision has to be made before the adopting firm knows whether the adoption is successful.

$$\pi_{SR}^{*a}(q_{LR}, p) = \left[\frac{A - q_{LR} - (pc_1 + (1-p)c_2)}{2}\right]^2.$$

For a given belief p, SR's expected profit for ***not adopting*** the technology is:

$$\pi_{SR}^{na} = \max_{q_{SR}}\left\{(A - q_{LR} - q_{SR})q_{SR} - \bar{c}q_{SR}\right\}.$$

The superscript "na" means "not adopting", in which case, its production cost remains the current production cost $\bar{c}$. Denote the optimal output and profit as: $q_{SR}^{na}(q_{LR})$ and $\pi_{SR}^{*na}(q_{LR})$, where

$$q_{SR}^{na}(q_{LR}) = \frac{A - q_{LR} - \bar{c}}{2}$$

and

$$\pi_{SR}^{*na}(q_{LR}) = \left[\frac{A - q_{LR} - \bar{c}}{2}\right]^2.$$

Notice that SRs' optimal variables are functions of LR's output. To see SRs' adoption rules, we need to compare the expected utility from adopting with not adopting. That is, SR will adopt the technology if $\pi_{SR}^{*a}(q_{LR}, p) \geq \pi_{SR}^{*na}(q_{LR})$. In other words, SR will adopt if $p \geq p_2^*(c_1, \bar{c}, c_2)$, and not adopt if $p < p_2^*(c_1, \bar{c}, c_2)$, where $p_2^*(c_1, \bar{c}, c_2) = \dfrac{c_2 - \bar{c}}{c_2 - c_1}$ is the critical belief that the SR firm is indifferent between adopting and not adopting.

Two points are worth noticing: firstly, SR's belief will affect both its adoption and production decisions. The intuition is: since we assume a process innovation, if SR decides to adopt the innovation, the output decision has to be made before knowing the true state of the innovation and hence the belief will affect the output. Secondly, SR's adoption decision is irrelevant to LR's output. Its decision follows a rule of thumb: if the proportion of the possible cost increase over the dispersion of total cost change is higher, SR will be more cautious towards adoption. An explanation of the irrelevance comes from the assumption of linear demand: SR's profits are negatively related to LR's output *with* or *without* adoption. Since the extent that LR's output affects SR's profits is dependent on SR's adoption decision, SR needs only takes into account the cost effect from adoption. Although a non-linear demand function will cause the profits comparison to depend on LR's output, it is suspected that in equilibrium we can have more useful insights[24].

For further use, we summarise SR's adoption and output decisions as follows:

For $p \in (0,1)$, SR will adopt if $p \geq p_2^*$; otherwise it will not adopt.

The optimal respective outputs for adopting and not adopting are:

$$
\begin{aligned}
&q_{SR}^{a}(q_{LR}, p) = \tfrac{1}{2}(A - q_{LR} - (pc_1 + (1-p)c_2)) && \text{if } \; p \geq p_2^*(c_1, \bar{c}, c_2), \\
&q_{SR}^{na}(q_{LR}) = \tfrac{1}{2}(A - q_{LR} - \bar{c}) && \text{if } \; p < p_2^*(c_1, \bar{c}, c_2).
\end{aligned}
\tag{2.2}
$$

2.2.2 LR's decision

LR's adoption decision occurs in three cases: (i) at $t = 1$, it has to decide either to lead the adoption or to wait; (ii) if it decides to wait and SR decides to adopt at $t = 1$, then at $t = 2$ LR has to make its adoption decision according to its posterior belief; (iii) if it decides to wait but SR does not adopt at $t = 1$, LR faces a static adoption decision with its belief remaining the prior. As noted earlier, SR's decisions are affected by the cost

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[24] For example, we might need more assumptions to present the difference of LR and SR firms' adoption decisions in this paper.

uncertainty, and hence in LR's expected profit functions, both the anticipated cost and demand are related to this uncertainty.

At $t=1$ if LR **decides to adopt**, its intertemporal expected profit is :

$$\pi^{a}_{LR} = \max_{q_{LR}}\left\{p((A-q_{LR}-q^{a}_{SR}(q_{LR},1))q_{LR}-c_1 q_{LR})+(1-p)((A-q_{LR}-q^{na}_{SR}(q_{LR}))q_{LR}-c_2 q_{LR})\right\}$$
$$+p\max_{q_{LR}}\left\{(A-q_{LR}-q^{a}_{SR}(q_{LR},1))q_{LR}-c_1 q_{LR}\right\}$$
$$+(1-p)\max_{q_{LR}}\left\{(A-q_{LR}-q^{na}_{SR}(q_{LR}))q_{LR}-c_2 q_{LR}\right\}. \tag{2.3}$$

Again, the superscript "a" denotes "adopting". The first maximising term is LR's expected profit for the first stage and the second and third terms denote its second stage expected profits for possible adoption success (c_1) or failure (c_2) with probability p and $(1-p)$ respectively. Note that LR's optimal outputs in these terms are different. The first term is the maximisation over the weighted profits, instead of a weighted sum of maximised profits. The argument is similar to SR's decision: since the output is set before it knows the true state of the innovation, LR needs to set an output to minimise the possible loss from this uncertainty. The difference now is: LR has to take into account SR's reaction function in the anticipated demand. Recall the definitions of $q^{a}_{SR}(q_{LR},1)$ and $q^{na}_{SR}(q_{LR})$ from equation (2.2). $(A-q_{LR}-q^{a}_{SR}(q_{LR},1))$ means that if LR's adoption is successful (cost decreases to c_1), SR will observe the success and update its belief to $p=1$. From SR's adoption decision rule, we know that SR will adopt and set an optimal output $q^{a}_{SR}(q_{LR},1)$. Similarly, $(A-q_{LR}-q^{na}_{SR}(q_{LR}))$ means that if LR's adoption is unsuccessful (cost increases to c_2), SR will update its belief to $p=0$ and set an optimal output $q^{na}_{SR}(q_{LR})$.

The meaning of the second and third terms are similar. If LR's adoption at $t = 1$ is successful, it's production cost decreases to c_1. The SR firm at $t = 2$ also observes LR's success and hence updates its belief to $p = 1$, adopts the innovation and produces $q^{a}_{SR}(q_{LR},1)$. Therefore, LR's anticipated demand for a successful adoption is $(A - q_{LR} - q^{a}_{SR}(q_{LR},1))$. Likewise with probability $(1-p)$, LR's adoption is expected to be unsuccessful, and its cost and anticipated demand will be c_2 and $(A - q_{LR} - q^{na}_{SR}(q_{LR}))$ respectively. LR's expected profit in the second stage is the weighted sum of two maximising terms, because the uncertainty has been resolved through its own adoption at $t = 1$, and hence LR knows its product cost for sure and sets its output optimally.

If the LR firm **decides to wait**, its expected profit function will depend on whether SR adopts at $t = 1$. Therefore, two cases will be discussed : $p < p^{*}_{2}(c_1,\bar{c},c_2)$ and $p \geq p^{*}_{2}(c_1,\bar{c},c_2)$.

I. $p < p^{*}_{2}(c_1,\bar{c},c_2)$

LR's intertemporal expected profit from waiting will be:

$$\pi^{w}_{LR}(1) = 2\max_{q_{LR}}\left\{(A - q_{LR} - q^{na}_{SR}(q_{LR}))q_{LR} - \bar{c}q_{LR}\right\}. \tag{2.4}$$

The superscript "w" in $\pi^{w}_{LR}(1)$ denotes "waiting" and "1" in the argument denotes the first case: $p < p^{*}_{2}(c_1,\bar{c},c_2)$. In this case, SR will not adopt and hence LR's expected profits will be the same for both stages. To see this, since in the first stage LR decides to wait, its production cost will be $\bar{c}$ and the anticipated demand will be $(A - q_{LR} - q^{na}_{SR}(q_{LR}))$. In the second stage, as learning is endogenous and neither SR nor

LR adopts in the first stage, the belief remains the prior as in the first stage. Again, LR faces the choice between adopting and not adopting, but now the decision is static. We need to compare LR's single stage expected profits from both of its choices. If LR adopts now, its anticipated demand will be $p(A - q_{LR} - q^{a}_{SR}(q_{LR},1))$ $+(1-p)(A - q_{LR} - q^{na}_{SR}(q_{LR}))$, or in short, $\frac{1}{2}(A - q_{LR} + (pc_1 + (1-p)\bar{c}))$. This value is less than the anticipated demand for not adopting which is $(A - q_{LR} - q^{na}_{SR}(q_{LR}))$, or in short, $\frac{1}{2}(A - q_{LR} + \bar{c})$ (since $pc_1 + (1-p)\bar{c} < \bar{c}$). Moreover, LR's expected cost from adopting is $pc_1 + (1-p)c_2$, which is higher than the expected cost for not adopting $\bar{c}$ (since $p < p_2^* = \dfrac{c_2 - \bar{c}}{c_2 - c_1}$). Further, for a given q_{LR}, the marginal profit for not adopting is higher than from adopting, indicating that LR's optimal output for adopting will be less than not adopting as well. Therefore, we can conclude that LR will have a higher expected profit from not adopting the innovation in this case. The intuition for the disadvantage from adoption is: since LR's intertemporal benefit from successful adoption disappears in the static decision, if it is not worthwhile for LR to adopt the innovation in the first stage, it is not worthwhile to adopt in the second stage either. Hence its expected profit for the two stages are the same.

II. $p \geq p_2^*(c_1, \bar{c}, c_2)$

LR's intertemporal expected profit from waiting for this case is:

$$\begin{aligned}\pi^{W}_{LR}(2) = &\max_{q_{LR}}\left\{(A - q_{LR} - q^{u}_{SR}(q_{LR}, p))q_{LR} - \bar{c}q_{LR}\right\}\\ &+ p\max_{q_{LR}}\left\{(A - q_{LR} - q^{a}_{SR}(q_{LR},1))q_{LR} - c_1 q_{LR}\right\}\\ &+(1-p)\max_{q_{LR}}\left\{(A - q_{LR} - q^{na}_{SR}(q_{LR}))q_{LR} - \bar{c}q_{LR}\right\}.\end{aligned} \tag{2.5}$$

The superscript "w" in $\pi^{w}_{LR}(2)$ denotes "waiting" and "2" in the argument denotes the second case: $p \geq p_2^*(c_1, \bar{c}, c_2)$. In this case, the SR firm will adopt. The first term denotes the expected profit from waiting for SR to take the risk from early adoption. Anticipating that SR will produce an optimal output $q^a_{SR}(q_{LR}, p)$, LR has an anticipated demand $(A - q_{LR} - q^a_{SR}(q_{LR}, p))$ and the current cost $\bar{c}$. This is different from equation (2.3), where LR instead of SR bears the risk of early adoption. The second and third maximising terms have similar meanings to those in equation (2.3). The difference is: in this case, the information comes from SR instead of LR, hence in the third term LR is able to avoid the cost increase by observing SR's performance and not adopting the technology. In our notation, rather than producing with cost c_2 in π^a_{LR}, LR will produce with cost $\bar{c}$.

LR's decision rule is to lead the adoption in the first stage if $\pi^{*a}_{LR} \geq \pi^{*W}_{LR}(1)$ ($\pi^{*a}_{LR} \geq \pi^{*W}_{LR}(2)$) in the case of $p < p_2^*$ ($p \geq p_2^*$), and to wait in the first stage otherwise. Lemma 2.1 firstly shows the existence of a *unique* critical belief $p_1^{*(i)}(c_1, \bar{c}, c_2, A) \in [0,1]$[25] such that $\pi^{*W}_{LR}(i) = \pi^{*a}_{LR}$, $i = 1,\ 2$, and some properties of $p_1^{*(i)}(c_1, \bar{c}, c_2, A)$ when characterised in $(p, \bar{c})$ space.

Lemma 2.1

(1) Define $d_1 = \pi^{W}_{LR}(1) - \pi^{a}_{LR}$ *and* $d_2 = \pi^{W}_{LR}(2) - \pi^{a}_{LR}$ *to be the differences of LR's expected profits from waiting and adopting in the cases of* $p < p_2^*(c_1, \bar{c}, c_2)$ *and* $p \geq p_2^*(c_1, \bar{c}, c_2)$ *respectively. There exists a unique* $p_1^{*(1)}(c_1, \bar{c}, c_2, A) \in [0,1]$ *such that* $d_1 = 0$*. Similarly, there exists a unique* $p_1^{*(2)}(c_1, \bar{c}, c_2, A) \in [0,1]$ *such that* $d_2 = 0$*.*

[25] Since d_1 and d_2 (defined in Lemma 2.1) are polynomials of more than one degree, it is necessary to know whether there are solutions lying in the interval of [0,1].

(2) When presented in $(p,\bar{c})$ space with $\bar{c} \in [c_1, c_2]$, if market demand is sufficiently high (i.e., $A > \dfrac{2c_2^2}{3c_2 - c_1} + c_1$), $p_1^{*(1)}(c_1,\bar{c},c_2,A) > p_2^*(c_1,\bar{c},c_2)$ for all $\bar{c} \in (c_1, c_2]$ and with equality at $\bar{c} = c_1$.

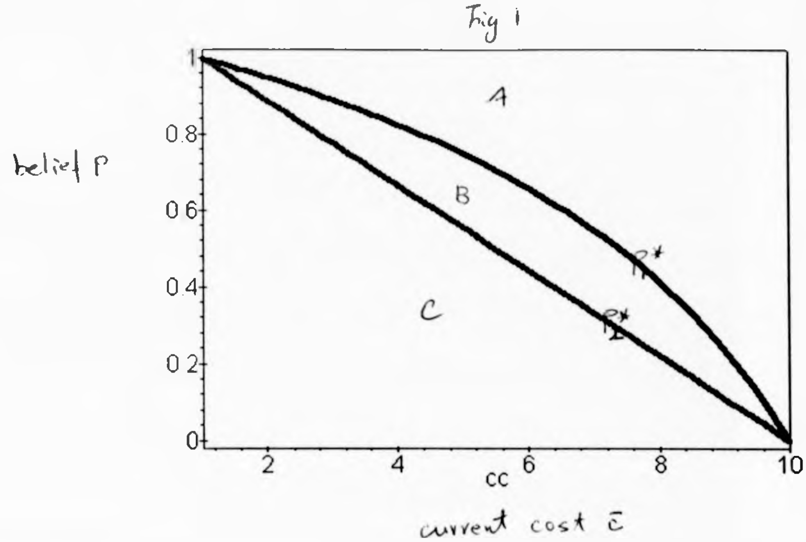
The proof is in Appendix 2.1. This lemma says that LR adopts a cut-off strategy in its adoption decision, and the cut-off value is proved to be higher than SR's cut-off point except when $\bar{c} = c_1$. Notice that $p_1^{*(1)}(c_1,\bar{c},c_2,A) \geq p_2^*(c_1,\bar{c},c_2)$ actually means that when SR does not want to adopt, it is also optimal for LR not to adopt. The more interesting case is when $p_1^{*(2)}(c_1,\bar{c},c_2,A)$[26] also lies to the right of $p_2^*(c_1,\bar{c},c_2)$. Hence in the following, we concentrate on this case. To illustrate this theoretical result, a numerical case $(c_1, c_2, A) = (1, 10, 50)$ is presented as Fig. 1.

As shown in Lemma 2.1 that except for $\bar{c} = c_1$, $p_1^{*(2)} > p_2^*$ for every $\bar{c}$, we can divide the rectangle $[0,1] \times [c_1, c_2]$ into three areas: A, B and C. The main result of this model is summarised as Proposition 2.1.

Proposition 2.1

A pure strategy equilibrium says that when the prior and current production cost pair $(p,\bar{c})$ is located in area A, LR will adopt first; when it is in B, SR will adopt first; and when it is in C, no adoption will happen. In other words, depending on parameters, the LR firm may or may not adopt earlier than the SR firm, or both firms will not adopt at all.

[26] The explicit function form of p_1^* is,
$$p_1^* = \{-2c_1A + 5Ac_2 + c_1c_2 + c_1\bar{c} + 4c_2\bar{c} - 3A\bar{c} - 5c_2^2 - \bar{c}^2 - [4c_2^4 - 20Ac_2^3 + 9A^2\bar{c}^2 - 4A\bar{c}^3 + c_2^2c_1^2 + 4c_2^3c_1 + \bar{c}^2c_1^2 + 4\bar{c}^3c_1 + 12c_2^2\bar{c}^2 - 16c_2\bar{c}^3 - 20A^2c_1c_2 + 12A^2c_1\bar{c} - 4Ac_1^2c_2 - 4Ac_1^2\bar{c} + 10Ac_1c_2^2 - 22Ac_1\bar{c}^2 - 30A^2c_2\bar{c} + 16Ac_2\bar{c}^2 + 2c_2c_1^2\bar{c} - 24c_2^2c_1\bar{c} + 8c_2c_1\bar{c}^2 + 28Ac_1c_2\bar{c} + 4A^2c_1^2 + 25A^2c_2^2 + 4\bar{c}^4]^{1/2}\} / (c_2 - \bar{c})(2c_1 + \bar{c} - 3c_2).$$



The existence of area B is the most interesting result of this model. The possibility of waiting gives LR an information advantage from delaying adoption, meaning that if SR ever adopts at $t=1$, LR can benefit by making production decisions under certainty. Hence compared to SR, the LR firm tends to be more conservative towards adoption, which can be seen from $p_1^{*(2)} > p_2^*$. Areas A and C coincide with Reinganum (1983) in the sense that if the current costs are sufficiently high (low), both (neither) of the firms will adopt. Moreover, we know from Lemma 2.1 that when both firms adopt in the first stage, LR will adopt first. Area B indicates the case when current cost is at an intermediate level. As LR's cost benefit form early adoption is less that the information advantage, so LR forgoes its priority in adoption.

The comparative statics about the equilibrium is presented in Proposition 2.2.

Proposition 2.2

(1) $p_1^{*(2)}(c_1,\bar{c},c_2,A)$ is increasing with c_1,c_2, and A, but decreasing with $\bar{c}$.
(2) $p_2^*(c_1,\bar{c},c_2)$ is increasing with c_1,c_2, but decreasing with $\bar{c}$.

The proof is in Appendix 2.1. Moreover, we can derive some implications regarding the possibility of each result in Corollaries 1-3.

Corollary 1. *The possibility that LR adopts earlier increases with the current cost.*

The possibility that LR will adopt earlier is described by $1 - p_1^{*(2)}(c_1, \bar{c}, c_2, A)$, which is area A in Fig 1. Combining the fact that p_1^* is decreasing with $\bar{c}$, we know that this possibility is increasing with the current cost. A higher current cost means that LR has higher cost benefit from adoption than in a lower cost case.

Corollary 2. *The possibility that neither firm adopts decreases with the current cost.*

The possibility that neither firm will adopt is described by $p_2^*(c_1, \bar{c}, c_2)$, which is area C. Again this is simply shown by the effect that p_2^* is decreasing in $\bar{c}$. A further implication is about the market concentration after adoption:

Corollary 3 *For a given current production cost and prior, if LR adopts a successful innovation earlier, the second stage market concentration*[27] *will remain at the pre-adoption level and the first stage market concentration will decrease.*

The second stage's market concentration following LR's successful adoption will remain at the pre-adoption level[28]: $\frac{2}{3}$. The intuition is because: if the cost decreases after adoption, the SR firms will follow suit immediately. As both LR and SR will produce

[27] Market concentration is defined as the ratio of LR's realised profit to SR's profit. Since the assumption of oligopoly, the alternative definition in terms of firm number does not suit our model.

[28] LR's second stage profit for successful adoption is: $\frac{(A-c_1)^2}{8}$; SR's profit is: $\frac{(A-c_1)^2}{16}$. Hence the concentration rate is $\frac{2}{3}$.

with a lower cost, the market concentration will remain the same. However, for the first stage, since LR's ex-ante output[29] will be lower than the optimal output for c_1, together with the fact that SR will produce the optimal output with cost c_1 (hence having a higher profit), we know that the concentration ratio will be lower than the current level. An interpretation for this disadvantage from adoption is the existence of high spillover effect (perfect learning). Hence, despite some empirical studies concluding that large firms adopting earlier will increase the market concentration (e.g., Hannan and McDowell (1990)[30]), our result says that the reverse will happen if the spillover or imitation effect is very strong.

The impact of increasing c_1 and c_2 is equivalent to decreasing the proportion of the cost reduction from a successful adoption over the cost increase from a unsuccessful adoption (i.e., $\frac{\bar{c} - c_1}{c_2 - \bar{c}}$). Hence, the impact from increasing c_1 and c_2 is the opposite of the effect of increasing $\bar{c}$. Finally, increasing the market demand raises the cut-off value $p_1^*(c_1, \bar{c}, c_2, A)$, and hence also decreases the possibility that LR adopts earlier. We can see the intuition for LR's conservative attitude from its expected profit functions: comparing π^a_{LR} and $\pi^W_{LR}(2)$ shows that the comparative advantage from adopting rather than waiting mainly comes from the cost benefit in the first stage. When market demand increases, the relative importance of the cost benefit decreases and hence LR is more likely to wait.

[29] LR's exante output for adopting in the first stage is: $q^{*a}_{LR} = \frac{1}{2}(A - pc_1 - 2(1-p)c_2 + (1-p)\bar{c})$; LR's optimal output for cost c_1 *is* $q^{*a}_{LR} = \frac{1}{2}(A - c_1)$.

[30] Hannan and McDowell (1990) give this conclusion from investigating bank adoptions of automated teller machines.

2.3 Welfare Analysis

In this section, the welfare effect is analysed by supposing a central planner, who wishes to decide which firm should adopt first if it is to be better for the whole economy[31].

This planner is also uncertain about the profitability of the innovation. To avoid confusion, let p_g be the planner's belief that the innovation will decrease the production cost to c_1. Each firm's belief and cost parameters are known by the planner. To see which firm should adopt first from the welfare point of view, we need to calculate the welfare effect for each decision. Let $W_i^{j,k}$ denote the realised welfare for each stage $i = 1,2$, each of LR's decision $j = a, w$ (a for adopting and w for waiting), and each possible result of the adoption $k = g, b$ (g for success and b for failure). Define $W_i^{j,k} = CS_i^{j,k} + \sum_{n=LR,SR} \pi_{in}^{j,k}$, which is the sum of consumer surplus $CS_i^{j,k}$ and the firms' realised profits $\pi_{in}^{j,k}$. With linear demand, we can easily calculate consumer's surplus ($= \frac{1}{2}(total\ output)^2$), and LR and SR's realised profits can be derived similarly to the analysis of each firm's adoption decision. The definition of $W_1^{a,g}$ is explained in detail here and we leave the others for Appendix 2.2. $W_1^{a,g}$ is stage 1's welfare level when LR decides to adopt first (a) and the planner thinks the adoption is going to be successful (g), which is:

$$\begin{aligned} W_1^{a,g} &= \tfrac{1}{2}\left[q_{LR}^a + q_{SR}^a(q_{LR}^a,1)\right]^2 + \left\{(A - q_{LR}^a - q_{SR}^a(q_{LR}^a,1))q_{LR}^a - c_1 q_{LR}^a\right\} \\ &\quad + \left\{(A - q_{LR}^a - q_{SR}^a(q_{LR}^a,1))q_{SR}^a(q_{LR}^a,1) - c_1 q_{SR}^a(q_{LR}^a,1)\right\}. \end{aligned} \tag{2.6}$$

---

[31] The welfare effect is restricted to a single industry and the assumption that the income effect is zero, that is, we are not using a general equilibrium approach.

q^a_{LR} is LR's first stage optimal output if it decides to adopt first (see footnote 26 for the explicit form of q^a_{LR}), and $q^a_{SR}(q^a_{LR},1)$ is SR's reaction function for $p=1$. Remember that in this case, the central planner thinks the adoption will be successful, so after LR's adoption the planner will expect SR to update its prior to $p=1$, adopt the technology and set its output as $q^a_{SR}(q^a_{LR},1)$. Hence the consumer surplus will be $\frac{1}{2}\left[q^a_{LR}+q^a_{SR}(q^a_{LR},1)\right]^2$, which is half of the squared total output in the industry. The second term $\left\{(A-q^a_{LR}-q^a_{SR}(q^a_{LR},1))q^a_{LR}-c_1q^a_{LR}\right\}$ is LR's realised profit for this case, where the central planner anticipates LR's production cost to be $c_1q^a_{LR}$. The definition for SR's realised profit $\left\{(A-q^a_{LR}-q^a_{SR}(q^a_{LR},1))q^a_{SR}(q^a_{LR},1)-c_1q^a_{SR}(q^a_{LR},1)\right\}$ can be explained in the same way.

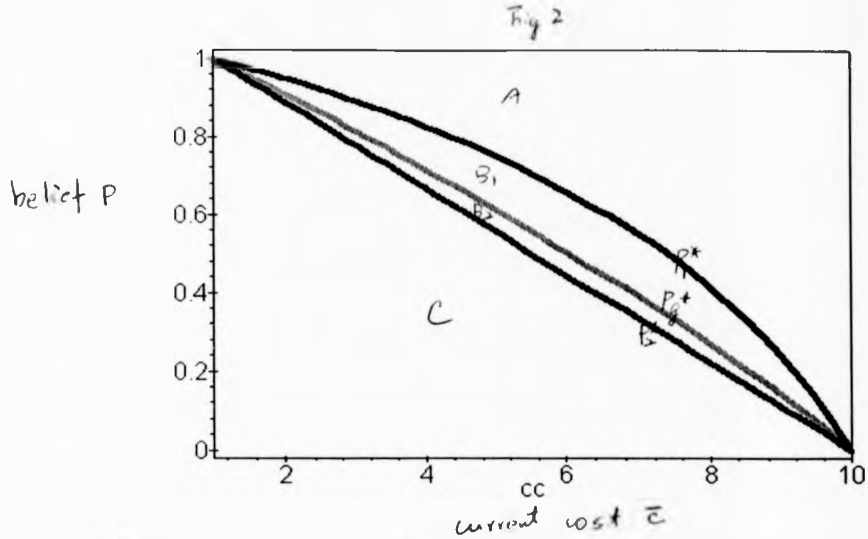
For this central planner, LR adopting earlier will be better for the whole economy if:

$$p_g(W_1^{a,g}+W_2^{a,g})+(1-p_g)(W_1^{a,b}+W_2^{a,b})\geq p_g(W_1^{w,g}+W_2^{w,g})+(1-p_g)(W_1^{w,b}+W_2^{w,b}) \quad (2.7)$$

By setting $p_g=p$, we can calculate the planner's cut-off belief p_g^*, when there is no welfare difference for LR to adopt or to wait in the first stage. Unfortunately, due to the complication of function form[32], it is not easy to derive any general implication from this cut-off belief. However, with the same numerical example (c_1,c_2,A)=(1,10,50) as Fig 1, we have Fig 2.

[32] The explicit form of p_g^* is:

$$p_g{}^* = \{-10c_1A+15Ac_2-5A\bar{c}-13c_1c_2+11c_1\bar{c}+36c_2\bar{c}+6c_1^2-19c_2^2-21\bar{c}^2-[196c_2^4-420Ac_2^3 +25A^2\bar{c}^4-120A\bar{c}^3+601c_2^2c_1^2-156c_2c_1^3-364c_2^3c_1-71\bar{c}^2c_1^2+132\bar{c}c_1^3-504\bar{c}^3c_1+420c_2^2\bar{c}^2-1008c_2\bar{c}^3 -300A^2c_1c_2+100A^2c_1\bar{c}-160Ac_1^2c_2+320Ac_1^2\bar{c}+770Ac_1c_2^2-110Ac_1\bar{c}^2-150A^2c_2\bar{c}+40Ac_2^2\bar{c} +420Ac_2\bar{c}^2-574c_2c_1^2\bar{c}-880c_2^2c_1\bar{c}+1764c_2c_1\bar{c}^2-620Ac_1c_2\bar{c}+100A^2c_1^2-120Ac_1^3+225A^2c_2^2 +36c_1^4+408\bar{c}^4]^{1/2}\}/\{-26c_1c_2-14c_1\bar{c}+36c_2\bar{c}+20c_1^2-5c_2^2-11\bar{c}^2\}.$$



When a $(p,\bar{c})$ pair is located above p_g^*, the central planner will think it optimal for LR to adopt first, and for SR to react to LR's adoption result afterwards; when a $(p,\bar{c})$ pair is below p_g^*, the central planner will think it optimal for LR to wait, and respond optimally after observing SR's adoption at stage one. Notice that in Fig 2, p_g^* lies between p_1^* and p_2^*, indicating a gap between the planner's desired equilibrium and the actual equilibrium. When $(p,\bar{c})$ is in area A or C, the actual equilibrium coincides with the planner's desired equilibrium.

Interesting implications come from areas B_1 and B_2. Area B_2 is the case when both the actual and desired equilibria are characterised by LR waiting and SR adopting in the first stage. In other words, there is no conflict between LR's decision and welfare. Area B_1 is the situation when the actual equilibrium describes LR to wait and SR to adopt in the first stage, but the desired equilibrium says LR should adopt earlier. In other words, area B_1 denotes a situation when LR's optimal decision will cause welfare inefficiency. The intuition for the relatively optimistic attitude of the central planner is because the expected cost increase from an unsuccessful adoption for the whole society is less than that for the LR firm alone. Hence, the area B_1 illustrates a need for policy intervention in firms' adoption decisions about this cost uncertain innovation. An example of government interventions in technology adoption is in the water industry, where water price reforms are increasingly used to encourage improvements in irrigation efficiency (Green et al. (1996)).

2.4. Conclusion and Further Research

Although most of the evidence shows large firms' leadership in adopting new technologies, there are some cases when small firms do adopt earlier. The existing literature can only explain one possible outcome which asserts that large firms always adopt earlier. To interpret the missing aspect, the present paper proposes a two-stage, endogenous learning, Stackelberg model to analyse firms' adoption decisions towards an innovation with uncertain profitability. By assuming identical prior and cost for each firm, our model derives a pure strategy equilibrium in which the LR firm may adopt first, the SR firm may adopt first, or neither of them may adopt. More specifically, it is concluded that when current cost or the belief is sufficiently high, the LR firm is more likely to adopt first. The SR firm will adopt first for intermediate levels of initial cost and belief, and no adoption will happen if initial cost or belief is sufficiently low. This result explains the missing aspect in the adoption literature. The comparative statics shows that the possibility of LR adopting earlier is negatively related to market demand and positively related to the ratio of possible cost reduction over possible cost increase. It also says that the realised market concentration for LR adopting early is very likely to fall below the pre-adoption level. The welfare analysis provides a justification for policy intervention with firms' adoption decisions. An interesting extension of the model is to assume that there are more than one following firms. By forming an adoption coalition, there could be an equilibrium where one small firm takes the lead in adoption under co-ordination. Moreover, since adoption is basically an irreversible investment, the model can be applied to various investment cases, such as the launch of McDonald into the Chinese market. The uncertainty associated with the investment may come from consumers' preferences, and natural or bureaucratic environments. We leave the detail for future discussion.

Appendix 2.1

Proof for Lemma 2.1: (1) Recall the definitions of π^{u}_{LR}, $\pi^{W}_{LR}(1)$ and $\pi^{W}_{LR}(2)$ from equation (2.3), (2.4) and (2.5). Calculate the optimal outputs and substitute into the respective profit functions. In order to tell the sign of the derivative, the envelope theorem is applied to the first term of equations (2.3) and (2.5):

$$
\begin{aligned}
\partial d_1 / \partial p &= 0 - \left[\tfrac{1}{2} q^{*u}_{LR}(2c_2 - c_1 - \bar{c}) + \tfrac{1}{8}(2c_2 - \bar{c} - c_1)(2a - 2c_1 - \bar{c} + 2c_2)\right] < 0, \\
d_1\big|_{p=0} &= (A - c_2)(c_2 - \bar{c}) > 0, \\
d_1\big|_{p=1} &= \tfrac{1}{4}(\bar{c} - c_1)(c_2 - 2A + \bar{c}) < 0.
\end{aligned}
$$

and

$$
\begin{aligned}
\partial d_2 / \partial p &= \left[\tfrac{1}{2}(c_1 - c_2) q^{*W}_{LR}(2) - \tfrac{1}{8}(A - \bar{c})^2\right] - \left[(c_2 - \tfrac{1}{2}c_1 - \tfrac{1}{2}\bar{c}) q^{*u}_{LR} - \tfrac{1}{8}(A - \bar{c} - 2c_2)^2\right] < 0, \\
d_2\big|_{p=0} &= \tfrac{1}{8}(c_2 - \bar{c})(10A - 7c_2 - 3\bar{c}) > 0, \\
d_2\big|_{p=1} &= \tfrac{1}{2}(c_1 - \bar{c})(A - \bar{c}) < 0.
\end{aligned}
$$

$q_{IR}^{*u} = \frac{1}{2}(A - pc_1 - 2(1-p)c_2 + (1-p)\bar{c})$ is the optimal output for the first maximising term of π_{IR}^{u}, and $q_{IR}^{*W}(2) = \frac{1}{2}(A + pc_1 + (1-p)c_2 - 2\bar{c})$ is the optimal output for the first maximising term of $\pi_{IR}^{W}(2)$. Since both functions are negatively related to p and the function values at $p = 0$ and $p = 1$ have different signs, we can conclude that there exists a unique $p_1^{*(1)}(c_1, \bar{c}, c_2, A) \in [0,1]$ such that $d1 = 0$ and a unique $p_1^{*(2)}(c_1, \bar{c}, c_2, A) \in [0,1]$ such that $d2 = 0$.

(2) The proof of the second part of the proposition is less intuitive, because the explicit forms of $p_1^{*(1)}$ and $p_1^{*(2)}$ are complicated. However, several properties can be examined to obtain general implications regarding $p_1^{*(i)}$ and p_2^{*} in $(p,\bar{c})$ space. Firstly, when $\bar{c} = c_1$, both $p_1^{*(1)}$ and $p_1^{*(2)}$ will be one. When $\bar{c} = c_2$, these values are not defined, because the denominators of $p_1^{*(i)}$ are 0. However, by applying L'Hospital's rule, it can still be checked that both $p_1^{*(1)}$ and $p_1^{*(2)}$ approach 0 when $\bar{c}$ approaches c_2. Secondly, it can be calculated that both $p_1^{*(1)}$ and $p_1^{*(2)}$ intersect with p_2^{*} only once at the corner $(p,\bar{c}) = (1, c_1)$. Thirdly, by applying the implicit function theorem, we know $\frac{\partial p_1^{*(1)}}{\partial \bar{c}} < 0$ and $\frac{\partial p_1^{*(2)}}{\partial \bar{c}} < 0$, where

$$\frac{\partial p_1^{*(1)}}{\partial \bar{c}} = -\frac{\partial d_1 / \partial \bar{c}}{\partial d_1 / \partial p} = -\frac{\{(-\frac{1}{2}A + \frac{1}{2}\bar{c}) - \frac{1}{2}(1-p)q_{IR}^{u} + \frac{1}{2}(1-p)(\frac{1}{2}A + \frac{1}{2}\bar{c} - c_2)\}}{\partial d_1 / \partial p} < 0,$$

and

$$\frac{\partial p_1^{*(2)}}{\partial \bar{c}} = -\frac{\partial d_2 / \partial \bar{c}}{\partial d_2 / \partial p} = -\frac{\{(-q_{IR}^{W} - \frac{1}{2}(1-p)(\frac{1}{2}A - \frac{1}{2}\bar{c})) - \frac{1}{4}(1-p)(2q_{IR}^{u} + A + \bar{c} - 2c_2)\}}{\partial d_2 / \partial p} < 0$$

Moreover at the point $(p,\bar{c}) = (1, c_1)$, the slopes of $p_1^{*(1)}$ and $p_1^{*(2)}$ are bigger than p_2^{*} for sufficiently high market demand, i.e.,

$$\frac{-\partial p_1^{*(1)} / \partial \bar{c}}{-\partial p_2^{*} / \partial \bar{c}} = \frac{\frac{2(A-c_1)}{(c2-c1)(4A-5c_1+2c_2)}}{\frac{1}{(c_2-c_1)}} < 1 \,,$$

and

$$\frac{-\partial p_1^{*(2)} / \partial \bar{c}}{-\partial p_2^{*} / \partial \bar{c}} = \frac{\frac{2(A-c_1)}{3c_1^2-3c_1A+5c_2A-5c_2c_1-2c_2^2}}{\frac{1}{(c_2-c_1)}} < 1, \qquad \text{if} \qquad A > \frac{2c_2^2}{3c_2-c_1} + c_1 \,.$$

Hence, we can conclude that if market demand is sufficiently high, then $p_1^{*(i)}(c_1,\bar{c},c_2,A) > p_2^{*}(c_1,\bar{c},c_2)$ for all $\bar{c} \in (c_1, c_2]$ and with equality at $\bar{c} = c_1$. Q.E.D.

Proof for Proposition 2.2: (1) Lemma 2.1 shows that $p_1^{*(2)}$ decreases with respect to $\bar{c}$. The rest is proved by applying the implicit function theorem and the envelope theorem:

$$\frac{\partial p_1^{*(2)}}{\partial c_1} = -\frac{\partial d_2 / \partial c_1}{\partial d_2 / \partial p} = -\frac{\{\frac{1}{2} pq_{LR}^{*W}(2) + \frac{1}{2} pq_{LR}^{*a}\}}{\partial d_2 / \partial p} > 0 \,,$$

$$\frac{\partial p_1^{*(2)}}{\partial c_2} = -\frac{\partial d_2 / \partial c_2}{\partial d_2 / \partial p} = -\frac{\{\frac{1}{2}(1-p)q_{LR}^{*W}(2) - [(p-1)q_{LR}^{*a} + \frac{1}{2}(p-1)(A+\bar{c}-2c_2)]\}}{\partial d_2 / \partial p} > 0 \,,$$

and

$$\frac{\partial p_1^{*(2)}}{\partial A} = -\frac{\partial d_2 / \partial A}{\partial d_2 / \partial p} = -\frac{\{[\frac{1}{2}q_{LR}^{*W}(2) + \frac{1}{2}(1-p)(\frac{1}{2}A - \frac{1}{2}\bar{c})] - [\frac{1}{2}q_{LR}^{*a} + \frac{1}{2}(1-p)(\frac{1}{2}A + \frac{1}{2}\bar{c} - c_2)]\}}{\partial d_2 / \partial p} > 0$$

$$\text{if} \qquad p > p_2^{*} \,.$$

$q_{LR}^{*W}(2)$ and q_{LR}^{*a} are defined in the proof of Lemma 2.1.
(2) It can be checked from the definition. Q.E.D.

Appendix 2.2

The following optimal outputs are from LR and SR's maximisation problems, and will be applied to the calculation of $W_i^{j,k} = CS_i^{j,k} + \sum_{n=LR,SR} \pi_{in}^{j,k}$.

$$q_{LR}^{a} = q_{LR}^{a*} = \tfrac{1}{2}(A - pc_1 - 2(1-p)c_2 + (1-p)\bar{c}) \,,$$
$$q_{LR}^{W}(2) = q_{LR}^{W*}(2) = \tfrac{1}{2}(A + pc_1 + (1-p)c_2 - 2\bar{c}) \,,$$
$$q_{LR}(1) = \tfrac{1}{2}(A - c_1) \,,$$
$$q_{LR}(0) = \tfrac{1}{2}(A - c_2) \,,$$
$$q_{SR}^{a}(q_{LR}, p) = \tfrac{1}{2}(A - q_{LR} - (pc_1 + (1-p)c_2)) \,,$$
$$q_{SR}^{na}(q_{LR}) = \tfrac{1}{2}(A - q_{LR} - \bar{c}) \,.$$

$$W_1^{a,g} = \tfrac{1}{2}\left[q_{LR}^{a} + q_{SR}^{a}(q_{LR}^{a},1)\right]^2 + \left\{(A - q_{LR}^{a} - q_{SR}^{a}(q_{LR}^{a},1))q_{LR}^{a} - c_1 q_{LR}^{a}\right\}$$

$$+\left\{(A - q_{LR}^{a} - q_{SR}^{a}(q_{LR}^{a},1))q_{SR}^{a}(q_{LR}^{a},1) - c_1 q_{SR}^{a}(q_{LR}^{a},1)\right\} \tag{2.6}$$

$$W_1^{a,b} = \tfrac{1}{2}\left[q_{LR}^{a} + q_{SR}^{na}(q_{LR}^{a})\right]^2 + \left\{(A - q_{LR}^{a} - q_{SR}^{na}(q_{LR}^{a})q_{LR}^{a} - c_2 q_{LR}^{a}\right\}$$

$$+\left\{(A - q_{LR}^{a} - q_{SR}^{na}(q_{LR}^{a}))q_{SR}^{na}(q_{LR}^{a}) - \bar{c}q_{SR}^{na}(q_{LR}^{a})\right\} \tag{2.6-1}$$

$$W_1^{w,g} = \tfrac{1}{2}\left[q_{LR}^{w} + q_{SR}^{a}(q_{LR}^{w},p)\right]^2 + \left\{(A - q_{LR}^{w} - q_{SR}^{a}(q_{LR}^{w},p))q_{LR}^{w} - \bar{c}q_{LR}^{w}\right\}$$

$$+\left\{(A - q_{LR}^{w} - q_{SR}^{a}(q_{LR}^{w},p))q_{SR}^{a}(q_{LR}^{w},p) - c_1 q_{SR}^{a}(q_{LR}^{w},p)\right\} \tag{2.6-2}$$

$$W_1^{w,b} = \tfrac{1}{2}\left[q_{LR}^{w} + q_{SR}^{a}(q_{LR}^{w},p)\right]^2 + \left\{(A - q_{LR}^{w} - q_{SR}^{a}(q_{LR}^{w},p))q_{LR}^{w} - \bar{c}q_{LR}^{w}\right\}$$

$$+\left\{(A - q_{LR}^{w} - q_{SR}^{a}(q_{LR}^{w},p))q_{SR}^{a}(q_{LR}^{w},p) - c_2 q_{SR}^{a}(q_{LR}^{w},p)\right\} \tag{2.6-3}$$

$$W_2^{a,g} = W_2^{w,g} = \tfrac{1}{2}\left[q_{LR}(1) + q_{SR}^{a}(q_{LR}(1),1)\right]^2 + \left\{(A - q_{LR}(1) - q_{SR}^{a}(q_{LR}(1),1))q_{LR}(1) - c_1 q_{LR}(1)\right\}$$

$$+\left\{(A - q_{LR}(1) - q_{SR}^{a}(q_{LR}(1),1))q_{SR}^{a}(q_{LR}(1),1) - c_1 q_{SR}^{a}(q_{LR}(1),1)\right\} \tag{2.6-4}$$

$$W_2^{a,b} = \tfrac{1}{2}\left[q_{LR}(0) + q_{SR}^{na}(q_{LR}(0))\right]^2 + \left\{(A - q_{LR}(0) - q_{SR}^{na}(q_{LR}(0)))q_{LR}(0) - c_2 q_{LR}(0)\right\}$$

$$+\left\{(A - q_{LR}(0) - q_{SR}^{na}(q_{LR}(0)))q_{SR}^{na}(q_{LR}(0)) - \bar{c}q_{SR}^{na}(q_{LR}(0))\right\} \tag{2.6-5}$$

$$W_2^{w,b} = \tfrac{1}{2}\left[q_{LR}^{na} + q_{SR}^{na}(q_{LR}^{na})\right]^2 + \left\{(A - q_{LR}^{na} - q_{SR}^{na}(q_{LR}^{na}))q_{LR}^{na} - \bar{c}q_{LR}^{na}\right\}$$

$$+\left\{(A - q_{LR}^{na} - q_{SR}^{na}(q_{LR}^{na}))q_{SR}^{na}(q_{LR}^{na}) - \bar{c}q_{SR}^{na}(q_{LR}^{na})\right\} \tag{2.6-6}$$

3. Optimal Contract Design for Long-term Projects With Moral Hazard and Adverse Selection

3.1 Introduction

Most R&D funding contracts take the form of "long-term contracts". The reason is not only because a long-term contract is an optimal way to implement efficient investments (if possible), but also, most importantly, because R&D activities are actually time consuming and the results of R&D are either successful or not (binary). One can think of the research for AIDS medicine for example: although AIDS was first identified in 1981, there is still no effective remedy today. Due to the fact that researchers usually possess better knowledge about the research object and their effort is not easy to verify, the monitoring or progress-checking devices that we usually find in, say, construction contracts are not really applicable to R&D projects. The purpose of this paper is therefore to design an optimal funding contract for activities that are time consuming and confronted with opportunism[33] problems.

Despite the fact that R&D expenditures have been increasing year by year, for example, "Japanese government spending on science and technology has increased about 5% annually over the last decade"[34], there is little theoretical literature specifically

[33] Throughout this chapter, the terms "opportunism" and "moral hazard" will be interchangeably used.
[34] From East Asian Executive Reports (1996).

addressing the issues of R&D funding[35]. One exception is Aghion and Tirole (1994), who mention the funding issue in their discussion of property right allocation and innovation efficiency. Funding is interpreted as a specific investment from the financier. Their basic argument is similar to Grossman and Hart (1986), that is, the choice of property right should best protect two parties' (the research unit and the financier) specific investments in the relationship. Since the agent's effort and the financier's investment are substitutable for the success of the innovation, it is possible that the financier alone can undertake R&D if she owns the right for the innovation. In the present model, we suppose that both the agent's effort and principal's financing are indispensable in the relationship. More specifically, we assume that the completion of R&D depends only on the agent's effort, but the agent has no initial wealth and hence is unable to put in effort without the principal's funding. Our setting is closer to reality for both the employee-inventors and independent research units cases. In addition, our discussion of the long-term compensation scheme, the adverse selection problem, auctions, and the choice of long-term and short-term contracts is not addressed in their paper.

There has been an extensive literature on optimal contract design with moral hazard and adverse selection problems. Hart and Holmstrom (1987) provide a comprehensive review of contract theory. Most of the literature addresses implications on financial[36], labour[37] and procurement[38] issues, but the topic of funding a long-term activity is seldom mentioned. Hence, the present model can provide a guideline to a broad context of funding contracts, especially for time consuming projects. Moreover, the present model

[35] There are several discussions on agents' pre-auction R&D investments, for example, Piccione and Tan (1996). However, this is not the issue addressed in the present paper.
[36] For example, Chemmanur and John (1996), and Singh (1997).
[37] For example, Baily (1974), Gorden (1974), Addison and Chilton (1997).
[38] For example, Cox et al. (1996), Piccione and Tan (1996).

contributes to the determination of contract length (duration), optimal auctioning contract, and the choice between long-term and short-term contracts.

Firstly, there is only a small literature examining the determination of contract length. Under the assumption that new information is resolved over time, Dye (1985) emphasises the incompleteness of contracting under uncertainty and shows that it is efficient to recontract in response to the arrival of new information. In a labour market model, Cantor (1987) also argues that a contract needs to be expired to revise wages to adjust to the new information. Cantor stresses the deterministic rather than the stochastic (Dye) property of the expiry date. By assuming costly observation of the information, Harris and Holmstrom (1987) determine the contract length as the period between costly observations. Bodman and Devereux (1993) argue that the optimal contract duration depends on a trade-off between the benefit of wage rigidity and the cost of lacking flexibility. In the present model, the optimal contract length stands for the funding periods during which the agent puts in full effort in a time consuming project.

Secondly, when there is more than one candidate for a project, an auction is usually held to select the agent to undertake the project. Section 3.5 derives the optimal auction form via mechanism design. This approach is pioneered by the work of Harris and Raviv (1982), Myerson (1981), Riley and Samuelson (1981), Milgrom and Weber (1982), Matthews (1983), and Maskin and Riley (1984). Moreover, Milgrom (1987) and McAfee and McMillan (1987) provide excellent reviews of early auction literature. Laffont and Tirole (1987) bridge the connection between auctions and incentive contracts. In the first part of this section, we follow Laffont and Tirole's approach and solve the optimal auctioning contract. Later, the result from the optimal auction is compared to another auction form: the second-price auction (SPA). An interesting result arises from the comparison: when agents are bidding for the project's total expenditure, neither the *revenue equivalence theorem* nor the *separation property* will hold when there is a moral hazard problem in the long term contract. We also derive some notes on "built-in cost-overruns", mentioned by Scherer (1964) in research on US weapon procurements. The connection between selection bias and cost overrun has been mentioned by Quirk and Terasawa (1984), and Gaspar and Leite (1989/1990) in common value and single stage models. Since their selection rule is to assign the project to the lowest cost bidder, neither an actual auction form nor the opportunism problem is discussed in their papers.

Finally, in the context of symmetric beliefs[39] where both parties have identical beliefs about the time needed for completion, our model draws implications on the choice of long-term and short-term contracts. There have been many debates on this topic, for example, Barcena-Ruiz and Espinosa (1996) stress the strategic role of the intertemporal dimension of contracts in a duopoly market, and since in the linear case there is strategic substitution in the product market, the incentive variables (contract lengths) are also strategic substitutes. Hence a long-term contract makes a firm a leader in incentive, while a short-term contract makes it a follower. Under Bertrand competition, the equilibrium has one firm sign a long-term contract and the other firm sign a short-term incentive contract; however, under Cournot competition, both firms' dominant strategies are to sign a long-term incentive contract. Another important issue in the literature is whether long-term efficiency can be implemented by a series of short-term contracts. For instance, Chiappori et al. (1994) show that two conditions are necessary for the optimal long-term contract to be implemented by spot contracts: (1) the long-term optimum should be renegotiation-proof; (2) spot contracts should provide efficient consumption smoothing. As pointed out by Rey and Salanie (1996), this approach ignores the discussion about

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[39] This is corresponding to the stochastic setting in the R&D literature (e.g., Lee and Wilde (1980), Reinganum (1982), Harris and Vickers (1987)).

both moral hazard and adverse selection problems at the contracting date. They instead analyse a multi-period agency model with adverse selection, and conclude that renegotiable short-term contracts can be as efficient as long-term renegotiation-proof contracts. However, some limited commitments are both necessary and sufficient to achieve the long-term efficiency. The present model shows that when contract renewal is not anticipated by the involved parties, a sequence of short-term contracts is better than one single long-term contract from the principal's point of view. Intuitively, since short-term contracts provide the involved parties opportunities to update their beliefs, the principal can pay less incentive rent to induce the same amount of effort in the presence of a moral hazard problem.

To emphasise the opportunism problem and to set a benchmark of efficiency, the basic model in Chapter 3 first supposes that the total time (expense) needed to complete the project is deterministic and known by both the principal and the agent. With a further assumption of no initial wealth for the agent (so a penalty is impossible and there is a moral hazard problem), Section 3.2 derives the optimal contract form from a general compensation scheme, which implements the agent's full effort in the context of complete information. The optimal contract describes a funding period and an end-of-contract reward, which happens to be a multi-stage version of the "Cost-Plus-Fixed-Fee" (CPFF) contract in the literature.

Next, we consider the case where the agent has better information about the time needed for completion (due to experience or expertise). Following the literature, we denote the value that is better known by the agent as a "type[40]". Sections 3.3 and 3.4 hence determine the optimal contracts with both moral hazard and adverse selection problems for cases when the principal thinks the agent's type is discretely distributed and

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when it is continuously distributed. The discussion of both discrete and continuous settings serves two aims: (1) to see if the optimal contract will vary with the setting of type; (2) to provide a basic structure for the discussion of optimal auction design. The solution says that when there are only two types (a simplified discrete type setting), the optimal contract will not induce efficiency loss to either type, but instead pays an extra information rent to the efficient type[41]. The intuition is: any shortage in funding will result in the failure of R&D, hence the principal would rather pay more rent than lose the whole project value. When the type is continuously distributed, the principal will adopt a cut-off strategy in funding, that is, to stop funding for types greater than some critical value. It is concluded that the agent's production efficiency remains for efficient types (types smaller than the cut-off point), and the principal will take a more conservative attitude in funding, since the inefficient types will definitely take the contract and shirk.

Section 3.5 derives the optimal auctioning[42] contract in a discrete type setting, as it provides a clearer idea about how an auction works in our model. In the optimal auction, both allocation and production efficiency persist, that is, the project will be assigned to the bidder with the lowest cost and the winner(s) always finishes the project. The principal can benefit from the agents' competition in two ways. First, the project is more likely to be completed by an efficient type under an auction. Second, competition reduces the incentive rent for the efficient type as he is less likely to mimic the inefficient type who might have less chance to win. However, this rent reduction varies with the difference between the two types, that is, when the inefficient type is not sufficiently greater than the efficient type, the former might be better off shirking under the efficient type's contract (which gives him a higher winning probability). Hence, to motivate the

[41] The observation of types comes from the direct mechanism (to be discussed later).
[42] The agents' beliefs are assumed independent to avoid the complication from correlated beliefs.

inefficient type (and the efficient type) to choose his own contract, the principal has to reward more than when there is a big difference between the two types.

Finally, we relax the assumption of private information in Section 3.6, and assume that both parties have identical beliefs about the time needed for completion. This setting corresponds to the stochastic[43] nature in the R&D literature. Section 3.6 firstly discusses how opportunism affects the agent's shirking decisions under symmetric beliefs. The optimal contract is derived and we show that the principal's optimal funding length with an opportunism problem is no longer than the contract without an opportunism problem. Later, we introduce the possibility of contract renewal and show that under some constraints, the lock-in effect persists and the principal will prefer a sequence of short-term contracts to a long-term contract. The intuition is because the former provides both parties opportunities to update their beliefs in this symmetric setting.

The rest of the chapter is organised as follows. With unverifiable effort, Section 3.2 derives the optimal contract form from a general compensation scheme, which consists of a funding deadline and an end-of-contract reward. Sections 3.3 and 3.4 discuss both moral hazard and adverse selection problems in discrete and continuous type settings. Section 3.5 derives the optimal auctioning contract, the result of which is later compared to another auction form: SPA. Section 3.6 relaxes the assumption of private information and considers the case with symmetric beliefs about the time needed for completion. Section 3.7 contains conclusions and suggestions for further research.

3.2 The Model

[43] Most R&D models adopt the exponential distribution function (e.g. Lee and Wilde (1980)),which will be imposed in the following sections.

This section describes the basic structure of our model, including the involved parties, information structure, actions, payoff functions and the equilibrium. Our purpose is to find the optimal contract for a self-interested principal to assign an agent to undertake a time-consuming project. As we can see, most R&D projects are time-consuming, for example, the research for AIDS medicine. Although AIDS was first identified in 1981, there is still no effective remedy today. The assumption of a "self-interested" principal is in contrast to the assumption of a "benevolent" principal, which could be a government agency who wishes to find a regulation scheme for the benefit of the whole society. The case of multiple principals is not considered in this model; but the case where the principal selects among several candidates will be discussed in Section 3.5. It is assumed that the agent has limited liability and no initial wealth, and moreover he cannot maintain the residual profit, which implies that self-funding and financial penalty are impossible. It is further assumed that no non-pecuniary penalty is feasible. As this assumption could be too restrictive for most construction contracts, we probably need to concentrate on R&D contracts, where the "no penalty" assumption applies to most cases.

To emphasise the opportunism problem and to set a benchmark of efficiency, we first assume the innovation to be deterministic. More specifically, it is assumed that the project takes the agent Δ periods of effort under full capacity (i.e., no shirking). In each period, £1 will be needed to cover the agent's effort and rental costs, such as the labour wage, the rental cost for machine or lab equipment and the cost of inputs. Δ could be associated with the agent's cost structure or production technology. In this section, Δ is assumed to be known by the principal so that we can concentrate on the effect of opportunism problem. The cases with incomplete information will be discussed in the following sections. Finally, it is assumed that there is no discounting across time[44].

The design starts with the principal offering the agent a contract, including the funding of £1 each period till the deadline and a reward scheme. The agent responds by taking the offer or rejecting it[45]. If the agent rejects the offer, the project will not be undertaken and both parties have the reservation profits (normalised to zero); if the agent accepts the offer, he needs to make a sequence of working and shirking decisions which are *unobservable* or *too expensive* for the principal *to observe or monitor*. In other words, there is a moral hazard problem in the design of the optimal contract. This is again a fair assumption for R&D projects. However, whether there is ultimately an innovation or not will be publicly known. Concealing the innovation is excluded in our model. As this game features a leader (principal) and follower (agent) structure, we need to know the follower's best response to derive the optimal contract. The following first discusses the agent's response to an arbitrary contract and then derives the optimal contract form.

Consider an arbitrary contract which specifies a funding length of T periods, and a contingent reward scheme for the agent's effort. The funding is to give the agent £1 at the beginning of each period so that the agent is able to put in effort. Since the principal does not observe the agent's effort, the reward scheme can only depend on the observable variable: the completion date. For a committed completion date τ, denote $r_i(\tau)$ as the reward paid at the end of each period i from the moment that the contract is accepted. The whole reward scheme hence has the form $\bar{R}(\tau) := \{r_1(\tau), r_2(\tau), \ldots r_\tau(\tau), r_{\tau+1}(\tau), \ldots\}$. A

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[44] The no discounting assumption is to simplify the analysis, as the profit value is irrelevant to the agent. In Chapter 4, the discount factor is introduced to discuss the protection scheme when the success of investment will affect the agent's future profits.
[45] This excludes the possibility that the final contract is settled by a sequence of bargains.

contract c is defined as $c := \left\{T, \{\bar{R}(\tau)\}_{\tau=\Delta..\infty}\right\}$[46]. This general contract form considers the reward scheme for every possible finishing date $\tau \in \{\Delta...\infty\}$.

Given a contract c, the agent has to make a sequence of effort decisions at each time t. Since the funding stops after the deadline, an index f_t is introduced to distinguish funding periods from non-funding periods, i.e.,

$$
\begin{aligned}
f_t &= \pounds 1 \qquad \text{for } t \le T \\
&= 0 \qquad \text{for } t > T.
\end{aligned}
$$

With funding, if the agent puts in effort, £1 will be used up as effort and rental costs; if the agent decides to shirk, he can only divert an exogenous fraction α, $0 < \alpha < 1$, of £1 into his pocket. The sunk cost $(1-\alpha)$ comes from the rental or input cost which can not be avoided even if the agent shirks. Without funding (for $t > T$), the agent still spends £1[47] if he puts in effort, and since no funding is available, there will be no shirking benefit. Let e_t =1 if the agent's choice at time t is to put in effort, and e_t =0 if the agent chooses to shirk. Define n_t as the accumulated effort level up to time $t-1$, i.e. $n_t := \sum_{i=1}^{t-1} e_i$. We can write the agent's value function at time t as $W_t^c(n_t)$, where the superscript denotes the contract c and the subscript is the time index starting from the moment that the offer is accepted by the agent.

$$
\begin{aligned}
W_t^c(n_t) &:= \max\left\{f_t(1-(1-\alpha)) + r_t(\tau) + W_{t+1}^c(n_t),\ f_t - 1 + r_t(\tau) + W_{t+1}^c(n_t+1)\right\} \\
&= \max\left\{\alpha f_t + r_t(\tau) + W_{t+1}^c(n_t),\ f_t - 1 + r_t(\tau) + W_{t+1}^c(n_t+1)\right\}. \qquad (3.1)
\end{aligned}
$$

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[46] The renegotiation of the contract is excluded for the moment to simplify the discussion. However, later in Section 3.3, there will be some implications about the renegotiation issue.

[47] Since the agent can not fund himself, his choice must be shirking. However, we need to take into account this case to describe the decision function.

It is clear that $\alpha f_t > f_t - 1$. The terms in the brackets denote the values from shirking and putting in effort respectively. Equation (3.1) says that shirking gives the agent a higher current profit αf_t, a reward $r_t(\tau)$ and a next period value with accumulated effort level n_t; however, putting in effort gives him a lower current profit $f_t - 1$, the same reward $r_t(\tau)$ but higher accumulated effort $n_t + 1$ next period.

Given the agent's decision in equation (3.1), we next show that a single end-of-contract reward can implement the same effort vector as the reward scheme $\bar{R}(\tau)$. The argument proceeds in several steps. Firstly, since no effort will be needed after the completion of the project, there is no loss to squeeze the compensations after time τ to a sum of rewards which is paid at the end of period τ, that is, the compensation scheme becomes:

$$\left\{r_1(\tau), r_2(\tau), \ldots, r_{\tau-1}(\tau), \sum_{i=\tau}^{\infty} r_i(\tau), 0, 0, \ldots\right\}.$$

Secondly, the optimal rewards for time before the completion of the project should be independent of the completion date, that is, for $\tau \neq \tau'$, $r_i(\tau) = r_i(\tau')$ for $i < \min\{\tau, \tau'\}$. To see the reason, suppose $r_i(\tau) < r_i(\tau')$ for an arbitrary $i < \min\{\tau, \tau'\}$ and the others remain unchanged. We know from equation (3.1) that the agent's effort decisions with both $r_i(\tau)$ and $r_i(\tau')$ are the same. That is, if $\alpha f_t + r_t(\tau) + W_{t+1}^c(n_t) > f_t - 1 + r_t(\tau) + W_{t+1}^c(n_t + 1)$, then we still have $\alpha f_t + r_t(\tau') + W_{t+1}^c(n_t) > f_t - 1 + r_t(\tau') + W_{t+1}^c(n_t + 1)$, where by supposition $r_i(\tau) < r_i(\tau')$.

However, by replacing $r_i(\tau')$ with $r_i(\tau)$, the principal will be better off as the reward is costly to the principal. Therefore, we can rewrite the compensation scheme as:

$$\{r_1, r_2, \ldots \overline{r_\tau}(\tau), 0, 0, \ldots\}, \tag{3.2}$$

where $\overline{r_\tau}(\tau) := \sum_{i=\tau}^{\infty} r_i(\tau)$ from the general form. The intuition is: the principal will *not* compensate the agent in such a way that the agent would rather choose the contract with τ' (instead of τ) for higher pre-completion rewards.

Finally, the following lemma shows that any effort vector implemented by the reward scheme in equation (3.2) can also be implemented by a single end-of-contract reward. An effort vector e describes the agent's decision at each time t, i.e. $e = (e_1, e_2 \ldots e_t, \ldots)$, $e \in E$, where E is a set of infinite binary sequences.

Lemma 3.1

Any effort vector e which is implemented by the compensation scheme $\overline{R}(\tau) = \{r_1, r_2, \ldots \overline{r_\tau}(\tau), 0, 0, \ldots\}$ can be implemented by a single end-of-contract reward scheme, i.e., $\overline{R'}(\tau) = \{0, 0, \ldots \overline{r_\tau}(\tau), 0, 0 \ldots\}$.

Proof: Firstly, suppose $\overline{R}(\tau) = \{r_1, r_2, \ldots \overline{r_\tau}(\tau), 0, 0, \ldots\}$ implements a given effort vector e. At any time t, since r_t is given whenever the agent shirks or works, we know that if e_t =0, i.e., $\alpha f_t + r_t + W^c_{t+1}(n_t) > f_t - 1 + r_t + W^c_{t+1}(n_t + 1)$, then still $\alpha f_t + W'^c_{t+1}(n_t)$ $> f_t - 1 + W'^c_{t+1}(n_t + 1)$, where we replace $\overline{R}(\tau)$ with $\overline{R'}(\tau)$. Similarly, if e_t =1, i.e., $\alpha f_t + r_t + W^c_{t+1}(n_t) \le f_t - 1 + r_t + W^c_{t+1}(n_t + 1)$, then still $\alpha f_t + W'^c_{t+1}(n_t)$ $\le f_t - 1 + W'^c_{t+1}(n_t + 1)$, if we replace $\overline{R}(\tau)$ with $\overline{R'}(\tau)$. Q.E.D.

Thus, abusing the notation to some extent, I denote $R(\tau)$ as a single end-of-contract reward for the finishing date τ.

Up to now, the finishing date τ has not been defined properly as a function of the agent's effort. The following will define this function and discuss a standard issue in moral hazard problems, that is, to look for the cheapest way to motivate the agent to complete the project at an arbitrary date. Firstly, the finishing date is defined as the earliest date that the accumulated effort level exceeds Δ, i.e.,

$$\tau(e) = \min\left\{ s \,\middle|\, \sum_{i=1}^{s} e_i \geq \Delta \right\} \quad , \quad \text{where } \tau(e) \text{ could be } \infty.$$

$\tau(e)$ is a function of effort and it is possible that two different effort vectors e' and e'' ($e' \neq e''$) finish the project at the same date, i.e., $\tau(e') = \tau(e'')$. The multiplicity is because, under the assumption of no discounting, the agent has no preference over the order of efforts. For distinction, I denote the cases where e' and e'' induce different finishing dates as $\tau'(e')$ and $\tau''(e'')$. Fortunately, the project value (to be defined later) will be realised as long as the project is completed, so we can concentrate on the set of the effort vectors that finish the project at an arbitrary date s. Define E^s as this set:

$$E^s := \left\{ e \in E \,\middle|\, \tau(e) = s \text{ and } e_i = 0 \forall i > s \right\}.$$

Since funding is indispensable for the innovation, unlike the standard moral hazard problem, the setting of the cheapest rent will also be related to the contract length, beyond which there will be no funding to the agent. Considering this limitation, for a given T, we can separate the discussion about the cheapest reward into two cases:

$\tau(e) > T$ and $\tau(e) \leq T$. Recall that the "cheapest" way means the smallest end-of-project reward, as the whole compensation scheme can be replaced by an end-of-project reward.

Firstly, for any committed finishing date $\tau(e) > T$ (or any effort vector $e \in E^S$ for $S > T$), the cheapest compensation is to pay nothing, i.e.,

$$R(\tau(e)) = 0, \text{ for } \tau(e) > T. \tag{3.3}$$

Given $R(\tau(e)) = 0$ for $\tau(e) > T$, we have the following lemma regarding the agent's effort decisions:

Lemma 3.2

For either $\Delta > T$ or $\Delta \leq T$ but with a committed completion date $\tau(e) > T$, shirking right through the funding period is the dominant strategy.

We can see the reason from the agent's decision (3.1) and equation (3.3). Since for both $\Delta > T$ or $\Delta \leq T$ but with a committed completion date $\tau(e) > T$, the project will not be finished on T. Equation (3.3) implies that the agent would be better off shirking throughout the funding period in his effort decisions (3.1).

Secondly, to derive the cheapest reward for $\tau(e) \leq T$, we need to have more information about the agent's choice over different contracts. For this end, we firstly describe the involved parties' utility functions. For a given contract c, the agent's utility for completing the project[48] is

$$\alpha(\tau(e) - \Delta) + R(\tau(e))\text{[49]}.$$

[48] The principal prefers the agent finishing the project to shirking all throughout, for which case the agent will have the shirking benefit (to be discussed later).

[49] The principal and agent's intertemporal commitments do not have the "false dynamics" problem mentioned by Laffont and Tirole (1993, p. 103). As the innovation process is time consuming and the

The meaning of this function is: as the outcome is ex-post observable, there is no need to provide funding after $\tau(e)$. Hence for $\tau(e) \le T$, the agent can get £1 funding for $\tau(e)$ periods. Since he only needs Δ to finish the project, he will shirk for $(\tau(e) - \Delta)$ periods and divert shirking benefit $\alpha(\tau(e) - \Delta)$ from the funding. Once the project is finished, the principal will give him an end-of-contract reward: $R(\tau(e))$.

The principal's utility is:

$$V(\tau(e)) - R(\tau(e)) - T + (T - \tau(e)).$$

V is a constant project value, implying that any delay in the completion date does not directly affect the project value, provided there is no discounting. However, the agent's effort does matter with the value in the sense that it will never be realised if the project is not completed. Therefore, in this basic model with only the moral hazard problem, we can rewrite the value as $V(\tau(e))$[50], where

$$\begin{aligned} V(\tau(e)) &= V \text{ if } \tau(e) \le T, \\ &= 0 \text{ if } \tau(e) > T. \end{aligned}$$

In order to get the project value, the principal has to spend £1 funding for at least $\tau(e)$ periods, plus an end-of-contract reward $R(\tau(e))$. As the contract assigns a funding for T periods, if the agent finishes the project earlier, the principal can save funding for $(T - \tau(e))$ periods.

agent's effort is unobservable, the principal can not actually learn from the performance of the agent's efforts in previous periods.

[50] $\tau(e)$ will be omitted in later sections after we solve this basic opportunism model.

Now, we are back to the search for the cheapest compensation to implement a completion date $\tau(e) \leq T$. For a given funding period T, the reward must be designed in such a way that, firstly the agent has at least the reservation utility as from not taking the contract (Individual Rationality constraint, IR). Secondly, finishing the project at $\tau(e)$ will give the agent at least the same utility as finishing at some other time $\tau'(e')$ (Incentive Compatibility constraint, IC), or shirking right through the funding periods (Moral Hazard constraint, MH). In notation, IR is:

$$\alpha(\tau(e) - \Delta) + R(\tau(e)) \geq 0 . \qquad \text{(IR)}$$

Since the agent has no initial wealth and hence self-funding is impossible, the agent will have the reservation of zero if he does not participate. Note that the assumption of weak inequality is "to assume that ties are broken in a fashion that favours the first mover" in order to ensure the existence of an equilibrium (Kreps (1990), p. 604). IC requires that for $\tau(e)$, $\tau'(e') \leq T$ and $\tau(e) \neq \tau'(e')$,

$$\alpha(\tau(e) - \Delta) + R(\tau(e)) \geq \alpha(\tau'(e') - \Delta) + R(\tau'(e')), \quad e' \in E^S \text{ and } S \leq T . \qquad \text{(IC)}$$

IC constraints say that if $\tau(e) \leq \tau'(e')$, $R(\tau(e)) \geq R(\tau'(e'))$. In other words, the end-of-contract reward must be decreasing in the finishing date to satisfy the IC constraint. Finally, due to the unobservable effort assumption, the agent is able to shirk all throughout T (as penalty is infeasible) and has the shirking benefit: αT. The reward must ensure that finishing the project at time $\tau(e)$ will bring him at least the same benefit, i.e.,

$$\alpha(\tau(e) - \Delta) + R(\tau(e)) \geq \alpha T . \qquad \text{(MH)}$$

Since MH implies IR, the IR constraint can be ignored in what follows.

Put in terms of equilibrium, we are looking for an equilibrium where the agent completes the project in an efficient way and the principal maximises her utility. To solve the optimal contract, we need to maximise the principal's utility subject to capacity, IC and MH constraints (denoted as ***P***). The capacity constraint is because: if $T < \Delta$, the project will never be finished before or at the deadline. As the principal would prefer the agent finishing the project, the funding period has to be at least Δ. In the following, we first solve the cheapest reward for implementing an arbitrary finishing date $\tau(e)$ and later show that it is optimal to implement $\tau(e) = T$.

To determine the cheapest reward, firstly, since the reward is costly to the principal and IC says that the end-of-contract reward has to be decreasing in the completion date, let us firstly guess that only MH is binding, i.e.,

$$R(\tau(e)) = \alpha(T + \Delta) - \alpha\tau(e). \tag{3.4}$$

This setting says that the reward is decreasing in $\tau(e)$ and hence IC is binding. Substituting $R(\tau(e))$ by the definition in equation (3.4), we can rewrite the principal's problem[51] (***P***) as:

$$\max_{T,\tau(e)}\{V(\tau(e)) - \alpha(T + \Delta) + \alpha\tau(e) - T + (T - \tau(e))\},$$
$$\text{St.} \quad T - \Delta \geq 0.$$

Since T has a negative coefficient, meaning funding is costly to the principal, the deadline should be set as short as possible. However, the capacity constraint says that any shortage in funding will fail to complete the project, therefore we set the deadline at its

[51] The solution proceeds without setting up multipliers, because the utility is linear in each variable.

lowest possible value: $T = \Delta$. Finally from the objective function we know that except for $V(\tau(e))$, $\tau(e)$ also has a negative coefficient, implying that although finishing the project earlier or later does not affect the project value, longer funding periods will cost the principal more. There is no explicit restriction to $\tau(e)$ as the capacity constraint to T, but we know that the project value will become zero at time T if $\tau(e) > T$. The smallest possible value that satisfies all these requirements is hence $\tau(e) = T = \Delta$. By equation (3.4), the agent has the optimal reward $R(T) = \alpha\Delta$. The principal's optimal utility is therefore $V - (1+\alpha)\Delta$.

The derivation of $\tau(e)$ indicates that when there is only a moral hazard problem, the principal can concentrate on a contract which induces a completion date exactly on the funding deadline T and rewards the agent for $R(T)$. In other words, the optimal contract form is a multi-stage version of Cost-Plus-Fixed-Fee (CPFF) contracts in the literature. The following proposition summarises the optimal contract for implementing a successful project.

Proposition 3.1

Consider a time-consuming investment that lasts for Δ periods under the agent's full capacity. The optimal contract for complete information with an opportunism problem is to assign a funding period Δ and an end-of-contract reward proportional to the contract length.

Finally, it is interesting to compare the optimal contract with the one without a moral hazard problem. In the latter, the principal solves the following problem:

$$\max_{T,e}\{V(\tau(e)) - T\}$$

$$\text{St.} \quad T - \Delta \geq 0.$$

Since the effort is observable and hence contractible, there is no need to pay an extra reward. The agent will have the reservation utility (0), and the optimal contract implements an effort vector $e \in E^{\Delta}$ (i.e., the full capacity effort vector $\left\{\overbrace{1,1,\ldots 1}^{\Delta},0,0,\ldots\right\}$) with funding periods $T = \Delta$. The presence of the moral hazard problem costs the principal an extra incentive rent $\alpha\Delta$ to extract the same effort vector $e \in E^{\Delta}$.

This section is closed by the comparative analysis of the equilibrium. Firstly, since the project will only be undertaken if $V > (1+\alpha)\Delta$, a higher project value will increase the possibility that the project is taken. V may represent the profitability of a R&D project, or the return for a long-term loan for developing countries. Since the principal in this model is assumed to be self-interested, V is very likely to be under-evaluated by private investors. Policies such as patents are often used by the welfare-maximising government to improve this kind of under-evaluation. The bias could be worse if there is a serious moral hazard problem, measured by the size of α. A bigger α means that the agent has to give up more in order to put in full effort, and hence as α increases, the principal needs to give a higher incentive rent to keep incentive compatibility. Moreover, α may vary across industries. In industries where the force of work morale prevails, the compensation can be lower. But as pointed out by Frey (1993) who summarises the literature about the impact the other way around, "regulations may crowd out the agents' work morale, and negatively affect their behaviour". This effect will be ignored in the present model. Finally the longer the project actually takes (bigger Δ), the more compensation the principal has to pay to implement the efficient effort.

3.3. Δ Uncertain to the Principal (Discrete Type)

This section extends the basic model by considering the case when the agent has private information about the time for completion: Δ. The superiority of information comes from the agent's expertise or past experience. Following the literature, we denote the value that is better known by the agent as a "type[52]". In this section, we discuss the case when the principal thinks that the agent's type is discretely distributed. The purpose for discussing this case is: from the last section we know that even when Δ is known by the principal, there is a moral hazard problem in the contract design. By assuming incomplete information about Δ, there will be both moral hazard and adverse selection problems. This is of course a standard discussion in mechanism design, and it helps us to understand the way that asymmetric information together with the agent's opportunism affect the design of long-term contracts. By assuming that there are only two types, we can gain some interesting implications for production efficiency, which will be shown to sustain for continuous types. The derivation of the optimal contract relies on applying the *revelation principle*, proposed by Gibbard (1973), Green and Laffont (1977), Dasgupta et al. (1979) and Myerson (1979), which says that any efficient outcome of any Bayesian game can be represented by a truth-telling incentive compatible direct mechanism. In this incomplete information setting, it is even difficult to characterise the set of feasible contracts, which may involve very complicated forms. The significance of the revelation principle is that we can restrict our attention to a *direct mechanism* which requests the privately informed agent to report its type to the uninformed principal. The allocation of resources then depends on what is reported. Of course, the agent could mis-report in its

[52] The underlying assumption is consistent beliefs, in the sense that they can be regarded as conditional probability distributions derived from a certain "basic probability distribution" over the parameters unknown to the various players (Harsanyi (1967)).

own interest. An incentive compatible direct mechanism requires that the allocation among resources is designed in such a way that the informed agent's best response will be to report truthfully. Denote the optimal screening[53] contract as the "incentive contract". We then compare this incentive contract to the pooled contract of the efficient type and the pooled contract of the inefficient type to find out a better contract from the principal's point of view. A remark regarding efficiency and renegotiation concludes this section.

Keeping the assumption of a single self-interested principal and a single agent, we now assume that the agent has better information about the time for completion. Specifically, it is assumed that the agent knows Δ for sure, but the principal thinks that Δ could take two possible values: Δ_1 with probability υ and Δ_2 with $(1-\upsilon)$, where $\Delta_1 < \Delta_2$. Refer to Δ_1 as the efficient type and Δ_2 as the inefficient type. Given that the agent accepts the offer of contract, he has to decide on a sequence of effort level, which are not observable by the principal. As shown in the basic model, the principal can use an end-of-contract reward to provide enough incentive for the agent to finish the project. With asymmetric information, the revelation principle says that the principal can provide a menu of contracts (including the funding length and rewards), and let the agent self-identify (i.e., to report his type $\hat{\Delta}_i$). The menu of contracts needs to be designed in such a way that in equilibrium $\hat{\Delta}_i = \Delta_i$ and the project will be completed. Let $C_2 := \{\{T_1, R(T_1)\}, \{T_2, R(T_2)\}\}$ denote the menu of contracts offered to the agent[54]. Since we are looking for a truth-telling equilibrium, by taking the contract that is meant for him

[53] The optimal screening (separating) contract assigns different contracts to different types in equilibrium.
[54] The following is meant to find out the screening contract, however, it is not excluded that $\{T_1, R(T_1)\}$ could be the same as $\{T_2, R(T_2)\}$.

(i.e., $\{T_i, R(T_i)\}$), type Δ_i will have utility $\alpha(T_i - \Delta_i) + R(T_i)$ for completing the project. The principal's expected utility is then:

$$\upsilon\{V - R(T_1) - T_1\} + (1-\upsilon)\{V - R(T_2) - T_2\}.$$

For the following discussion to make sense, we restrict to the case where the principal will find it worthwhile to finance the project for both types, i.e.,

Assumption 3.1: $V \geq \max\{(1+\alpha)\Delta_2, (T_i + R(T_i))_{i=1,2}\}$.

Assumption 3.1 says that, the project's value will be at least as great as the sum of funding and reward in both the complete[55] and incomplete information case.

The optimal incentive contract is the solution to the principal's maximisation problem subject to the constraints that each type will take the contract and finish the project, and each type will not be better off mis-reporting his value and taking the contract for the other type. That is, we have (***P2***):

$$\max_{T_1, T_2, R(T_1), R(T_2)} \upsilon\{V - R(T_1) - T_1\} + (1-\upsilon)\{V - R(T_2) - T_2\}, \qquad (\textbf{\textit{P2}})$$

St.

$$T_1 - \Delta_1 \geq 0, \qquad \text{(capacity constraint)}$$

$$T_2 - \Delta_2 \geq 0,$$

$$\alpha(T_1 - \Delta_1) + R(T_1) \geq \alpha T_1, \qquad \text{(MH1)}$$

$$\alpha(T_2 - \Delta_2) + R(T_2) \geq \alpha T_2, \qquad \text{(MH2)}$$

$$\alpha(T_1 - \Delta_1) + R(T_1) \geq \alpha(T_2 - \Delta_1) + R(T_2), \qquad \text{(IC1)}$$

$$\alpha(T_2 - \Delta_2) + R(T_2) \geq \alpha(T_1 - \Delta_2) + R(T_1), \quad \text{if } T_1 \geq \Delta_2. \qquad \text{(IC2)}$$

---

[55] Complete information case means the case with only a moral hazard problem. We need to assume the availability for the complete information case as well in order to compare the result with the pooled efficient contracts.

Assumption 3.1 says that V will be realised under each contract. The principal's expected utility is the weighted sum of utilities from offering $\{T_i, R(T_i)\}$ to each type i. The capacity constraints come from Lemma 3.2 which says that if $T_i < \Delta_i$, the agent's dominant strategy is shirking right through T_i. Hence, in order to have the project completed, the funding periods for each type should at least cover the true value. The MH constraints say that, by taking $\{T_i, R(T_i)\}$, type Δ_i would prefer finishing the project to shirking all through T_i. Since $\alpha T_i \geq 0$, the MH constraints also imply the requirements that each type will be better off finishing the project than not taking the contract at all (IR constraint). Moreover, for truth telling, IC1 says that type Δ_1 will not be better off finishing the project under type Δ_2's contract $\{T_2, R(T_2)\}$. IC2 describes a similar requirement for type Δ_2 but is only true for $T_1 \geq \Delta_2$. For $T_1 < \Delta_2$, Lemma 3.2 has shown that if taking $\{T_1, R(T_1)\}$, type Δ_2 will shirk all through T_1 and have the shirking benefit αT_1. But MH2 will have considered this case if $T_1 \leq T_2$, which is obvious since the capacity constraints together with $T_1 < \Delta_2$ imply $T_2 \geq \Delta_2 > T_1$. Therefore, IC2 will only apply for $T_1 \geq \Delta_2$.

In addition to the shirking possibilities restricted by MH1 and MH2, each type can also take the other type's contract, and shirk throughout the funding periods rather than finish the project. Firstly, type Δ_1 may take the contract $\{T_2, R(T_2)\}$ and shirk through T_2, which gives shirking benefit αT_2. But we know from IC1 and MH2 that

$$\begin{aligned}\alpha(T_1 - \Delta_1) + R(T_1) &\geq \alpha(T_2 - \Delta_1) + R(T_2) \\ &> \alpha(T_2 - \Delta_2) + R(T_2) \geq \alpha T_2 .\end{aligned}$$

That is, these two constraints have already restricted that type Δ_1 would rather complete the project under contract $\{T_1, R(T_1)\}$ than take type Δ_2's contract and shirk. Secondly, type Δ_2 may take $\{T_1, R(T_1)\}$ and shirk through T_1, which gives shirking benefit αT_1. MH2 should have included this case if $T_1 \leq T_2$. To proceed, suppose that $T_1 \leq T_2$, which will be justified by the solution later.

To find the solution, the first task is to look for the cheapest reward to motivate type i to finish the project at T_i. Replacing Δ_2 by Δ_1 in MH2 shows that if the principal gives each type the efficient contract in Proposition 3.1, type Δ_1 will be better off mimicking type Δ_2. Next, IC1 alone requires $R(T_2) \leq R(T_1)$ if $T_1 \leq T_2$. Since rewards are costly to the principal, $R(T_2)$ should be set at the minimal value, that is, MH2 has to be satisfied with equality:

$$R(T_2) = -\alpha(T_2 - \Delta_2) + \alpha T_2 = \alpha\Delta_2. \tag{3.5}$$

To derive $R(T_1)$, we need to check the IC constraints. For $T_1 < \Delta_2$, only IC1 applies. Substituting the definition of $R(T_2)$ from equation (3.5) into IC1 gives:

$$R(T_1) \geq \alpha(T_2 - T_1) + \alpha\Delta_2. \tag{3.6}$$

As the same way of deriving $R(T_2)$, $R(T_1)$ should be set at the minimal value, that is, equation (3.6) is binding, which gives

$$R(T_1) = \alpha(T_2 - T_1) + \alpha\Delta_2. \tag{3.6'}$$

Next, for $T_1 \geq \Delta_2$, IC2 will also apply. After substituting $R(T_2)$ by $\alpha\Delta_2$, IC2 requires:

$$R(T_1) \leq \alpha(T_2 - T_1) + \alpha\Delta_2 . \tag{3.7}$$

To simultaneously satisfy IC1 and IC2, both equations (3.6) and (3.7) will bind, that is, we have $R(T_1) = \alpha(T_2 - T_1) + \alpha\Delta_2$. Hence $R(T_1)$ has the same setting for both $T_1 < \Delta_2$ and $T_1 \geq \Delta_2$. Notice that this setting also implies MH1, where $R(T_1) \geq \alpha\Delta_1$.

Substitute the settings of $R(T_1)$ and $R(T_2)$ into the principal's objective function. The principal's maximisation problem becomes:

$$\max_{T_1 T_2} \upsilon\{V - (1-\alpha)T_1 - \alpha T_2 - \alpha\Delta_2\} + (1-\upsilon)\{V - T_2 - \alpha\Delta_2\},$$
$$\text{St} \quad T_1 \geq \Delta_1,$$
$$T_2 \geq \Delta_2.$$

For $\alpha < 1$, both T_1 and T_2 are costly to the principal. Therefore, to maximise the principal's expected utility and satisfy the capacity constraints, both capacity constraints should bind, i.e., $T_1 = \Delta_1$ and $T_2 = \Delta_2$. In other words, in this mechanism, the agent reports his type truthfully (as required by MH and IC constraints) and the principal will provide the funding for as long as the actual time needed. Since $\Delta_1 < \Delta_2$, the assumption that $T_1 < T_2$ is justified. Furthermore, substituting $T_1 = \Delta_1$ and $T_2 = \Delta_2$ into equations (3.5) and (3.6)' gives the optimal compensations: $R(T_1) = \alpha(2\Delta_2 - \Delta_1)$ and $R(T_2) = \alpha\Delta_2$. The principal's expected utility is:

$$V - \upsilon\{2\alpha\Delta_2 - \alpha\Delta_1 + \Delta_1\} - (1-\upsilon)\{\alpha\Delta_2 + \Delta_2\}. \tag{3.8}$$

The result says that apart from the incentive rent for the unobservable effort, the principal has to pay an information rent of $\alpha(\Delta_2 - \Delta_1)$ to the efficient type to induce truth-telling. Keeping other constraints constant, a bigger difference between the two types means a higher extra rent in the screening contract. The intuition for this rent is: by taking the inefficient type's contract, type Δ_1 has $(\Delta_2 - \Delta_1)$ more funding periods than taking his own contract. Hence, to motivate type Δ_1 to report truthfully, the screening contract has to compensate the efficient type for mimicking benefit in addition to the opportunism reward.

Finally, we can conclude a different view regarding the agent's production efficiency. That is, due to the time consuming assumption (the capacity constraint needs to be satisfied), the equilibrium contract has both the efficient and inefficient types finish the project without delay. There is no distortion in type Δ_2's production efficiency, which is in contrast to most contract literature in addressing the trade off between efficiency and rent extraction, in addition to "no distortion at the top (by IR constraint)" (e.g., Laffont and Tirole (1993)). The intuition is: as a result of assuming unobservable effort and binary outcome (success or failure), the principal's fear that the whole project value will disappear in case of any shortage in funding has led the principal not to distort the production efficiency in the optimal contract. Furthermore, the principal's belief affects only her expected utility, and has no influence on the production efficiency of the project. The main result of this section is summarised as Proposition 3.2.

Proposition 3.2

For a long-term project with both moral hazard and adverse selection problems, the incentive contract has both types complete the project, induces no efficiency loss to either type and pays an extra information rent to the efficient type.

In the following, we first present the principal's expected utilities from the incentive and pooled contracts, and then discuss the principal's choice among these contracts. First of all, the benchmark case is when there is only a moral hazard problem, that is, each type is offered the efficient contract described in Proposition 3.1. Denote the principal's expected utility for this case as $\bar{\Lambda}$:

$$\bar{\Lambda} = V - \upsilon(1+\alpha)\Delta_1 - (1-\upsilon)(1+\alpha)\Delta_2 .$$

The principal's expected utility from the incentive contract is (equation (3.8)):

$$\begin{aligned} &V - \upsilon\{\alpha(\Delta_2 - \Delta_1) + \alpha\Delta_2 + \Delta_1\} - (1-\upsilon)\{\alpha\Delta_2 + \Delta_2\} \\ &= \bar{\Lambda} - 2\alpha\upsilon(\Delta_2 - \Delta_1) . \end{aligned}$$

The term $2\alpha\upsilon(\Delta_2 - \Delta_1)$ is the incentive cost to prevent the efficient type from mimicking the inefficient type. For a positive belief of the efficient type, the incentive contract always costs more than if the principal knows the agent's type for sure.

Secondly, offering the pooled contract $\{\Delta_1, \alpha\Delta_1\}$ to both types will cause the inefficient type to shirk all through T_1. Hence the principal's expected utility with this contract is:

$$\begin{aligned} &\upsilon\{V - (1+\alpha)\Delta_1\} + (1-\upsilon)\{-\Delta_1\} \\ &= \bar{\Lambda} - (1-\upsilon)\{V - (1+\alpha)\Delta_2 + \Delta_1\} . \end{aligned}$$

The last term $(1-\upsilon)\{V - (1+\alpha)\Delta_2 + \Delta_1\}$ is the probability of the inefficient type times the sum of expected cost saving $(1+\alpha)\Delta_2$ and expected revenue loss $V - \Delta_1$. Under Assumption 3.1, this pooled contract is worse than the first best by definition. For υ

close to zero, the incentive contract is better than this pooled contract, however, for υ close to one, we have the opposite result. In other words, if the principal is fairly confident that the agent is an efficient type (for $\upsilon > \upsilon^*$, where $\upsilon^* = \dfrac{V-(1+\alpha)\Delta_2+\Delta_1}{V-(1-\alpha)(\Delta_2-\Delta_1)-\alpha\Delta_1}$ [57]), the expected cost saving makes the pooled contract of the efficient type better than the incentive contract.

Further, the pooled contract of the inefficient type $\{\Delta_2, \alpha\Delta_2\}$ gives the principal:

$$
\begin{aligned}
&V-\upsilon(1+\alpha)\Delta_2-(1-\upsilon)(1+\alpha)\Delta_2 \\
&=\overline{\Lambda}-\upsilon(1+\alpha)(\Delta_2-\Delta_1).
\end{aligned}
$$

Given this contract, the efficient type will mimic the inefficient type, finish the project at time Δ_2, and get an extra benefit $\alpha(\Delta_2-\Delta_1)$ from shirking. Comparing this contract with the incentive contract shows that for $\alpha<1$ the principal is better off with the incentive contract, since the principal can avoid the rental cost for equipment $(1-\alpha)$ per period for the extra funding periods $(\Delta_2-\Delta_1)$. When this cost is close to zero, the pooled contract for the inefficient type will be identical to the incentive contract.

Finally, since this equilibrium always keeps the production efficiency, a different conclusion can be drawn in contrast to Laffont and Tirole (1993). They show that a direct mechanism is not renegotiation proof, as the solution of the direct mechanism in their model is suboptimal (the inefficient type will produce inefficiently), and hence "it would be optimal to renegotiate to ensure production at the efficient level (given the reported type), and share the gains from trade" (Laffont and Tirole (1993), Ch.1). However, in the present model, the solution will be renegotiation proof for the reason that the production

[57] It can be checked that $\upsilon^* < 1$, since $\Delta_2 > \Delta_1$.

is always efficient and any decrease in payment from the principal will decrease the agent's utility (and hence will not be accepted).

3.4 Δ Uncertain to the Principal (Continuous Type)

This section studies the case when the agent knows the value of Δ for sure and the principal thinks that types are continuously distributed. There are two reasons for discussing continuous types: First, it will be interesting to ask if the result from the discrete type setting will hold in the continuous case. Second, since it is assumed that Δ ranges from 0 to ∞ and the project value is constant, intuitively we can guess that the principal will stop funding for Δ greater than some critical point. The issues concerning this point are: Is this point unique? In other words, will the principal adopt a cut-off strategy? What determines this point? How will the unobservable effort affect the determination of this critical point? When there are both moral hazard and adverse selection problems, the effort and information rents paid by the principal will vary with the choice of this critical point. Most important of all, the principal cannot prevent those inefficient types[58] from taking the contract and shirking throughout (which will be their dominant strategy). The determination of this critical point proceeds in several steps: firstly, by supposing an *arbitrary critical point*, we discuss the principal and the agent's behaviour before and after this point. It can be seen that before this point the principal's utility flow is decreasing in Δ and after this point the utility flow is a constant which is dependent on the size of this point. This hence justifies the existence of such point. Secondly, since the choice of such a critical point will also affect the compensations for

[58] Inefficient types refer to those with $\Delta > \overline{\Delta}$, and efficient types for otherwise. Among efficient types, those with smaller values of Δ will be denoted as more efficient types, and less efficient types refer to smaller value of Δ.

efficient types, the optimal critical point is determined at a value where the principal's expected utility is maximised.

We keep the assumption of a single principal and a single agent. The agent knows the value of Δ for sure, but the principal thinks that Δ is drawn from $(0,\infty)$ according to a distribution function $F(\Delta)$, with density function $f(\Delta)$. Suppose an *arbitrary point* $\overline{\Delta} \in (0,\infty)$ beyond which the principal stops funding the project. For those efficient types we know from Section 3.2 that the contract has to include an end-of-contract reward to provide enough incentive for the agent to complete the project. In addition, to consider asymmetric information, we need to apply the *revelation principle*, and restrict our attention to a truth-telling direct mechanism. Let $\hat{\Delta}$ be the reported value from type Δ. In this equilibrium, $\hat{\Delta}=\Delta$ and the project will be finished. Let $C_3 := \{T(\Delta), R(T(\Delta))\}_\Delta$, or in short, $C_3 := \{T(\Delta), R(\Delta)\}_\Delta$ be the menu of contracts offered to the agent. Before solving the optimal contract, we need to change the notation slightly to express the connection between the agent's effort and the completion date in the continuous version. First of all, in the same way of dealing with the continuous version of a multi-stage game, denote the history of sequential effort decisions up to time t by an index $h_t = \int_0^t e_j dj$, which is actually the accumulated effort level at time t. Note that, as in the discrete types case, there can be more than one path of sequential decisions that result in the same accumulated effort level. Since the principal can only observe the completion date, we can focus on the set of paths that accumulates the same level of effort h_t. Denote E^h as such a set and $e \in E^h$ to be an element of this set. The finishing date is defined as $\tau(e) = \min\{t \mid h_t \geq \Delta\}$ for $\Delta \in (0,\infty)$.

For this truncated part ($\Delta \leq \bar{\Delta}$), each type's utility for completing the project under C_3 is:

$$U(\Delta, \Delta) = \alpha(T(\Delta) - \Delta) + R(\Delta), \qquad \text{for } \Delta \in (0, \bar{\Delta}]. \tag{3.9}$$

The first argument in $U(.,.)$ is the reported value and the second argument stands for the true value. The principal's truncated expected utility is:

$$\int_0^{\bar{\Delta}} \{V - R(\Delta) - T(\Delta)\} f(\Delta) d\Delta .$$

$\Delta \in (\bar{\Delta}, \infty)$ is not included, since for the moment we are not sure about whether there exists such a "single" critical point which then depends on both parties' behaviour (to be discussed below). For truth-telling, the contract must be designed in such a way that for every $\Delta \in (0, \bar{\Delta}]$, putting in effort and completing the project are preferable to shirking throughout the funding period. As in the previous section, denote these requirements as the Moral Hazard (MH) constraints. Furthermore, we need to consider that under the optimal contract more efficient types will not take the contracts meant for less efficient types, and vice versa. These requirements are the Incentive Compatibility (IC) constraints.

But first of all, the capacity constraints are necessary for each type to complete the project, i.e., $T(\Delta) \geq \Delta$. Next, the MH constraints require that:

$$\alpha(T(\Delta) - \Delta) + R(\Delta) \geq \alpha T(\Delta), \text{ for } \Delta \in (0, \bar{\Delta}]. \tag{MH}$$

That is, each type would rather finish the project than take the contract but shirk all the time. As $T(\Delta) > 0$ (capacity constraint), MH implies that the agent's utility will be higher than when not taking the contract. The incentive compatibility constraints are: for any Δ, $\Delta' \in (0, \bar{\Delta}]$ and suppose $\Delta < \Delta'$,

$$\alpha(T(\Delta) - \Delta) + R(\Delta) \geq \alpha(T(\Delta') - \Delta) + R(\Delta'), \tag{IC1}$$

$$\alpha(T(\Delta') - \Delta') + R(\Delta') \geq \alpha(T(\Delta) - \Delta') + R(\Delta), \quad \text{if } T(\Delta) \geq \Delta'. \tag{IC2}$$

As in the discrete case, due to the capacity constraints, the second line is only valid for $T(\Delta) \geq \Delta'$. For $T(\Delta) < \Delta'$, type Δ' physically can not finish the project. Lemma 3.2 tells us that the agent will shirk all through $T(\Delta)$ and have a utility $\alpha T(\Delta)$. The capacity constraint together with the supposition of $T(\Delta) < \Delta'$ imply that $T(\Delta') \geq \Delta' > T(\Delta)$. The MH constraint for type Δ' has already included this case. Therefore, IC2 is only valid when $T(\Delta) \geq \Delta'$.

Note that these constraints also exclude other shirking possibilities that are not written explicitly. Firstly, the more efficient types might take the contracts for the less efficient types and shirk throughout the funding periods. For $\Delta < \Delta'$ we know from MH and IC1 that

$$\begin{aligned}\alpha(T(\Delta) - \Delta) + R(\Delta) &\geq \alpha(T(\Delta') - \Delta) + R(\Delta') \\ &> \alpha(T(\Delta') - \Delta') + R(\Delta') \geq \alpha T(\Delta').\end{aligned}$$

Hence, IC1 together with MH have already included this case. Next, it is also possible that the less efficient types would like to take the contracts for the more efficient types and shirk through the funding period. This case would have been included in the MH constraints, if $T(\Delta)$ is increasing in Δ. To proceed, we need to temporarily assume that

$T(\Delta)$ is increasing and differentiable[59] in Δ and the solution will justify this assumption later.

The principal maximises the truncated expected utility function subject to the capacity, MH and IC constraints, i.e.,

$$\max_{R(\Delta),T(\Delta)} \int_0^{\bar{\Delta}} \{V - R(\Delta) - T(\Delta)\} f(\Delta) d\Delta, \qquad (\boldsymbol{P3})$$

$$\text{St.} \quad T(\Delta) \geq \Delta, \qquad \forall \Delta \in (0, \bar{\Delta}] \text{ and } \Delta < \Delta',$$

$$\alpha(T(\Delta) - \Delta) + R(\Delta) \geq \alpha T(\Delta), \qquad \text{(MH)}$$

$$\alpha(T(\Delta) - \Delta) + R(\Delta) \geq \alpha(T(\Delta') - \Delta) + R(\Delta'), \qquad \text{(IC1)}$$

$$\alpha(T(\Delta') - \Delta') + R(\Delta') \geq \alpha(T(\Delta) - \Delta') + R(\Delta), \quad \text{if } T(\Delta) \geq \Delta'. \qquad \text{(IC2)}$$

Notice that these constraints actually represent infinite numbers of constraints. Following the existing literature, we can replace the infinite numbers of IC constraints by the first order condition[60]. Recall the definition of the agent's utility function from equation (3.9), and for illustration, $\hat{\Delta}$ is kept to distinguish the reported value from the true value.

$$U(\hat{\Delta}, \Delta) = \alpha(T(\hat{\Delta}) - \Delta) + R(\hat{\Delta}), \quad \Delta \in (0, \bar{\Delta}] \qquad (3.9)'$$

It must be $T(\hat{\Delta}) \geq \hat{\Delta}$ to satisfy the capacity constraints: if $T(\hat{\Delta}) = \hat{\Delta}$, only IC1 applies and it says that $\alpha(T(\hat{\Delta}') - T(\hat{\Delta})) \leq R(\hat{\Delta}) - R(\hat{\Delta}')$. Since we temporarily assume that $T(.)$ is increasing and differentiable, $R(.)$ has to be decreasing and differentiable to satisfy the IC1 constraint. Therefore, IC1 together with equation (3.9)' imply that $U_2{}'(\hat{\Delta}, \Delta) \leq -\alpha$ (abbreviated as $U'(\Delta) \leq -\alpha$); If $T(\hat{\Delta}) > \hat{\Delta}$, both IC1 and IC2 will apply. IC2 says that

[59] The differentiability is necessary to derive the agent's marginal utility.
[60] Since in our model, the completion date is a linear function of effort, we can adopt this approach without further constraint (see Kreps (1990), Ch 16 for the constraints of using this approach).

$\alpha(T(\hat{\Delta}') - T(\hat{\Delta})) \geq R(\hat{\Delta}) - R(\hat{\Delta}')$, which is contrary to IC1. Therefore, to simultaneously satisfy IC1 and IC2, we need:

$$\alpha(T(\hat{\Delta}') - T(\hat{\Delta})) = R(\hat{\Delta}) - R(\hat{\Delta}'). \tag{3.10}$$

Again, $R(.)$ will be decreasing and differentiable if $T(.)$ is increasing and differentiable. From equations (3.9)' and (3.10), we have $U_2'(\hat{\Delta}, \Delta) = -\alpha$ (abbreviated as $U'(\Delta) = -\alpha$).

We can combine the capacity and IC constraints, and rewrite the maximisation problem as (*P3*)'

$$\max_{U(\Delta),T(\Delta)} \int_0^{\bar{\Delta}} \{V - (1-\alpha)T(\Delta) - \alpha\Delta - U(\Delta)\} f(\Delta) d\Delta\,, \tag{\textbf{\textit{P3}})'$$

$$\text{St.} \quad T(\Delta) \geq \Delta \qquad \Delta \in (0, \bar{\Delta}],$$

$$U'(\Delta) \leq -\alpha \text{ and } (T(\Delta) - \Delta)(U'(\Delta) + \alpha) = 0\,, \tag{IC}$$

$$U(\Delta) \geq \alpha T(\Delta)\,. \tag{MH}$$

Note that $R(.)$ has been replaced with the definition of $U(.)$ in equation (3.9), because $R(\Delta) + T(\Delta) = (1-\alpha)T(\Delta) + \alpha\Delta + U(\Delta)$. Since the agent's utility is decreasing in Δ ($U'(\Delta) < 0$) and under the assumption that $T(.)$ is increasing in Δ, MH will only apply to the most inefficient type, i.e., $U(\Delta) \geq \alpha T(\bar{\Delta})$. Since giving the agent any rent is costly (the coefficient of $U(.)$ is -1), MH for type $\bar{\Delta}$ should bind, that is, $U(\bar{\Delta}) = \alpha T(\bar{\Delta})$. Note that if $U'(\Delta) = -\alpha$, the integration of the utility function gives:

$$\begin{aligned} U(\Delta) &= \int_{\Delta}^{\bar{\Delta}} \alpha d\Delta + \alpha T(\bar{\Delta}) \\ &= \alpha(\bar{\Delta} - \Delta) + \alpha T(\bar{\Delta})\,. \end{aligned} \tag{3.11}$$

Using equation (3.11), we can rewrite the problem as $(P3)$'':

$$\max_{U(\Delta),T(\Delta)} \int_0^{\bar{\Delta}} \{V-(1-\alpha)T(\Delta)-\alpha\Delta-U(\Delta)\}dF(\Delta), \qquad (P3)''$$

St. $T(\Delta)\geq\Delta, \quad \Delta\in[0,\bar{\Delta}],$

$U(\Delta)\geq\alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta})$ and

$(T(\Delta)-\Delta)(U(\Delta)-\alpha(\bar{\Delta}-\Delta)-\alpha T(\bar{\Delta}))=0$.

To derive the optimal rent[61], firstly, if we set $T(\Delta)=\Delta$, the above constraints require that $U(\Delta)\geq\alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta})$. Since $U(\Delta)$'s coefficient is negative, it should be set at the lowest possible level, that is, $\alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta})$. However, if we set $T(\Delta)>\Delta$, it must be $U(\Delta)=\alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta})$ to satisfy all the constraints. Substitute the setting of $U(\Delta)$ into the objective function and after manipulation we can see that the coefficient of $T(\Delta)$ and $T(\bar{\Delta})$ are $-(1-\alpha)$ and -1 respectively. In this case, there will be no equilibrium values of $T(\Delta)$ and $T(\bar{\Delta})$ to maximise the utility function, because for any $T(\Delta)>\Delta$, we can find a smaller $T'(\Delta)$ that is greater than Δ, still satisfies all the constraints and is less costly to the principal. To conclude, setting $T(\Delta)$ at the efficient level Δ will be the only equilibrium solution, which hence justifies the supposition that the funding period is increasing and differentiable in Δ. For every $\Delta\in(0,\bar{\Delta}]$, the equilibrium utility is $U(\Delta)=\alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta})$. Finally, the principal's utility flow for this truncated case $\Delta\in(0,\bar{\Delta}]$ is:

$$V-(1-\alpha)\Delta-\alpha\bar{\Delta}-\alpha T(\bar{\Delta}). \qquad (3.12)$$

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[61] The solution proceeds without setting up multipliers, because the utility flow is linear in each variable.

Before we go on to determine the optimal critical point $\bar{\Delta}$, two remarks should be noticed: First, like the discrete type case, the optimal contract for the continuous type setting induces no efficiency loss to any type before $\bar{\Delta}$ (because the funding period is set at the efficient level Δ) and extra rewards will be given to the more efficient types as information rents. Second, the existence of a *single critical point* can be seen from the fact that $T'(\Delta) = 1$ and $R'(\Delta) = -\alpha$, implying the principal's profit flow to be decreasing in Δ. As the project value is constant, the existence of such a critical point can hence be justified. However, we need to consider the remaining part $\Delta > \bar{\Delta}$ to decide the optimal location of such critical point.

For a given $\bar{\Delta}$, the principal will stop funding those types with $\Delta > \bar{\Delta}$. However, since effort is un-contractible, the principal can not prevent those inefficient types from mimicking and taking the contracts for types $\Delta \le \bar{\Delta}$. If the contracts for type $\Delta \le \bar{\Delta}$ all have $T(\Delta) = \Delta$, it is infeasible for types $\Delta > \bar{\Delta}$ to finish the project and it will be better off for them to shirk throughout the funding period. To get the highest shirking benefit, they will choose the contract with $T(\bar{\Delta})$ and have a utility $\alpha T(\bar{\Delta})$. In other words, the principal has to waste $T(\bar{\Delta})$ for types $\Delta > \bar{\Delta}$, as it is a dominant strategy for them to claim $\bar{\Delta}$. If the contracts for type $\Delta \le \bar{\Delta}$ have $T(\Delta) > \Delta$, then some types $\Delta' \in [\bar{\Delta}, T(\Delta)]$ will find it feasible to finish the project. The problem with this case is that the principal will find it difficult to know exactly which type that Δ' is going to mimic, meaning that she can not tell when type Δ' is going to finish the project. Since the principal can not motivate any $\Delta' \in [\bar{\Delta}, T(\Delta)]$ to tell the truth (that is, to finish the project at Δ' if $\Delta' < T(\bar{\Delta})$), it is assumed that types Δ' will all choose the contract with $T(\bar{\Delta})$ and finish the project at $T(\bar{\Delta})$[62]. Therefore, instead of wasting $T(\bar{\Delta})$ as in the case of $T(\Delta)=\Delta$, the principal's utility flow for this case is $V-T(\Delta)-R(\Delta)$ for $\Delta' \in [\Delta, T(\bar{\Delta})]$ and $-T(\bar{\Delta})$ for $\Delta > T(\bar{\Delta})$. To cope with this situation, a complementary variable ς is defined together with the capacity constraint, that is,

$$\begin{aligned} \varsigma &= 0 \quad \text{if } T(\Delta)=\Delta, \ \forall \Delta \in [0,\bar{\Delta}], \\ &= 1 \quad \text{if } T(\Delta)>\Delta \quad \text{and} \quad \text{let } |\Delta| = T(\Delta)-\bar{\Delta}. \end{aligned}$$

The principal's total expected utility function is:

$$\begin{aligned} \max_{U(\Delta),T(\Delta)} \{ & \textstyle\int_0^{\bar{\Delta}} [V-(1-\alpha)T(\Delta)-\alpha\Delta-U(\Delta)]dF(\Delta) \\ & + \textstyle\int_{\bar{\Delta}}^{\bar{\Delta}+\varsigma|\Delta|} [V-(1-\alpha)T(\bar{\Delta})-\alpha\Delta-U(\bar{\Delta})]dF(\Delta) + \int_{\bar{\Delta}+\varsigma|\Delta|}^{\infty} [-T(\bar{\Delta})]dF(\Delta) \}, \qquad (\boldsymbol{P3})'' \end{aligned}$$

$$\begin{aligned} \text{St.} \quad & T(\Delta) \geq \Delta \quad \text{for} \quad \Delta \in (0,\bar{\Delta}], \\ & U(\Delta) \geq \alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta}) \ \text{and} \\ & (T(\Delta)-\Delta)(U(\Delta)-\alpha(\bar{\Delta}-\Delta)-\alpha T(\bar{\Delta}))=0. \end{aligned}$$

In the objective function, the first term is the truncated utility for $\Delta \in (0,\bar{\Delta}]$ as defined in (***P3***)'. The second term denotes the expected utility if $T(\Delta)>\Delta$, where some inefficient types could take the contract with $T(\bar{\Delta})$ and finish the project. Notice that $R(\bar{\Delta})+T(\bar{\Delta})$ has been replaced by $(1-\alpha)T(\bar{\Delta})+\alpha\Delta+U(\bar{\Delta})$ and this term exists only when $T(\Delta)>\Delta$; The last term is the principal's utility for types $\Delta > \bar{\Delta}+\varsigma|\Delta|$ who will find it infeasible to finish the project and hence will take the contract for type $\bar{\Delta}$ and shirk throughout.

The introduction of ς does not really complicate the problem, since if $T(\Delta)=\Delta$, we have $\varsigma=0$ and $U(\Delta) \geq \alpha(\bar{\Delta}-\Delta)+\alpha T(\bar{\Delta}) = 2\alpha\bar{\Delta}-\alpha\Delta$. As giving rent is costly to

[62] It is assumed that when the agent is indifferent between finishing and shirking, it will finish the project.

the principal, she will set the utility at the lowest possible value, that is, $U(\Delta) = 2\alpha\bar{\Delta} - \alpha\Delta$; If $T(\Delta) > \Delta$, we have $\varsigma > 0$ and $U(\Delta) = \alpha(\bar{\Delta} - \Delta) + \alpha T(\bar{\Delta})$, $\forall\Delta \in [0, \bar{\Delta}]$. Substitute $U(\Delta)$ into the first and second terms of the objective function, and collect terms. We can see that $T(\Delta)$ has a coefficient of $-(1-\alpha)$ and $T(\bar{\Delta})$ has -1 in both the first and the second terms, and $T(\bar{\Delta})$ has a coefficient of -1 in the last term. As argued earlier, there will be no equilibrium setting of $T(.)$. Hence, the only equilibrium contract length is set at the efficient level: $T(\Delta) = \Delta$, $\forall\Delta \in [0, \bar{\Delta}]$. The agent's rent is $U(\Delta) = 2\alpha\bar{\Delta} - \alpha\Delta$ and the principal's expected utility for a given $\bar{\Delta}$ is:

$$\begin{aligned} &\int_0^{\bar{\Delta}} [V - (1-\alpha)\Delta - \alpha\Delta - 2\alpha\bar{\Delta} + \alpha\Delta] dF(\Delta) - \int_{\bar{\Delta}}^{\infty} \bar{\Delta} dF(\Delta) \\ &= \int_0^{\bar{\Delta}} [V - (1-\alpha)\Delta - 2\alpha\bar{\Delta}] dF(\Delta) - \int_{\bar{\Delta}}^{\infty} \bar{\Delta} dF(\Delta). \end{aligned} \tag{3.13}$$

Integrating the first term by parts gives:

$$[V - (1-\alpha)\Delta - 2\alpha\bar{\Delta}]F(\Delta)\Big|_0^{\bar{\Delta}} + \int_0^{\bar{\Delta}} (1-\alpha)F(\Delta)d\Delta, \tag{3.14}$$

Substitute (3.14) into equation (3.13) and integrate the last term. The principal's total expected utility for a given $\bar{\Delta}$ becomes:

$$[V - \alpha\bar{\Delta}]F(\bar{\Delta}) - \bar{\Delta} + \int_0^{\bar{\Delta}} (1-\alpha)F(\Delta)d\Delta. \tag{3.15}$$

Equation (3.15) has a neat explanation, that is, since mimicking is not punishable, the screening contract has to give the efficient types extra information rents which are decreasing in Δ and bounded below by type $\bar{\Delta}$'s utility. The first and second terms of equation (3.15) summarise the principal's project value less the sum of type $\bar{\Delta}$'s funding and effort rent, and the mimicking loss from the inefficient types $\bar{\Delta}(1-F(\bar{\Delta}))$. The last term is the sum of saving in funding and extra information rent for the efficient types. This utility is smaller than without the moral hazard problem where the principal's value is:

$$\int_0^{\bar{\Delta}}(V-\Delta)dF(\Delta).$$

Integrating by parts gives:

$$[V-\bar{\Delta}]F(\bar{\Delta})+\int_0^{\bar{\Delta}}F(\Delta)d\Delta. \tag{3.16}$$

Moreover, differentiating equations (3.15) and (3.16) with respect to $\bar{\Delta}$ gives the principal's marginal utility. We can hence check that the optimal $\bar{\Delta}$ in equation (3.15) is less than in equation (3.16)[62]. In other words, due to the possibility that the agent can take the contract and shirk throughout, the principal turns to a conservative attitude in funding the long term project. Proposition 3.3 concludes the finding in this section:

Proposition 3.3

For a long term project with a moral hazard problem: (1) If $\Delta \in [0,\infty)$, the principal will adopt a cut-off strategy: she funds the project for type $\Delta \leq \Delta^*$ and stops funding if $\Delta > \Delta^*$; (2) The agent's production efficiency remains for the efficient type $\Delta < \Delta^*$; (3) Compared to the contractible effort case, the principal will take a more conservative attitude in funding.

[62] The second order conditions are satisfied if F(.) is concave.

3.5. Auction

When there is more than one candidate for a project, an auction is usually held to select the agent to undertake the project. The most often cited examples are EU leasing R&D projects through tender process. Motivated by its prevalence, we firstly discuss the design of the optimal auctioning contract, following the framework of Laffont and Tirole (1993). The outcome of this optimal auction is then compared to that of another auction form: the second-price auction. We obtain some interesting results concerning the *revenue equivalence theorem* and the *separation property*[63]. Later, using this second-price auction, we discuss the existence of a *built-in cost overrun* which is caused by the mixed effects of bidding competition and the setting of a cost ceiling in case of overrun. The relevant literature is discussed at the end of this section.

3.5.1 Optimal Auction[64]

The derivation of the optimal auctioning contract is presented in a discrete type setting, as it provides a clearer idea about how an auction works in our model. To simplify the analysis, we keep the single principal assumption and further assume that there are two agents, whose types are independently drawn from the set $\{\Delta_1, \Delta_2\}$: with probability υ to

[63] Both of them are important results in auction theory. The revenue equivalence theorem (Vickrey, 1961) says that, under some assumptions (see Fudenberg and Tirole, 1991, p.253 for detailed discussion of these assumptions), all of the traditional auctions give the principal the same expected revenue. However, as demonstrated in Fudenberg and Tirole, this theorem does not hold in a two-type framework. The separation property says that the winner's effort is the same as if the winner faced no bidding competition. (Laffont and Tirole, 1993, p.328).

[64] Since the agent's private information is due to a better understanding of its own cost structure, the auction we study here belongs to the class of "independent value model". The alternative settings are: the "common value model", where none of the bidders knows the cost (which is common to each agent) of the project although each agent may receive different information concerning this cost; the affiliated value model, where each bidder signals contain an idiosyncratic and private information (i.e., the observation of the common value) (see Milgrom (1987)).

type Δ_1 and with probability $(1-\upsilon)$ to type Δ_2. Each agent knows his own type but not the rival's type, and the principal knows only each agent's distribution. The assumptions of risk neutrality, no discounting, and a deterministic production technology still hold in this section. Furthermore, it is assumed that there is no collusion between two bidders. Denote the agents' true values as Δ^1 and Δ^2 respectively (note the difference between superscript and subscript). The auction starts with each agent submitting its bid $\hat{\Delta}^i$. The bid stands for the total duration equivalent to the total cost needed to complete the project, as we assume the cost per period to be £1. The bidding set is restricted to the type space $\{\Delta_1, \Delta_2\}$, since the principal knows both agents' distributions. The allocation of the project, funding periods and rewards are hence dependent on the bidding vector $(\hat{\Delta}^1, \hat{\Delta}^2)$. By the revelation principle, we can concentrate on a truth-telling direct mechanism. Let $\hat{\Delta} = (\hat{\Delta}^1, \hat{\Delta}^2)$ and $x^i(\hat{\Delta})$ be the probability that the project is assigned to agent i. Based on $\hat{\Delta}$, an auctioning contract specifies a probability $x^i(\hat{\Delta})$, a funding period $T_i(\hat{\Delta})$ and an end-of-contract reward $R_i(\hat{\Delta})$ to each agent i. The truth-telling Bayesian implementation requires that the mechanism is designed in such a way that each agent bids its true value $\hat{\Delta}^i = \Delta^i$ and the project will be finished.

First of all, there are some constraints on the project allocation:

$$\sum_i x^i(\hat{\Delta}) \le 1,$$ [65]

$$x^i(\hat{\Delta}) \ge 0, \qquad \text{for } i = 1,2.$$

[65] $\sum_i x^i(\hat{\Delta}) < 1$ stands for the case where none of the agents wins the project. In other words, it is allowed to have allocation inefficiency.

To set a benchmark of allocation efficiency, we need to check the allocation rules under complete information (i.e., when Δ is known):

$$x^1(\Delta_1,\Delta_1)+x^2(\Delta_1,\Delta_1)=1,$$
$$x^1(\Delta_2,\Delta_2)+x^2(\Delta_2,\Delta_2)=1,$$
$$x^1(\Delta_1,\Delta_2)=x^2(\Delta_2,\Delta_1)=1.$$

When each agent's type is known by the principal, the project will surely be assigned to the low cost agent. Notice that the sum of $x^i(.)$ is one, meaning that there is no efficiency loss in allocation. Recall that it is always efficient for the project to proceed. By submitting $\hat{\Delta}^1$, agent 1's expected utility for completing the project is:

$$\begin{aligned}E_{\Delta^2}x^1(\hat{\Delta}^1,\Delta^2)U(\hat{\Delta}^1,\Delta^2) &= E_{\Delta^2}\{x^1(\hat{\Delta}^1,\Delta^2)[\alpha(T_1(\hat{\Delta}^1,\Delta^2)-\Delta^1)+R_1(\hat{\Delta}^1,\Delta^2)]\}\\ &=\{\upsilon x^1(\hat{\Delta}^1,\Delta_1)[\alpha(T_1(\hat{\Delta}^1,\Delta_1)-\Delta^1)+R_1(\hat{\Delta}^1,\Delta_1)]\\ &\quad+(1-\upsilon)x^1(\hat{\Delta}^1,\Delta_2)[\alpha(T_1(\hat{\Delta}^1,\Delta_2)-\Delta^1)+R_1(\hat{\Delta}^1,\Delta_2)]\}.\end{aligned}$$

As the principal would prefer the agent to complete the project efficiently, she has to ensure that this utility is at least the same as if the agent commits to shirk throughout or finish the project inefficiently. Note that the agent's utility term goes after the winning probabilities $x^1(.)$, rather than being an isolated term, which setting is often found in the mechanism design literature. In order to generalise the analysis, the previous literature allows the principal to compensate the loser(s) of an auction if necessary. However, as argued in Section 3.2, any reward before the completion of the project has no effect in encouraging effort, hence it is optimal for the principal to use the end-of-contract reward. Since the agent can not get the reward unless he wins and finishes the project, we should put the compensation terms after the winning probabilities.

For truth-telling to form a Bayesian Implementation, several constraints need to be satisfied. Firstly, if given the project[66], each type of agent 1 will prefer completing the project to shirking throughout (Moral Hazard constraint: MH), that is,

$$\alpha(T_1(\Delta_1,\Delta^2)-\Delta_1)+R_1(\Delta_1,\Delta^2)\geq\alpha T_1(\Delta_1,\Delta^2) \qquad \text{for } \Delta^2=\Delta_1,\Delta_2, \tag{3.17}$$

and

$$\alpha(T_1(\Delta_2,\Delta^2)-\Delta_2)+R_1(\Delta_2,\Delta^2)\geq\alpha T_1(\Delta_2,\Delta^2) \qquad \text{for } \Delta^2=\Delta_1,\Delta_2. \tag{3.18}$$

These two equations are not in expectations, as shirking can only matter after the project is assigned to the agent[67]. For future reference, taking the expectation across Δ^2 on both sides of equations (3.17) and (3.18), we have:

$$E_{\Delta^2}x^1(\Delta_1,\Delta^2)[\alpha(T_1(\Delta_1,\Delta^2)-\Delta_1)+R_1(\Delta_1,\Delta^2)]\geq E_{\Delta^2}x^1(\Delta_1,\Delta^2)\alpha T_1(\Delta_1,\Delta^2), \tag{3.17'}$$

and

$$E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_2)+R_1(\Delta_2,\Delta^2)]\geq E_{\Delta^2}x^1(\Delta_2,\Delta^2)\alpha T_1(\Delta_2,\Delta^2). \tag{3.18'}$$

(3.17)' and (3.18)' say that even in expectations, committing to finish the project will give each type of agent 1 at least the expected value from shirking throughout.

Secondly, to have truth-telling, the principal needs to ensure that each type of agent 1 would prefer bidding the true value and committing to finish the project to bidding the other value and committing to finish or shirk throughout. In notation, the incentive compatibility constraint for type Δ_1 is:

$$\begin{aligned}&E_{\Delta^2}x^1(\Delta_1,\Delta^2)[\alpha(T_1(\Delta_1,\Delta^2)-\Delta_1)+R_1(\Delta_1,\Delta^2)]\\ &\geq E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_1)+R_1(\Delta_2,\Delta^2)].\end{aligned} \tag{3.19}$$

---

[66] We discuss agent 1's constraints here, and agent 2's constraints can be derived in the same way.
[67] Note that since other constraints are in expectation terms, it is not a type dominant strategy implementation.

Bidding Δ_2 gives type Δ_1 a different probability of winning the auction. Note that (3.19) also implies that Δ_1 will not be better off bidding Δ_2 and shirking throughout, which can be seen from (3.18)' and (3.19):

$$\begin{aligned}&E_{\Delta^2}x^1(\Delta_1,\Delta^2)[\alpha(T_1(\Delta_1,\Delta^2)-\Delta_1)+R_1(\Delta_1,\Delta^2)] \\ &\geq E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_1)+R_1(\Delta_2,\Delta^2)] \\ &> E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_2)+R_1(\Delta_2,\Delta^2)] \geq E_{\Delta^2}x^1(\Delta_2,\Delta^2)\alpha T_1(\Delta_2,\Delta^2).\end{aligned} \tag{3.20}$$

The incentive compatibility constraint for type Δ_2 is less straightforward, as whether type Δ_2 can finish the project is physically restricted by the capacity constraint. If $T_1(\Delta_1,\Delta^2)\geq\Delta_2$, it is possible that Δ_2 can finish the project by taking type Δ_1's contract and receive the rent from completing the project; if $T_1(\Delta_1,\Delta^2)<\Delta_2$, type Δ_2's dominant strategy is to shirk throughout, as finishing the project is infeasible. For this case, type Δ_2 has the shirking benefit $\alpha T_1(\Delta_1,\Delta^2)$. Since bidding will also affect type Δ_2's probability of winning the auction, MH2 will not cover this case as it does in the single agent case. Denote this part as the Incentive Moral Hazard constraint for type Δ_2 (IMH2). Hence, the incentive compatibility constraint for type Δ_2 is:

$$\begin{aligned}&E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_2)+R_1(\Delta_2,\Delta^2)] \\ &\geq E_{\Delta^2}x^1(\Delta_1,\Delta^2)\cdot\max\left\{[\alpha(T_1(\Delta_1,\Delta^2)-\Delta_2)+R_1(\Delta_1,\Delta^2)],\alpha T_1(\Delta_1,\Delta^2)\right\}.\end{aligned} \tag{3.21}$$

The constraints for agent 2 can be derived in the same manner. The principal maximises her expected utility, which is the expected project value less the expected funding and reward cost, with respect to $x^i(\Delta)$, $T_i(\Delta)$ and $R_i(\Delta)$. That is,

$$\max_{x^i(\Delta),T_i(\Delta),R_i(\Delta)} E_{\Delta^1,\Delta^2}\{x^1(\Delta^1,\Delta^2)[V-R_1(\Delta^1,\Delta^2)-T_1(\Delta^1,\Delta^2)]$$

$$+x^2(\Delta^1,\Delta^2)[V-R_2(\Delta^1,\Delta^2)-T_2(\Delta^1,\Delta^2)]\}, \tag{3.22}$$

subject to the capacity, moral hazard and incentive compatibility constraints.

To solve the problem, we first need to find out the cheapest rent to implement an effort level that finishes the project at time T_i. The analysis is similar to Section 3.2 but more complicated as we need to take into account each agent's winning probabilities[68]. So far, for the efficient type, we have the moral hazard constraint (MH1(3.17)) and the incentive compatibility constraint (IC1 (3.19)). Unlike the single agent case, the moral hazard constraint for type Δ_2 (MH2 (3.18)') will not imply MH1, as different bidding values will also affect the winning probability $x^i(\Delta)$. For the inefficient type, we have moral hazard constraint (MH2 (3.18)') and incentive compatibility constraint (IC2 (3.21)). Again unlike the single agent case, IMH2 will not be implied by MH2 constraint. The following discussion helps to cut down the number of constraints. Firstly, MH1 cannot bind, since if it is binding, IMH2 will be violated. That is, suppose MH1 is binding,

$$\begin{aligned}E_{\Delta^2}x^1(\Delta_1,\Delta^2)\alpha T_1(\Delta_1,\Delta^2) &= E_{\Delta^2}x^1(\Delta_1,\Delta^2)[\alpha(T_1(\Delta_1,\Delta^2)-\Delta_1)+R_1(\Delta_1,\Delta^2)]\\ &\geq E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_1)+R_1(\Delta_2,\Delta^2)]\\ &> E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha(T_1(\Delta_2,\Delta^2)-\Delta_2)+R_1(\Delta_2,\Delta^2)].\end{aligned}$$

Therefore, for the cheapest rent for type Δ_1, IC1 will be binding. Secondly, if $T_1<\Delta_2$, IC2 can be pinned down to only IMH2. To proceed, we guess that only IMH2 is valid, and leave it for justification later. Moreover, MH2 requires that for the winning agent to

[68] The following discussion concentrates on agent 1 and the same reasoning applies to agent 2.

complete the project, type Δ_2's utility must be bigger than $\alpha T_1(\Delta_2, \Delta^2)$ for $\Delta^2 = \Delta_1, \Delta_2$. This will be violated if only IMH2 is binding, provided $T_1(\Delta_1, \Delta^2) < T_1(\Delta_2, \Delta^2)$. Assume provisionally that $T_1(\Delta_1, \Delta^2) < T_1(\Delta_2, \Delta^2)$ and hence we can have either only MH2 binding or both MH2 and IMH2 binding. In the following, we proceed with the analysis by assuming only MH2 is binding, and leave the checking of IMH2 for the end of our discussion. Let $U^i(.,.)$ denote agent i's utility, and the principal's objective function can be written as:

$$E_{\Delta^1,\Delta^2}\{(x^1(\Delta^1,\Delta^2)(V-[(1-\alpha)T_1(\Delta^1,\Delta^2)+\alpha\Delta^1+U^1(\Delta^1,\Delta^2)])$$
$$+x^2(\Delta^1,\Delta^2)(V-[(1-\alpha)T_2(\Delta^1,\Delta^2)+\alpha\Delta^2+U^2(\Delta^1,\Delta^2)])\}.$$

For MH2 to be binding, we have type Δ_2's expected utility of agent 1 as:

$$E_{\Delta^2}x^1(\Delta_2,\Delta^2)U^1(\Delta_2,\Delta^2)=E_{\Delta^2}x^1(\Delta_2,\Delta^2)\alpha T_1(\Delta_2,\Delta^2), \qquad (3.18)''$$

which means that type Δ_2 is rewarded the shirking benefit from taking the contract of his own type. For IC1 to be binding, we have

$$E_{\Delta^2}x^1(\Delta_1,\Delta^2)U^1(\Delta_1,\Delta^2)=E_{\Delta^2}x^1(\Delta_2,\Delta^2)[\alpha T_1(\Delta_2,\Delta^2)-\Delta_1)+R_1(\Delta_2,\Delta^2)].$$

Likewise, we can derive the cheapest rents for agent 2. Substituting $U^i(.,.)$ with the cheapest rents and collecting terms, we can rewrite the principal's expected utility function as:

$$x^1(\Delta_1,\Delta_1)\upsilon^2[V-(1-\alpha)T_1(\Delta_1,\Delta_1)-\alpha\Delta_1]$$
$$+x^2(\Delta_1,\Delta_1)\upsilon^2[V-(1-\alpha)T_2(\Delta_1,\Delta_1)-\alpha\Delta_1]$$

$$
\begin{aligned}
&+x^1(\Delta_1,\Delta_2)\upsilon(1-\upsilon)[V-(1-\alpha)T_1(\Delta_1,\Delta_2)-\alpha\Delta_1]\\
&+x^2(\Delta_1,\Delta_2)\{\upsilon(1-\upsilon)[V-(1-\alpha)T_2(\Delta_1,\Delta_2)-\alpha\Delta_2]\\
&\qquad -(1-\upsilon)\upsilon\alpha T_2(\Delta_1,\Delta_2)-\upsilon^2[\alpha T_2(\Delta_1,\Delta_2)-\alpha\Delta_1+\alpha\Delta_2]\}\\
&+x^1(\Delta_2,\Delta_1)\{(1-\upsilon)\upsilon[V-(1-\alpha)T_1(\Delta_2,\Delta_1)-\alpha\Delta_2]\\
&\qquad -(1-\upsilon)\upsilon\alpha T_1(\Delta_2,\Delta_1)-\upsilon^2[\alpha T_2(\Delta_2,\Delta_1)-\alpha\Delta_1+\alpha\Delta_2]\}\\
&+x^2(\Delta_2,\Delta_1)(1-\upsilon)\upsilon[V-(1-\alpha)T_2(\Delta_2,\Delta_1)-\alpha\Delta_1]\\
&+x^1(\Delta_2,\Delta_2)\{(1-\upsilon)^2[V-(1-\alpha)T_1(\Delta_2,\Delta_2)-\alpha\Delta_2]\\
&\qquad -(1-\upsilon)^2\alpha T_1(\Delta_2,\Delta_2)-\upsilon(1-\upsilon)[\alpha T_1(\Delta_2,\Delta_2)-\alpha\Delta_1+\alpha\Delta_2]\}\\
&+x^2(\Delta_2,\Delta_2)\{(1-\upsilon)^2[V-(1-\alpha)T_2(\Delta_2,\Delta_2)-\alpha\Delta_2]\\
&\qquad -(1-\upsilon)^2\alpha T_2(\Delta_2,\Delta_2)-\upsilon(1-\upsilon)[\alpha T_2(\Delta_2,\Delta_2)-\alpha\Delta_1+\alpha\Delta_2]\}. \qquad (3.23)
\end{aligned}
$$

It can be checked that all the coefficients of $T_i(.)$ in equation (3.23) are negative, meaning that funding is costly to the principal. Hence, the capacity constraints should be binding:

$$T_1(\Delta_1,\Delta_2)=T_2(\Delta_2,\Delta_1)=\Delta_1,$$

and

$$T_1(\Delta_2,\Delta_1)=T_2(\Delta_1,\Delta_2)=\Delta_2.$$

In the solution, production efficiency will hold as each type finishes the project without delay (Δ_i). As we will see later, production efficiency does not hold in a second-price auction. Next, we need to find out the allocation rule in this auction. First of all, since the terms after $x^1(\Delta_1,\Delta_1)$ and $x^2(\Delta_1,\Delta_1)$ are identical, to maximise expected utility, the principal should set

$$x^1(\Delta_1,\Delta_1)+x^2(\Delta_1,\Delta_1)=1.$$

Likewise,

$$x^1(\Delta_2,\Delta_2)+x^2(\Delta_2,\Delta_2)=1\ .$$

Assuming symmetry, we have $x^1(\Delta_1,\Delta_1)=x^2(\Delta_1,\Delta_1)=x^1(\Delta_2,\Delta_2)=x^2(\Delta_2,\Delta_2)=\frac{1}{2}$. Secondly, since the value after $x^1(\Delta_1,\Delta_2)$ is greater than the value after $x^2(\Delta_1,\Delta_2)$, $x^1(\Delta_1,\Delta_2)$ should be set as large as possible, i.e., $x^1(\Delta_1,\Delta_2)=1$. In the same manner, we set $x^2(\Delta_2,\Delta_1)=1$. Comparing this result with the complete information case, we can conclude that the optimal auction keeps both allocation and production efficiency as in the complete information case.

Finally, we need to check whether the solution satisfies all the constraints. IC2 will be pinned down to only IMH2, as the funding period for the efficient type is Δ_1. Substituted with the settings of T_i and x^i, MH2 ((3.18)") says that the optimal rent for type Δ_2 is $\alpha\Delta_2$. However, IMH2 requires the expected utility for type Δ_2 to be at least as much as taking the contract for type Δ_1 and shirking throughout, i.e., $\upsilon 0+(1-\upsilon)\frac{1}{2}(\alpha\Delta_2)\ \geq \upsilon\frac{1}{2}(\alpha\Delta_1)+(1-\upsilon)(\alpha\Delta_1)$, which will hold if $\Delta_2\geq\Delta_1(1+\frac{1}{1-\upsilon})$. From IC1, type Δ_1's rent for this case is $\frac{1-\upsilon}{2-\upsilon}\alpha(2\Delta_2-\Delta_1)$, which is smaller than that in the single agent case: $\alpha(2\Delta_2-\Delta_1)$. The utility difference is because for this case type Δ_1 will be less likely to mimic Δ_2 under competition, as mimicking type Δ_2 will give him less chance to win the contract.

For $\Delta_2<\Delta_1(1+\frac{1}{1-\upsilon})$, IMH2 will be violated by the above solution. To have IMH2 satisfied, we can either adjust the reward $R_2(\Delta)$ or the probability of winning $x^i(\Delta)$.

Since the agent will be indifferent adjusting $R_2(\Delta)$ and $x'(\Delta)$, and since adjusting $x'(\Delta)$ will cause longer expected funding periods, it is optimal to adjust $R_2(\Delta)$. Having IMH2 bind, the inefficient type's incentive rent will be: $\alpha\Delta_1(1+\frac{1}{1-\upsilon})$, which is greater than $\alpha\Delta_2$ by the assumption of parameters. From IC1, type Δ_1's rent for this case is: $\frac{1-\upsilon}{2-\upsilon}\alpha(2\Delta_2-\Delta_1)+\frac{1}{2-\upsilon}\alpha\Delta_1$, which is higher than the rent for $\Delta_2 \geq \Delta_1(1+\frac{1}{1-\upsilon})$. However, it is still smaller than the single agent case (as $\frac{1}{2-\upsilon}\alpha\Delta_1 < \frac{1}{2-\upsilon}\alpha(2\Delta_2-\Delta_1)$). Intuitively, when there is a big difference between the two types, the inefficient type has a higher shirking benefit by taking his own contract although doing so will give him less chance to win the auction. As mimicking the inefficient type will give the efficient type less chance to win the auction, the incentive rent paid for his truth-telling can hence decrease. When there is a smaller difference between the two types, the inefficient type will mimic the efficient type in order to have a higher chance of winning. Hence, the principal has to give the inefficient type higher rent to choose its own type. Accordingly, to induce truth-telling from the efficient type, the principal has to increase the incentive rent for the efficient type. But still, this rent is less than the single agent case. Overall, the principal benefits from the competition between two firms, because the incentive rents can be decreased under competition and there is more chance to have the project completed by an efficient type.

3.5.2 Second-Price Auction

An interesting question is "Can the optimal outcome be achieved by a traditional auction?" There are four auction forms[69] in the traditional literature: ascending (English, oral), descending (Dutch, oral or outcry), first-price and second-price auctions (sealed-bid). Milgrom and Weber (1982) show that descending and first-price auctions are strategically equivalent, and ascending and second-price auctions are equivalent in the context of private value models. The *revenue equivalence* theorem says that these four auctions give the auctioneer the same expected revenue, and the *separation property* says that the winner's effort will be the same as no bidding competition. Apart from these two results, it is also well known in auction theory that a bidder's *weakly dominant strategy is to bid its true value* in a second-price auction (e.g., Vickrey (1961)). In the following, we discuss a second-price auction which incorporates the opportunism problem in our model, and conclude that "bidding the principal's reservation price" will be each agent's dominant strategy and neither the revenue equivalence theorem nor the separation property holds in this auction.

In a second-price auction, two agents simultaneously submit their bids b^i for the project's total cost. Recall that agent *i* has private information about the total cost Δ^i. The bidding set is *not* restricted to $\{\Delta_1, \Delta_2\}$, however we assume the principal adopts a reservation policy in the auction. There are many papers discussing the settings of optimal reservation price (e.g., Milgrom (1987), Levin and Smith (1996)). To avoid complication[70] and to make it comparable to the outcome from the optimal auction, it is assumed that the principal's reservation price is Δ_1. Moreover, since there is a moral hazard problem, to avoid the agents bidding a low cost, winning the contract and then

[69] The auction forms are not necessarily the optimal forms.
[70] One of the issues on the reservation price policy concerns whether to announce the true value or a false value. However, this is not the issue addressed in this paper.

shirking throughout afterwards, we need to put a constraint on each agent's bid. Specifically, for each value b^i, an end of contract reward αb^i [71] is required as part of the total cost. The lowest cost bidder wins the project and will be assigned the contract associated with the second lowest bid. The loser is given nothing. If both agents bid the same total cost, the project is allocated randomly between them.

Firstly, it can be checked that bidding the principal's reservation price is the dominant strategy. To see, suppose $b^i > \Delta_1$. If $b^i < b^j$ and $b^j \geq \Delta^i$, then the project will be finished by agent i and its utility for this case is: $\alpha(b^j - \Delta^i) + \alpha b^j$. If $b^i < b^j$ and $b^j < \Delta^i$, then the project is still given to i but will not be finished. Agent i has the shirking revenue αb^j. If $b^i = b^j$, then both agents share the project with funding associated with b^i. However, if $b^i > b^j$, then the project will be assigned to agent j and agent i's utility will be zero. Since bidding a lower value can guarantee at least a positive utility, to have the highest probability of winning the auction, it is dominant for each agent i to always bid Δ_1.

Secondly, given that each agent's dominant strategy is to bid the principal's reservation price, both agents will be assigned randomly (with probability $\frac{1}{2}$ in the symmetric case) the contract associated with Δ_1. There will be only a probability $\upsilon^2 + \upsilon(1-\upsilon) = \upsilon$ that the project can be finished at time Δ_1. For other cases, the agents will shirk right through Δ_1. Hence the principal's expected utility will be:

$$\upsilon\{V - \Delta_1 - \alpha\Delta_1\} + (1-\upsilon)\{-\Delta_1\},$$

[71] This constraint is equivalent to the moral hazard constraint. (Equivalently, the bid could be interpreted as including the reward αb_i).

which will be smaller than that from the optimal auction: $\upsilon\{V-\Delta_1\}+(1-\upsilon)\{V-(1+\alpha)\Delta_2-(1-\alpha)\upsilon(\Delta_2-\Delta_1)\}$ for a sufficiently big project value and a sufficiently big difference between two types[72]. Since for each winner there is only a probability υ that full effort will be put in, the separation property does not hold either. We write this result as a proposition.

Proposition 3.5

In a second-price auction where the bidding object is the total cost for a long term project and there is a moral hazard problem, each agent will bid the principal's reservation price and neither the revenue equivalence theorem nor the separation property will hold in this auction.

Next, we use this second-price auction to address an issue that is often confronted in long term contracts: *the cost overruns problem*. Cost overruns have already been noticed since early research, for example, Scherer (1964) concludes that "just as in weapons acquisition, cost overruns are quite common in advanced commercial product development efforts". However, there is little theoretical discussion concerning this issue. In a single agent repeated contract game, Lewis (1986) concludes a Bayesian equilibrium where the reputation effect keeps the agent performing well in early stages of production, but as the principal learns more about the agent's private information over time, the reputation effect decreases and hence production cost will be higher in later stages. Arran and Leite (1990) also show that the compensation scheme arises as the project nears its completion.

In addition to these compensation changes within the contracts, there is a different interpretation of cost overruns by Scherer (p.155): "overrun refers only to increases in

[72] The condition will be similar for a smaller difference between two types.

cost above the negotiated target when there has been no change in the contract's qualitative and quantitative requirements". In his study of the weapon acquisition process, Scherer mentions a very interesting piece of evidence about cost overruns: "Secretary of Defence... claimed that cost estimates submitted by both Boeing and General Dynamics... were unrealistically optimistic (p.176)". In other words, there is a *built-in cost overrun* induced by the competition among potential contractors. To proceed with our analysis, I would like to quote another piece of evidence in the same report: "Usually a ceiling price (historically, from 115% to 135% of the target cost) is negotiated, setting a firm limit on the amount of cost plus profit the government will pay in the event of a large overrun".

It is argued that this kind of built-in cost overrun does exist and is caused by the mixed effects of competition among agents and expectation of the price ceiling in case of overrun[73]. The intuition is as follows. The setting of a price ceiling actually extends the effective deadline to the extent of the ceiling. Imagine a contracted agent who knows in advance that there will be contingent extension of the funding period (and the reward). Since a longer funding period implies a higher utility, the agent will find it optimal to delay his effort (which is unobservable by the principal) and make the contingent extension realised. Hence in a single agent case, there will be an extra rent from extension. However, when there is more than one potential agent, each of them knows that its effective deadline is the target deadline plus the extended period. Given the other agents bid the lowest possible value and obtain this extra rent, agent *i* will find it optimal to forgo some of his extra rent and bid a lower value to have a higher chance of winning the contract. Therefore, in equilibrium, each agent will underbid their values to the extent

[73] Quirk and Teresawa (1984), and Gaspar and Leite (1989/1990) address independently the relation between selection bias and cost overrun. The intuition they use is the "winner's curse phenomenon". As they use common value and single stage models, the present model is therefore different from theirs.

the contract. Therefore, in equilibrium, each agent will underbid their values to the extent that the extra rent from extension is driven down to zero and hence there is a built-in cost overrun. The detail of this idea is left for further research.

3.6. Symmetric Beliefs

In this section, it is assumed that neither of the involved parties has private information about Δ, which corresponds to the stochastic setting in the R&D literature. Under symmetric[74] beliefs, we discuss how the opportunism problem affects the agent's effort decisions and then look for the optimal funding contract. It is shown that the funding length is not longer than the contract without the opportunism problem. Later, we investigate the impact of contract renewal, the issues of lock-in effect and the choice between long-term and short-term contracts. To simplify the analysis, it is first assumed that both parties do not anticipate the renewal of the contract. We can justify this case by picturing that there is a sequence of principals and agents, and each match of them is allowed only one attempt at finishing the project (i.e., one contract). The result shows that the lock-in effect persists and a series of short-term contracts is preferable to a single long-term contract. A short-term contract refers to a contract that lasts for one unit of time (such as one execution period), and a long-term contract refers to the optimal contract. Finally, we discuss the case when both parties can anticipate the contract renewal, for which case our result shows that no transaction will ever happen.

3.6.1 Symmetric Beliefs Without Renewal

[74] More specifically, the literature assumes the distribution to be an exponential function. See Lucas (1971) for an example of a monopoly firm, and Lee and Wilde (1980), Reinganum (1982), Harris and Vickers (1987) for examples with rival firms.

Keeping the assumption of a single self-interested principal and single agent, we assume that neither of the involved parties has private information about Δ. Both parties have the same belief that Δ is drawn from $(0,\infty)$ by a distribution function $F(\Delta)$, with density function $f(\Delta)$[75] and $f(\Delta)>0$ for $\forall\Delta$. This setting corresponds to the stochastic nature in the R&D literature. One can think of "eureka" kind of projects, where the agent puts in effort without knowing how long more it will take before completion. It is assumed that once the innovation comes out[76], it becomes publicly known. Concealing the innovation is excluded in this model. Further assumptions on the distribution form will be imposed as we proceed with the analysis.

The principal starts by offering the agent a contract[77] $\{T,G\}$, where she commits the funding for *T* period, and if the innovation comes out any time before or at *T*, the funding stops immediately and the agent is given *G* as reward; however, if the innovation never happens before or at *T*, the funding stops after *T* and the agent is not given any reward. The constant reward can be interpreted as the prize (a patent or monopoly profit) of R&D activities (e.g., Reinganum (1989)). The agent responds by accepting or rejecting this offer. If the agent takes the offer, he has to make a sequence of working and shirking decisions as described in Section 3.2. Keeping the no discounting assumption, Lemma 3.3 says that if the agent decides to put in effort, he will delay the effort till the last part of the funding periods (i.e., he will not put in effort and then shirk at any point). The proof of Lemma 3.3 is presented in a discrete version, as it provides a better picture of the

[75] The setting of distribution is the same as section 3.4, but now even the agent does not know $F(.)$. The assumption of continuity is for technical convenience, as the derivation of optimal contract will be very difficult in a discrete setting.
[76] Only when the innovation comes out, the involved parties know the true value of Δ.
[77] We restrict to this contract form as it is most used in the R&D literature. G can be seen as a patent.

agent's choice at each point. To do so, we need to re-define the variables. Firstly, assume the index in discrete setting takes the form of natural numbers, that is, t=1, 2, 3.... Hence, a number t refers to the value from $t-1$ till t in the continuous version. Next, denote $p(\Delta = t) := \int_{t-1}^{t} f(\Delta)d\Delta$ as the probability that the completion time needed is t. As it is assumed that $f(\Delta) > 0$, we know $p(\Delta) > 0$. Further, define $p(\Delta = t|\Delta > k)$ $:= \int_{t-1}^{t} f(\Delta|\Delta > k)d\Delta$, where $f(\Delta|\Delta > k)$ is the conditional density function given $\Delta > k$. As $f(\Delta) > 0$, it is also true that $f(\Delta|\Delta > k) > 0$. Lemma 3.3 is proved using this adjusted setting.

Lemma 3.3

It is not optimal for the agent to put in effort first and shirk later.

Proof : At an arbitrary time t, $t \leq T$, assume that the agent has put in effort for k periods. Conditional on the project not being finished before t, denote $p(\Delta = k+1|\Delta > k)$ as the conditional probability that the project will be completed if the agent puts in effort once again. Consider the following two strategies from t on, with the only difference in the order of actions at time t and $t+1$: *strategy A* specifies the agent to work at t and then shirk at $t+1$; *strategy B* specifies the agent to shirk first at t and then work at $t+1$. The expected values for these two strategies are denoted by W_t^A and W_t^B, where

$$W_t^A = p(\Delta = k+1|\Delta > k)\cdot G + (1 - p(\Delta = k+1|\Delta > k))(\alpha + W_{t+2}^A),$$

and

$$W_t^B = \alpha + p(\Delta = k+1|\Delta > k)\cdot G + (1 - p(\Delta = k+1|\Delta > k))\cdot W_{t+2}^B,$$

where W^i_{t+2}, $i = A, B$ is the agent's value function at $t+2$ given $k+1$ ($\Delta > k+1$) periods of effort from *Strategy A* and *Strategy B* respectively. The explanation for W_t^A is: by putting in effort for the $k+1^{th}$ time, the agent has a probability $p(\Delta = k+1 | \Delta > k)$ to finish the project, and obtain the reward G from completion. If the project is not finished, *Strategy A* specifies the agent to shirk from $t+1$ till $t+2$ and get the shirking benefit α. W^A_{t+2} is the value at time $t+2$ provided the project is not finished after $k+1$ periods of effort. W_t^B is explained in a similar manner. Note that, since the two strategies coincide from $t+2$ on, we have $W^A_{t+2} = W^B_{t+2}$. Further, since $p(\cdot) > 0$ by assumption, $W_t^B - W_t^A$ $= \alpha p(\Delta = k+1 | \Delta > k) > 0$. Hence, the agent can be better off using *strategy B*, and cannot be worse off. Since we can take *t+1* to be the last effort period before a period of shirking, we can conclude the lemma. Q.E.D.

Given Lemma 3.3, denote n as the agent's committed shirking period before he puts in effort henceforth until T. In the following, we look for the optimal n for a given contract $\{T, G\}$, and note that we are back to the continuous setting. The agent's utility for a given contract is:

$$\alpha n + \int_0^{T-n} G dF(\Delta).$$

The agent's expected utility is the sum of shirking benefit αn and the expected reward from completion $G \cdot F(T-n)$. To ensure the existence of the maximum and simplify analysis, we assume $F''(\Delta) < 0$, which can be supported by an exponential density function e^{-n}, as most assumed in the R&D literature. The agent maximises his expected utility with respect to n, that is,

$$\max_{n}\{\alpha n + G \cdot F(T-n)\} \tag{3.24}$$

$$\text{St. } n \geq 0 .$$

Denote n^* as the optimal value of n, and the FOC is:

$$\alpha - G \cdot f(T - n^*) = 0 ,$$

or equivalently,

$$n^* = T - f^{-1}(\frac{\alpha}{G}). \tag{3.25}$$

The existence of n^* is defined, since $\frac{\alpha}{G} > 0$ and f is continuous. Two implications can be drawn: firstly, n^* is positively related to T with derivative 1, which means that when the agent is also uncertain about the time needed to complete the project, a longer funding period will only induce more shirking. Secondly, as we assume $F''(\Delta) < 0$, it is clear that n^* is negatively related to G, implying that a higher reward can motivate the agent to put in more effort. For notational simplification, denote $f^{-1}(\dfrac{\alpha}{G})$ as $\tau(\alpha, G)$. Together with the concavity assumption, we know that $\tau(\alpha, G)$ is increasing in α and decreasing in G.

Next, the principal's expected utility for a given $\{T, G\}$ is:

$$\int_0^{T-n^*} (V - G) dF(\Delta) - [n^* + \int_0^{T-n^*} \Delta dF(\Delta) + (1 - \int_0^{T-n^*} dF(\Delta))(T - n^*)].$$

As there is no discounting, the principal will have to waste n^* before the agent actually puts in effort (the second term). For the third term, note that since the agent will put in effort from n^* until T, the expected cost for this part will be $\int_0^{T-n^*}\Delta\, dF(\Delta)$, where the funding stops once the project is completed. Simultaneously, the principal can obtain the project value V deducted by the reward G (the first term). Finally, if the project is never finished within T, the probability of which is $(1-\int_0^{T-n^*}dF(\Delta))$, then the principal has to waste the funding $T-n^*$ in the end. To make the following analysis reasonable, we restrict to the case when V is sufficiently big so that the principal's expected utility will be positive for any optimal values of T and G.

The principal's problem is to maximise her expected utility with respect to the contract $\{T,G\}$:

$$\max_{T,G}\int_0^{T-n^*}(V-G)dF(\Delta)-[n^*+\int_0^{T-n^*}\Delta dF(\Delta)+(1-\int_0^{T-n^*}dF(\Delta))(T-n^*)] \quad (3.26)$$

$$\text{St} \quad n^*\geq 0.$$

The constraint comes from the requirement that any funding period inducing a negative n^* will be infeasible. To solve the problem, firstly, since funding is costly to the principal, without violating the feasibility constraint, T should be set at the lowest possible value $T^*=\tau(\alpha,G)$, implying that in equilibrium the principal will fund the project just long enough to avoid any shirking. Secondly, since when $G\rightarrow 0$ the expected utility approaches 0, the optimal G must be bigger than zero[78]. G^*[79] is given by:

[78] Recall that V is sufficiently big for a positive expected utility in the solution.
[79] The existence of G* is justified by the differentiability assumption of F(.).

$$G^* = \arg\max_{G}\left\{(V-G)F(\tau(\alpha,G)) - [\int_0^{\tau(\alpha,G)} \Delta dF(\Delta) + (1-F(\tau(\alpha,G))\cdot\tau(\alpha,G)]\right\}. \qquad (3.26)'$$

To sum up, when the agent's effort is unobservable, the optimal contract $\{T^*, G^*\}$ describes a funding period which induces no shirking, and a positive reward for completion. A useful exercise is to compare this contract to the contract with observable (contractible) effort. If the effort is observable, the agent will not shirk. Hence G has no incentive effect for the agent. As G is costly to the principal, the optimal G for this case is therefore zero. To decide the contract length, the principal has to maximise her expected utility which is:

$$\max_{T}\left\{\int_0^T VdF(\Delta) - [\int_0^T \Delta dF(\Delta) + (1-\int_0^T dF(\Delta))T]\right\}.$$

The expected utility consists of the expected project value and the expected funding cost. Since the agent will put in full effort, the expected project value will be $\int_0^T VdF(\Delta)$. The funding stops once the project is completed, and hence the expected cost will be $\int_0^T \Delta dF(\Delta)$. However, if the project is not finished within the funding period, the principal will waste the funding T, the probability of which is $(1-\int_0^T dF(\Delta))$.

Proposition 3.6 shows that the funding period with unobservable effort is no longer than the contract with observable effort.

Proposition 3.6

When neither the principal nor the agent has private information about the finishing time, the principal funds the project for a period no longer than the contract without a moral hazard problem.

Proof: Let T, $\hat{T} < \infty$ denote the optimal funding periods for the principal's maximisation problems with observable and unobservable effort respectively, that is,

$$T = \arg\max_{T}\{VF(T) - [\int_0^T \Delta dF(\Delta) + (1 - F(T))T]\},$$

and

$$\hat{T} = \tau(\alpha, G^*) = \arg\max_{T}\{(V - G^*)F(T) - [\int_0^T \Delta dF(\Delta) + (1 - F(T))T]\},$$

where G^* is the optimal reward defined in (3.26)' and $\hat{T}$ is the optimal funding period such that $n^*=0$. Recall from equation (3.26) that shirking is costly, hence it is optimal to set $T = \tau(\alpha, G)$ which induces $n^*=0$. As G* is the optimal reward, *ceteris paribus*, $\hat{T} = \tau(\alpha, G^*)$ will be the optimal setting of T that maximises the principal's expected utility. The proposition says that $T \geq \hat{T}$, which is to be proved by contradiction. Suppose $T < \hat{T}$. Then by definition of maximisation:

$$VF(T) - [\int_0^T \Delta dF(\Delta) + (1 - F(T))T] \geq VF(\hat{T}) - [\int_0^{\hat{T}} \Delta dF(\Delta) + (1 - F(\hat{T}))\hat{T}], \tag{3.27}$$

and

$$(V - G^*)F(\hat{T}) - [\int_0^{\hat{T}} \Delta dF(\Delta) + (1 - F(\hat{T}))\hat{T}] \geq (V - G^*)F(T) - [\int_0^{T} \Delta dF(\Delta) + (1 - F(T))T], \tag{3.28}$$

Equations (3.27) and (3.28) mean that,

$$V(F(T) - F(\hat{T})) - \{-\int_T^{\hat{T}} \Delta dF(\Delta) + [(1 - F(T))T - (1 - F(\hat{T}))\hat{T}]\} \geq 0, \tag{3.27'}$$

$$(V - G^*)(F(\hat{T}) - F(T)) - \{\int_T^{\hat{T}} \Delta dF(\Delta) + [(1 - F(\hat{T}))\hat{T} - (1 - F(T))T]\} \geq 0. \tag{3.28'}$$

Let $\quad X := (F(\hat{T}) - F(T)) > 0,$

$$Y := -\int_{\hat{T}}^{T} \Delta dF(\Delta) + [(1-F(T))T - (1-F(\hat{T}))\hat{T}].$$

Hence equations (3.27)' and (3.28)' mean that

$$-VX - Y \geq 0 \quad \Rightarrow -VX \geq Y,$$

$$(V - G^*)X + Y \geq 0 \quad \Rightarrow -(V - G^*)X \leq Y,$$

which is a contradiction. Thus it must be $T \geq \hat{T}$. Q.E.D.

Intuitively, due to the unobservability of effort, the agent can possibly shirk without being detected. As putting in effort will not necessarily result in the success of R&D, for a given reward, the agent has to trade off the expected reward from innovation and the shirking benefit. Accordingly, for any given funding period, the agent will only work up to a certain period which is positively related to the size of reward. Anticipating the agent's shirking, the principal would like to set a funding length such that the agent's shirking period will be driven down to zero. Therefore, the presence of opportunism leads to a decrease in funding.

3.6.2 The Renewal of the Contract

3.6.2.1 When the Agent Can Not Anticipate the Renewal

We address this problem by assuming that the contract is not in a form of "*redetermiable fixed price contract*"[80], hence we need not worry about the renewing problem within the

[80] Scherer (1964, p137) defines the *redetermiable fixed price contract* as "At the outset, ... the buyer and the seller negotiate a tentative base price and a firm ceiling price ... Then, after the contractor has accumulated some experience in performing the contract (typically after 30% to 40% of expected costs has been increased, but sometimes also at the 100% point), the parties negotiate a final firm fixed price, adjusting the original base price to reflect any changes in their cost expectation".

funding period. The principal faces the contract renewal problem at the end of the funding period if the project has not been completed any time before. Provisionally, it is assumed that both parties do not anticipate this renewal from the outset, which is indeed a strong assumption and will be relaxed later. However with this assumption, we can imagine that there is a sequence of principals and agents, and each match of them is allowed only one attempt at finishing the project. Whenever the agent cannot finish the project within the funding period, the project will be delegated to another match of principal and agent[81]. The issues to be addressed are: How will both parties react in each renewed contract? and Will the principal necessarily renew the contract? In other words, will there be a lock-in effect?

First of all, to understand both parties' behaviour, we need to check the posterior belief after the k^{th}, $k = 0,1,2...$, round of renewal (if it exists). Denote T_k as the optimal funding period in each renewed contract. In equilibrium, both players know that the principal will set a funding period which induces no shirking. In other words, in each renewed contract, the funding period can induce the full effort of T_k. Define $T(k) = \sum_{i=0}^{k} T_i$, which is the accumulated effort that has been put into the project within the past k contracts. At the end of time $T(k)$ and provided the project is not finished, the posterior belief of Δ will be:

$$f(j|T(k)) = \frac{f(j)}{1 - F(T(k))}, \qquad j \in (T(k), \infty). \tag{3.29}$$

[81] It is assumed that the transferability of information to the next match of principal and agent is possible and free of charge (i.e., there is no intellectual property right problem).

Given the distribution function, clearly $f(j|T(k)) > f(j)$ for $j \in (T(k), \infty)$. For the $k+1^{th}$ renewal, the new match of principal and agent face a similar maximisation problem as in the previous section, except that the belief function is now replaced by a posterior defined in equation (3.29). Instead of replicating the maximising process, we look at the FOC of the agent's maximisation problem directly. Given $T(k)$, let $\hat{n}$ be the optimal shirking period such that

$$f(T - \hat{n} + T(k)|T(k)) = \frac{\alpha}{G}. \tag{3.30}$$

The accumulated effort $T(k)$ has two effects[82] on the agent's shirking decision. Equation (3.29) says that the posterior assigns higher probabilities to time after $T(k)$ than the original function. However, since $F''(\Delta) < 0$, the optimal n should be lower as it is $T - n + T(k)$ rather than $T - n$ in the argument of $f(\cdot|T(k))$. These two effects make it difficult to measure the total impact of contract renewal on the agent's willingness to work. However, rewrite equation (3.29):

$$f(\Delta + T(k)|T(k)) = \frac{f(\Delta + T(k))}{1 - F(T(k))},$$

and take the partial differentiation of this function with respect to $T(k)$:

$$\frac{\partial f(\Delta + T(k)|T(k))}{\partial T(k)} = \frac{f'(\Delta + T(k))(1 - F(T(k))) + f(\Delta + T(k))f(T(k))}{(1 - F(T(k))^2}, \tag{3.31}$$

whose sign depends on whether

[82] With an exponential function, due to the "memoryless" property, both effects will be cancelled out and hence the updated belief is the same as the original one.

$$f'(\Delta + T(k))(1 - F(T(k))) + f(\Delta + T(k))f(T(k)) \geq 0,$$

or equivalently,

$$\frac{-f'(\Delta + T(k))}{f(\Delta + T(k))} \leq \frac{f(T(k))}{(1 - F(T(k)))}.$$

In words, the agent may or may not increase his willingness to work depending on the relative sizes of marginal probability rate and the hazard rate. Moreover, the sign of the second order differentiation of $f(\Delta + T(k)|T(k))$ with respect to $T(k)$ is also ambiguous. However, it can be checked that when $T(k) \to \infty$, by twice using L'Hospital's rule, the sign of equation (3.31) is positive[83]. The extreme case says that the agent will increase the willingness to work as the project approaches its later stages.

An interesting question is " Will $k \to \infty$?", that is, Will the principal keep on renewing the project if it is not finished any time before? or Will there be a *lock-in effect* in funding the project? The answer is yes provided $\dfrac{\partial f(\Delta + T(k)|T(k))}{\partial T(k)} > 0$[84]. To see why, let us look at the principal's expected utility when it comes to the $k+1^{th}$ renewal. Recall that in each renewal, it is assumed that the project will be delegated to a new match of principal and agent. The problem is similar to equation (3.26), with the difference being that the probability function is replaced by a posterior belief:

$$\begin{aligned}\max_{T_i, G}\{&\int_0^{T_i-\hat{n}} (V - G)dF(\Delta + T(k)|T(k)) \\ &-[\hat{n} + \int_0^{T_i-\hat{n}} \Delta dF(\Delta + T(k)|T(k)) + (1 - (\int_0^{T_i-\hat{n}} dF(\Delta + T(k)|T(k)))(T_i - \hat{n})]\},\end{aligned}$$

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[83] This is true under the additional assumptions that $F''' < 0$ and F'''' close to zero.
[84] This condition will be violated by the exponential distribution.

St $\quad \hat{n} \geq 0$,

or

$$\max_{T_t, G} \int_0^{T_t - \hat{n}} \{[V - G + (T_t - \hat{n}) - \Delta]\} dF(\Delta + T(k) | T(k)) - T_t \tag{3.32}$$

St $\hat{n} \geq 0$.

By applying the envelope theorem, equation (3.32) shows that the principal will have a higher expected utility if $\frac{\partial f(\Delta + T(k) | T(k))}{\partial T(k)} > 0$. Therefore, we can conclude that the lock-in effect exists in this model when it comes to later stages of production. The intuition for this lock-in behaviour is because previous funding has become ***sunk cost,*** which has no influence to the contract renewal. Therefore as the probability of completing the project becomes higher, the principal will find it more valuable to fund the project.

Now, let us look at the choice between long-term and short-term contracts. Refer to the contract decided by equation (3.26) as the long-term contract, and the contract that lasts for only one unit of time as the short-term contract. As there is no clear definition about the short-term contract length, to simplify, I assume this "one unit of time" to be one in natural numbers, but other splits of time will not change the analysis. Recall that for the moment renewal is possible and both parties cannot anticipate this renewal. We need to compare the principals' total expected utilities from a long-term contract and from a sequence of short-term contracts which are renewed up to the end of funding period in the long-term contract. Proposition 3.7 shows that from the principal's point of view, a sequence of short-term contracts is better than a single long-term contract.

Proposition 3.7

With symmetric beliefs and the possibility of contract renewal, if both parties do not anticipate the renewal, a sequence of short-term contracts is better than a long-term contract from the principal's point of view.

First of all, recall $T = \tau(\alpha, G^*)$ as the optimal funding period determined by equation (3.26). $\tau(\alpha, G^*)$ can be either < 1 or ≥ 1. If $\tau(\alpha, G^*) < 1$, then our argument is not relevant. If $\tau(\alpha, G^*) = 1$, the long-term and short-term contracts coincide. For $\tau(\alpha, G^*) > 1$, note that the optimal funding period is dependent on the optimal G^* which maximises the principal's expected utility, and is defined in equation (3.26)':

$$G^* = \arg\max_G \left\{ (V - G)F(\tau(\alpha, G)) - [\int_0^{\tau(\alpha,G)} \Delta dF(\Delta) + (1 - F(\tau(\alpha, G)) \cdot \tau(\alpha, G)] \right\}.$$

Moreover, let $\hat{G}_0$ be the reward such that $\tau(\alpha, \hat{G}_0) = 1$. For $\tau(\alpha, G^*) > \tau(\alpha, \hat{G}_0) = 1$, it must be that $\hat{G} < G^*$. From equation (3.32) we know that after i rounds of renewal, the principal will set a funding period T_i which induces no shirking, that is, $T_i = f^{-1}(\frac{\alpha}{G} | \ i)$, where $f(\cdot|i)$ is defined in (3.29). As we are concentrating on short-term contracts with duration 1, we need to define the reward such that 1 will be the optimal duration, that is,

$$\hat{G}_i = \left\{ G_i \left| \ \frac{\alpha}{G_i} = f(1|i) \right. \right\}, \quad i = 1,2,\ldots.$$

As $f(\cdot|i) > f(\cdot)$, $\hat{G}_i > \hat{G}_{i+1}$. Further define $|T|$ as the greatest integer for T, and let $\Delta\tau = T - |T|$. At the very beginning of the project, each value of Δ is conceived to happen with density $f(\Delta)$, and therefore the principal's total expected utility from a sequence of short-term contracts renewed up to time $\tau(\alpha, G^*)$ is:

$$\int_0^1 [(V-\hat{G}_0)-\Delta]dF(\Delta)+\int_1^2 [(V-\hat{G}_1)-\Delta]dF(\Delta)+\ldots+\int_{|\tau(\alpha,G^*)|-1}^{|\tau(\alpha,G^*)|} [(V-\hat{G}_{|\tau(\alpha,G^*)|-1})-\Delta]dF(\Delta)$$

$$+\int_{|\tau(\alpha,G^*)|}^{|\tau(\alpha,G^*)|+\Delta\tau} [(V-\hat{G}_{|\tau(\alpha,G)|})-\Delta]dF(\Delta)-[1-\sum_{i=0}^{|\tau(\alpha,G^*)|-1}\int_i^{i+1} dF(\Delta)-\int_{|\tau(\alpha,G^*)|}^{|\tau(\alpha,G^*)|+\Delta\tau} dF(\Delta)]\tau(\alpha,G^*),$$

which is equivalent to

$$\sum_{i=0}^{|\tau(\alpha,G^*)|-1}\int_i^{i+1}(V-\hat{G}_i)dF(\Delta)+\int_{|\tau(\alpha,G^*)|}^{|\tau(\alpha,G^*)|+\Delta\tau}(V-\hat{G}_{|\tau(\alpha,G)|})dF(\Delta)-\{\sum_{i=0}^{|\tau(\alpha,G^*)|-1}\int_i^{i+1}\Delta dF(\Delta)$$
$$+\int_{|\tau(\alpha,G^*)|}^{|\tau(\alpha,G^*)|+\Delta\tau}\Delta dF(\Delta)+[1-\sum_{i=0}^{|\tau(\alpha,G^*)|-1}\int_i^{i+1}dF(\Delta)-\int_{|\tau(\alpha,G^*)|}^{|\tau(\alpha,G^*)|+\Delta\tau}dF(\Delta)]\tau(\alpha,G^*)\}. \tag{3.33}$$

Since $\hat{G}_0$ is smaller than G* as shown above and $\hat{G}_i > \hat{G}_{i+1}$, by comparing equations (3.26)' and (3.33), we can conclude that the principals' total utility will be higher from a sequence of short-term contracts. The intuition for this result is: short-term contracts provide both involved parties opportunities to update their beliefs about the time needed to complete the project. Hence the principals in the later contracts can pay less compensation to induce the same level of effort from the agents. On the other hand, we can infer that the traditional R&D contract $\{T,G\}$ may not be an optimal contract form for this case.

3.6.2.2 When the Agent Can Anticipate the Renewal

When the agent can anticipate the renewal, no transaction will ever happen[85]. The intuition can be seen from the combination of the lock-in effect and the agent's optimal behaviour described in Lemma 3.3. The lock-in effect says that the principal will keep on renewing the contract if the project has not been finished. Anticipating this, the agent will

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[85] In other words, the commitment to the contract fail to fulfil the intuition criterion.

expect a total funding period that lasts for ∞ period provided that project is not finished. The maximising behaviour in Lemma 3.3 then suggests that the agent will only put in effort at the very end of period ∞. In the first round of contract (equation (3.26)), the principal will expect a working period $T - n^* = 0$. Hence, the principal will not fund the project in the first place and no transaction will ever happen. In this case, there is no difference between long-term and short-term contracts.

3.7. Conclusion and Further Research

Despite the fact that R&D expenditures have been increasing year by year, there is little theoretical literature specifically addressing the issues on R&D funding. Our model establishes a guideline for funding long-term contracts when confronted with moral hazard problems. As a benchmark of comparison, we first derive the optimal contract for a long-term project with only a moral hazard problem. The optimal contract form happens to be a multi-stage version of cost-plus-fixed-fee contracts, where the optimal fixed fee refers to the agent's shirking benefit from the contract. After considering the agent's private information, we derive the screening contracts for both discrete and continuous type settings. The screening contracts assign no efficiency loss to either type, which is in contrast to the usual conclusion in the literature. Moreover, within the continuous setting, we show that the principal will adopt a cut-off strategy in funding, and the cut-off point is affected by the fact that inefficient types (types greater than the cut-off point) will take the contract and shirk all through the funding period. Hence, the principal will fund the project for a shorter period in the presence of an opportunism problem. Furthermore, the discussion of the optimal auctioning contract shows that the principal will benefit from the competition among agents in two ways: First, the project is more likely to be completed by an efficient type under an auction. Second, competition reduces the incentive rent for the efficient type as he is less likely to mimic the inefficient type who might have less chance to win the auction, however, this rent reduction will vary with the difference between the two types. Comparing the optimal auction with a second-price auction, we show that bidding the principal's reservation price (rather than truth-bidding) will be the bidders' dominant strategies, and neither the revenue equivalence theorem nor the separation property will hold. Finally, when neither of the players has private information about the time needed for completion, we show that a longer funding period will actually induce more shirking, and the optimal funding length is determined as the point where the agent's shirking period is driven down to zero. With an additional assumption that neither of the involved parties can anticipate the contract renewal, we show that the lock-in effect persists under some constraints and a sequence of short-term contracts is preferable to a long-term contract.

The basic model can be extended in several ways. Firstly, in the stochastic setting, we can also discuss when the agent has private information about the distribution of completion time. The analysis will be similar to the deterministic setting but all in terms of expected values. Secondly, further research can consider the case of private information for both involved parties and discuss the optimal contract for this case. Thirdly, following the existing auction literature, we can further analyse the effects of risk aversion, correlated types and (when there is an auction) collusion among bidders. Finally, we can explore the cost-overruns issue in more detail.

4. Incentive and Optimal Protection Scheme For A Time-Consuming Investment

4.1 Introduction

Despite the recent liberalisation waves in international trade and service industries, we cannot deny that protection still has its popularity all around the world. In international trade, "since the launching of the Uruguay Round in 1986, over 60 developing nations have unilaterally lowered their barriers to imports" (Safadi and Laird (1996)), however the infant industry argument is still heavily applied in the hope that "with appropriate trade policies, the domestic government can alter the nature of market competition by raising the marginal cost of the foreign firm (via a tariff) or lowering the marginal cost of the domestic firm (via an export subsidy), shifting more of the rents towards the domestic producers" (Krugman and Smith (1994)). Likewise, in developed countries, protection is often requested by the injured industries to let them "*buy time*" to catch up (Miyagiwa and Ohno (1995)). The form of protection has changed from tariffs to non-tariff barriers (NTBs), which include quotas, voluntary export restraint agreements, various domestic price support schemes and other administrative measures. For example, as reported by Harrigan (1993), Japan has an overall weighted average NTB coverage of almost 40%

against ten major trading partners, with France a distant second with an index of almost 27%.

Protection is also an important issue in industrial economics, for example, *patent protection* plays a significant role in solving the un-appropriability problem in R&D activities, especially in highly imitating industries. Recently, intellectual property right protection has become a new issue in GATT negotiations, which "develop rules designed to extend the protection of intellectual property rights to all participating countries" (Safadi and Laird (1996)). Another example is in the area of environmental protection: before the authority launches a severe anti-pollution law, a *preparation allowance period* is usually granted for the affected firms to install anti-pollution equipment.

A common feature of the various examples is that protection is granted on the grounds that the protected firms can undertake a welfare-improving investment in order to adopt new equipment for international competition, to update machinery, to install anti-pollution equipment, or to invest in creating a new product or production process. The difference is that the preparation allowance period and infant or injured industry protection put emphasis on protection *during the investment*, but patents are usually granted *after the success of the investment*.

The literature of trade protection has focused on two issues: (1) the justification for protection (reasons for market failure), for example, the existence of externalities (e.g., Corden (1974)), informational barriers to entry (e.g., Grossman and Horn (1988)), and imperfect capital market (see Baldwin (1969) for critics); (2) the policy instruments to carry out the protection. The instruments include both price interventions (tariff, import tax or export subsidy) and quantity interventions (quota or voluntary export restraint) (Vouseen (1990)). Our model addresses another important but often ignored dimension, that is, "How long should the protection last?" For this timing problem, most protection literature concentrates on comparing the welfare effects from temporary protection and permanent protection. For example, Miyagiwa and Ohno (1995) discuss whether temporary or permanent protection can speed up the protected firm in adopting a new technology. There is little discussion in the literature on how to determine exactly the optimal protection length[86]. As concluded by Head (1994) in his study of the steel rail industry protection, "it seems that from an aggregate welfare perspective, the form of intervention matters less than *duration*". The protection length is a critical factor for the success of protection and hence deserves more attention.

The patent length, on the contrary, has always been a main subject in its association with innovation efficiency. References can be found in Gilbert and Shapiro (1990), Klemperer (1990), Gallini (1992) and Cornelli and Schankerman (1995). Our model is related to Cornelli and Schankerman in making conclusions concerning patent policy in the context of incomplete information. In a different framework, they conclude: "to ensure that the optimal patent schedule is incentive compatible, the government must increase the patent life span" with firms' innovation efficiency. Our results show that this is not always true when we take into account firms' profits after the investment.

This paper uses a principal and agent model to discuss how, under various cost and revenue circumstances, a benevolent government should design the protection scheme so that the target firm with a moral hazard problem will undertake a time-consuming and welfare improving investment. Of course, the optimal scheme may involve not protecting at all. "Protection" is a general term for government interventions and can take the form

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[86] Matsuyama (1990) uses an infinite horizon and perfect information timing game to model the threat of liberalisation as the incentive for the protected firm to invest, and concludes that only immediate liberalisation and successful fixed period protection are pure strategy Nash outcomes.

of, for example, an export or import tax and subsidy, a voluntary export restraint, or a patent. In other words, this is a general protection model[87], which covers a rich class of both *during-investment protection* and *post-investment protection*. The assumption of a "time-consuming" rather than "one-shot" investment is to cope with the fact that most investments take time, and to avoid making counter-intuitive policy implication from the one-shot investment setting. For example, as written in a note of Miyagiwa and Ohno (1995): "the government can do better by imposing the permanent protection just before the date at which the protected firm would adopt new technology". They apply Fudenberg and Tirole's (1985) model to analyse the policy effect on the timing of technology adoption. As production cost is assumed to decrease over time, the firm has to trade off between early and late adoption. The optimal adoption date is determined as the moment when the marginal value of adoption is equal to the marginal cost of adoption. Government policy will affect a firm's marginal value of adoption. Hence in the case of a quota, a permanent quota will increase the value of adoption and thus speed up the adoption, but at the same time it will create a negative welfare effect. Since their model has imposed the quota from the beginning of time, it is suggested that the government will be better off delaying the quota till the date just before the firm would adopt the technology (to reduce the welfare loss).

The basic model of this chapter firstly analyses the case with only a moral hazard problem. Since the investment outcome will also affect the target firm's future profits, the incentive scheme has to consider different cost and revenue environments in order to give the target firm the right motivation. Various cases are classified according to the target firm's investment ability and investment willingness. The investment ability refers to

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[87] On the other hand, since we concentrate on the welfare effect of a single market, our model is a partial equilibrium model.

whether the target firm can afford the investment cost under its current profit, and the investment willingness refers to the target firm's future expected profits after the completion of the investment. Hence depending on parameters, the optimal protection could involve no protection, *one-part protection* or *two-part protection*. One-part protection refers to using only during- or post-investment protection, and two-part protection involves both during- and post-investment protection. This result gives a significant policy implication, that is, as empirical evidence shows different conclusions about protection effects, some of which are positive (e.g., Baldwin and Krugman (1988)) and some are negative (e.g., Krueger and Tuncer (1982), Luzio and Greenstein (1995)), our result suggests that using a correct protection form will be critical for the success of investment and not all cases fit in the same protection form.

Furthermore, we conclude that whether the during-investment protection rate is increasing, decreasing or constant will not affect the investment efficiency, which is in contrast to the prevalent argument that decreasing protection rates can mitigate protected firms' pain when adjusting towards liberalisation. Finally, after considering the target firm's private information about the time needed to complete the investment, our results show that: (1) The screening protection scheme could possibly coincide with the efficient scheme when only the inefficient type is lacking in investment willingness, or when there are only liquidity problems; (2) The screening scheme is strictly better than the pooled scheme of the efficient type; however, whether it is better than the pooled scheme of the inefficient type is dependent on parameter values; (3) Whenever there is a liquidity problem, the efficient type's post-investment protection will be no shorter than that of the inefficient type; otherwise, the reverse result applies. In terms of patents, this means that a more efficient firm does not necessarily need a longer patent life span to keep incentive compatibility. The intuition is: when the target firm's future profits are also connected to the success of the investment, the incentive rent (patent life) will vary with the cost and revenue environments.

The rest of Chapter 4 is organised as follows. Section 4.2 first derives the optimal protection form from a general protection scheme, including a deadline and a sequence of protection rates. Next by assuming only a moral hazard problem, we discuss the optimal protection schemes under various cost and revenue conditions. Section 4.3 derives the screening protection schemes in the context of incomplete information, and we make the comparison between the screening scheme and pooled schemes to find a better protection contract. Section 4.4 contains conclusions and suggestions for further research. Appendices 4.1 and 4.2 contain the proof for Lemma 4.2 and the welfare comparison among various protection schemes.

4.2 The Model[88]

Consider the case where a monopoly (domestic) firm[89] is facing a time-consuming investment, for example, this investment could be to equip the basic technology (experience) in the case of an infant industry, or to update machinery to catch up rival firms in the case of an injured industry, or to help retraining employees to change their jobs in the case of a sunset industry, or to install anti-pollution equipment before the launch of an environmental law, or to research and develop a new product for the firm

[88] The major difference between this model and Chapter 3 is that the investment outcome will affect the target firm's future profits, but the success of the project in Ch 3 belongs to only the principal. The discounting is also new in this model.
[89] This is a single principal and single agent framework. The cases with multiple agents or principals will not be discussed.

itself[90]. Indeed, these kinds of investments usually cannot be completed at once. Suppose further that this investment is welfare improving to the whole society. The main purpose of this paper is to answer the following questions in both complete and incomplete information contexts: "Under what circumstances should a benevolent government provide protection to the target firm? How should the government design the protection scheme to achieve efficient investment?" The important issue is not how to implement the protection but how long and how much the protection should be. Finally, this is not a general equilibrium framework, as the protection effect is restricted to a single market.

The following cost and revenue structures are common knowledge. Firstly, let δ be the discount factor, where $0 < \delta < 1$ (i.e., we are using a discrete time setting). To use notation consistent with the previous chapter, let Δ be the investment time needed for completion[91] under the target firm's *full capacity* (i.e., no shirking). The value of Δ is related to the target firm's investment efficiency. For the basic model, Δ is now assumed to be common knowledge both parties, so that we can concentrate on the moral hazard problem first. The incomplete information case will be discussed in the next section.

To undertake the investment, it is assumed that whenever the target firm puts in effort, it will incur an opportunity cost of £k per period. The opportunity cost includes the direct investment cost and the indirect capital loss. For each t, the target firm's profit and consumer surplus before and after the success of investment are denoted as:

$\pi(L)$:firm's current profit[92],

[90] Emphasising "for itself" is to distinguish from Chapter 3 where the benefit of project only goes to the principal.
[91] The deterministic setting is assumed throughout this chapter, as except for the R&D investment, the protected firms usually have better information about the investment time. For the R&D case, the literature for the deterministic setting can be traced to, for example, Katz and Shapiro (1985).
[92] The target firm's reservation profits are not normalised to zero, as it is easier to stress the problem with the agent's investment ability.

S(L): current consumer surplus,

$\pi(H)$:firm's profit after the completion of the investment,

S(H) :consumer surplus after the completion of the investment.

Finally, it is assumed that the target firm has *limited credit*, which is bounded above by its current profit $\pi(L)$. This limit can be interpreted as a consequence of an imperfect capital market or the requirement of down payment or collateral on loans. This assumption is crucial, as when the credit is limitless, it will not be necessary to impose any government intervention, which would cause welfare distortion due to public funding.

For a welfare-improving investment, we need as a necessary condition Assumption 4.1:

Assumption 4.1. $[\pi(L) + S(L)] < [\pi(H) + S(H)]$[93].

Assumption 4.1 gives the government an environment to consider protection. The derivation of the optimal protection scheme starts with the government offering a protection scheme to the target firm, and the target firm reacts by rejecting or accepting the offer. In other words, the government is acting as a first mover and the target firm is a follower. It is assumed that the government can commit to not change the scheme in the future[94]. If the target firm accepts the offer of scheme, it needs to make a sequence of effort decisions; if it rejects the offer, then it will stay in autarky which, depending on the environment, could be investing or not investing. We further assume that the target firm's

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[93] There is no specification to the source of welfare improvement (which could come from producer or consumer).

[94] The time inconsistency problem will be discussed briefly in the conclusion.

effort is unobservable or *cannot be monitored* by the government, or equivalently, monitoring could be too costly to execute. The unobservability in the R&D area seems justifiable. In the "employees retraining" case, for example, it is difficult to know how much the employees actually learn from a training course. However, we assume the outcome of the effort to be perfectly[95] observed, for example, the innovation of R&D activities will be publicly known.

Now, consider a general protection scheme which consists of a deadline and a sequence of incremental compensation. Since the target firm's effort is not observable, the government can only relate the compensation scheme to the observable variable: the completion date. In the following, we first discuss a general compensation scheme without imposing a specific deadline, and turn back to the deadline issue later. Assume an arbitrary completion date τ, where the target firm commits to finish the investment at the contracting date, and a sequence of contingent compensations of the following form[96]:

$$\{r_1(\tau), r_2(\tau), \ldots, r_\tau(\tau), r_{\tau+1}(\tau), \ldots\}_{\tau=1}^{\infty}, \tag{4.1}$$

where $1,2,\ldots\infty$ is the time index starting from the moment the target firm accepts the offer. $r_t(\tau)$ is the incremental profit added to the target firm's profit at time t[97]. Note that this setting does not exclude the possibility of a non-contingent scheme, that is, $r_t(\tau) = r_t(\tau')$ for $\tau \neq \tau'$.

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[95] In other words, we exclude the case with "imperfect" observation of the outcome.
[96] It will be shown later that the government will not give the target firm a lump sum transfer at $t = 1$ and nothing afterwards. The reason is because an excess protection during the investment has no effect in encouraging effort, and the maximal protection rate is bounded above by, say, a budget limit.
[97] That is, the protection will give the target firm an extra benefit in addition to its current profits.

Like most protection cases, we assume the government cannot punish the target firm if it does not finish the investment within the protection period. Hence, we have the first constraint on the general scheme:

Constraint 4.1. $\pi(L) \leq \pi(L) + r_t(\tau) \leq \bar{\pi}$.

Constraint 4.1 says that negative protection (punishment) is not allowed, and the maximal protection is bounded above by $\bar{\pi}$. $\bar{\pi}$ can be interpreted as the government's budget limit or the target firm's monopoly profit (without competition from foreign rivals or new entrants).

Given the agent accepts the scheme, the effort decision at each time t is defined as follows. Let $e_t = 1$ denote the case where the target firm puts in effort and $e_t = 0$ for shirking. Define n_t as the accumulated investment (effort) at the beginning of time t, that is, $n_t = \sum_{i}^{t-1} e_i$. Denote $V_t(n_t)$ as the target firm's value at time t as a function of the accumulated investment, i.e.,

$$V_t(n_t) = \max\{\pi(L) + r_t(\tau) + \delta V_{t+1}(n_t),\ \pi(L) + r_t(\tau) - k + \delta V_{t+1}(n_t + 1)\}. \tag{4.2}$$

Equation (4.2) says that in each period, the protected firm trades off the values from shirking and putting in effort. Shirking gives the target firm a profit $\pi(L) + r_t(\tau)$ and a future value with accumulated investment remaining at n_t. However, putting in effort gives it the same current profit $\pi(L) + r_t(\tau)$, an opportunity cost k and a next period value with accumulated effort $n_t + 1$. The completion date is defined as the earliest date that the accumulated effort level exceeds Δ, i.e.,

$$\tau(e)=\min\left\{s\left|\sum_{i=1}^{s}e_i\geq\Delta\right.\right\}\quad,\ \text{where } e=(e_1,e_2,\ldots,e_s,\ldots)\text{ and }\tau(e)\text{ could be }\infty.$$

For simplification, denote $\tau=\tau(e)$.

It is interesting to ask whether $r_t(\tau)$ should vary or be kept constant in the protection scheme (4.1). Since $r_\tau(\tau)$ appears on both sides of the effort decision, we know that whether the protection rate is increasing, decreasing or constant does not make any difference to the target firm's choice between shirking and putting in effort in each period. Hence there is no loss to restrict them to be constant before the finishing date, i.e., $r_1(\tau)=r_2(\tau)=\ldots=r_\tau(\tau)=r(\tau)$. The compensation pattern after τ is not yet known, as no effort will be needed after the completion. Therefore we can rewrite the protection scheme in equation (4.1) as:

$$\{r(\tau),r(\tau),r(\tau),\ldots,r(\tau),r_{\tau+1}(\tau),r_{\tau+2}(\tau)\ldots\}_{\tau=1}^{\infty}. \tag{4.3}$$

Now consider an arbitrary deadline T, where $1\leq T\leq\infty$. The deadline does not necessarily mean the moment to terminate the protection, as the post-investment compensation is not restricted to zero. T is interpreted as a committed inspection date, after which the compensation will depend on whether the investment has been finished on that date[98].

As a leader (government) needs to take into account followers' (firm) reaction to make her decision, we have to discuss the target firm's effort decisions first and then determine the optimal protection form. First of all, we can classify several cases

[98] It means "at the end of time T".

according to the target firm's investment ability and willingness. When $k > \pi(L)$, the target firm is constrained by credit limit, and hence will not put in effort without protection. When $k \le \pi(L)$ but $k > k^*$, where k^* is defined as satisfying

$$\sum_{i=1}^{\Delta} \delta^{i-1}\pi(L) - \sum_{i=1}^{\Delta} \delta^{i-1} k^* + \sum_{i=\Delta+1}^{\infty} \delta^{i-1}\pi(H) = \sum_{i=1}^{\infty} \delta^{i-1}\pi(L),$$

or equivalently,

$$k^* = \frac{\sum_{i=\Delta+1}^{\infty} \delta^{i-1}[\pi(H) - \pi(L)]}{\sum_{i=1}^{\Delta} \delta^{i-1}}, \tag{4.4}$$

then although the target firm's current profit can cover the investment cost in each period, the cost is so high that the future benefit from the investment cannot cover the overall opportunity cost. As k^* is the critical value where the target firm is indifferent between investing and not investing, when $k \le \min\{\pi(L), k^*\}$, the target firm will invest in its own interest and hence there is no need to provide protection under complete information[99]. We can ignore this case in what follows (as the solution is trivial). When $k > \min\{\pi(L), k^*\}$, the targeted firm will not put in effort[100] without protection, and it is required that the first τ elements of the protection scheme satisfy:

Constraint 4.2: $r(\tau) + \pi(L) \ge k$.

[99] For the incomplete information case (Δ unknown), it is possible that a protection scheme is needed to screen the types.
[100] The size of k will also affect the reservation utility of the individual rationality constraint; however, this issue will only matter when it comes to the incomplete information case in the next section.

One can imagine that the target firm is able to borrow $\pi(L)$ at the beginning of each period, as its credit is constrained by the current profit. Constraint 4.2 requires that this loan together with the incremental compensation must be big enough to cover the investment cost. The following lemma will simplify our discussion about the target firm's effort decisions. The government would prefer the investment to be finished before the deadline, hence

Lemma 4.1

For $\tau > T$ *, the cheapest compensation is to give* $\{r_{T+1}(\tau), r_{T+2}(\tau)\ldots\} = \{0,0,\ldots\}$.

Lemma 4.1 says that if the target firm cannot finish the investment at any time before the deadline (i.e., $\tau > T$), then since any effort afterwards will not change the outcome on the inspection date, the cheapest compensation is to provide no protection after *T*. However, for the case of $\tau \leq T$, we cannot say anything about it yet, so we leave this part as general.

The next lemma describes the target firm's effort decision *in each period* within *T*. The following discussion can simplify the proof for Lemma 4.2. First, by Lemma 4.1 we know that the government is better off providing no protection after *T* if the target firm can not finish before T. Hence, the firm's present value at time *T+1* for not finishing the investment is the discounted sum of future profits: $V_{T+1}(n_{T+1} < \Delta) = \sum_{i=1}^{\infty} \delta^{i-1}\pi(L)$.

However, if the target firm finishes the investment, the government will still provide protection $\{r_{T+1}(\tau), r_{T+2}(\tau)\ldots\}$, whose form is still unknown, and the firm's present value at time *T+1* for this case will be $V_{T+1}(n_{T+1} \geq \Delta) = \sum_{i=1}^{\infty} \delta^{i-1}[r_{T+i}(\tau) + \pi(H)]$. To simplify the notation, denote $\sum_{i=1}^{\infty} \delta^{i-1}[r_{T+i}(\tau) + \pi(H)] = H$ and $\sum_{i=1}^{\infty} \delta^{i-1}\pi(L) = L$. To motivate the target firm to put in effort, the protection scheme must satisfy[101]:

Constraint 4.3: $\sum_{i=1}^{\infty} \delta^{i-1} r_{T+i}(\tau)$ must be such that $\frac{(1+\delta+\ldots\delta^{\Delta-1})}{\delta^{\Delta}} k \leq (H-L)$[102].

The intuition for this constraint is to require the protection scheme to provide a sufficiently high post-investment profit. The exact structure of post-investment compensation $\{r_{T+1}(\tau), r_{T+2}(\tau)\ldots\}$ will be discussed after Lemma 4.2.

Lemma 4.2[103]

For a general protection scheme that satisfies Constraints 4.1-3, there is a unique decision path where: (i) If $T < \Delta$, the protected firm does not put in effort for each $t \leq T$; (ii) If $T \geq \Delta$, it will shirk from the beginning till period $T - \Delta$ and undertake the investment for the last Δ periods.

Proof in Appendix 4.1.

Two implications can be drawn from Lemma 4.2. First, as $r_i(\tau)$ appears on both alternatives of the target firm's decision function, we can conclude that whether the during-investment protection rate is increasing, decreasing or constant will not affect the investment efficiency, which is in contrast to the prevalent argument that decreasing the protection rates can mitigate the protected firms' pain when adjusting towards

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[101] The analysis of the protection scheme is available for either $\pi(H) > \pi(L)$ or $\pi(H) \leq \pi(L)$. Instead of directly imposing an assumption on $\pi(H)$ and $\pi(L)$, which will greatly restrict this model, we put it as a requirement for the protection scheme.

[102] This constraint comes from the proof of Lemma 4.2 in the Appendix 4.1.

[103] Recall that after the target firm accepts the scheme, the effort decision happens in every period within T. That is, it is not a static decision that happens only at the contracting date.

liberalisation and that the government should provide excess protection to induce efficient investment (Staiger and Tabellini (1987)). Hence, we have the following proposition.

Proposition 4.1

Excessive protection before the completion date cannot induce higher investment efficiency.

Second, the proof of Lemma 4.2 says that when $\pi(H) = \pi(L)$ or $\pi(H) < \pi(L)$, no investment will be undertaken without government intervention, since unless $H - L$ is sufficiently high, the target firm will lack incentive to put in effort. This is a problem often confronted in most R&D activities as the *un-appropriability problem*, which is prevailing in industries with high spillover or imitation. A cure to this market failure of R&D activities is to provide patent protection (see Nordhaus (1969), Klemperer (1991), Gilbert and Shapiro (1991) for discussion of patent length and patent width). In the present model, this is equivalent to the truncated part of the protection scheme: $\{r_{\tau+1}(\tau), r_{\tau+2}(\tau)\ldots\}$.

So far we know that, after imposing the deadline T, Lemma 4.1 says that for $\tau > T$, the cheapest compensation is to give $\{r_{T+1}(\tau), r_{T+2}(\tau)\ldots\} = \{0,0,0,\ldots\}$. Lemma 4.2 says that for reasonably high post-investment protection rates (restricted by Constraint 4.3), the government can only implement a completion date at $\tau \geq T$, as each agent will find it as best response to delay its effort till the last Δ periods of protection and hence $\tau < T$ is not implementable. While $\tau < T$ is not implementable, $\tau > T$ is not desirable (by the definition of the deadline) to the principal. Therefore, we can concentrate on implementing a completion date such that $\tau = T$. The structure of this "reasonably high" post-investment protection sequence to implement $\tau = T$ is defined as follows. As Constraint 4.3 requires only the *sum* of this truncated part to be sufficiently high so that $\frac{(1+\delta+\ldots\delta^{\Delta-1})}{\delta^{\Delta}}k \leq \sum_{t=1}^{\infty}\delta^{t-1}[r_{T+t}(\tau)+\pi(H)-\pi(L)]$, there is no further restriction on the components of the sequence $\{r_{T+1}(T), r_{T+2}(T)\ldots\}$. However, Constraint 4.1 says that each component cannot exceed an upper bound $\overline{\pi}$. Therefore, let $\hat{\pi} = \overline{\pi} - \pi(H)$ and there is no loss in assuming that the sequence after T takes the form $\{r_{T+1}(T), r_{T+2}(T)\ldots\}$ $= \Pi(T,M) := \{\overbrace{\hat{\pi},\hat{\pi},\ldots\hat{\pi}}^{M},0,0,\ldots\}$[104]. The interpretation of this form is similar to the setting of a *patent*, which guarantees the target firm a particular level of profit (through for instance, licences) within the patent length. Together with equation (4.3) and the definition of $\Pi(T,M)$, we can rewrite the protection scheme as: $\{\overbrace{r(T), r(T),\ldots, r(T)}^{T},\ \Pi(T,M)\}$. For simplification, define $\Pi(r,T) := \{\overbrace{r(T),\ldots,r(T)}^{T}\}$. Hence the protection scheme becomes $\{\Pi(r,T),\Pi(T,M)\}$. Furthermore, we can abbreviate the protection scheme as:

$$\{r,T,M\} := \{\Pi(r,T),\Pi(T,M)\} \tag{4.5}$$

Thus, we have pinned down the derivation of the optimal protection scheme into the determination of three variables: ***r***, *T* and *M*, subject to Constraints 4.1-3 and other constraints to be discussed below.

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[104] Any smaller $r_t(T) < \hat{\pi}$ will require a longer post investment protection. As there is no other restriction, we follow the idea of most patent literature and set the unit protection rate to the highest possible profit (usually monopoly). Also remind that *M is not restricted to be an integer*.

To sum up, when the investment opportunity cost is not too high (or equivalently, the future profits from a successful investment are sufficiently high), the optimal scheme is to provide no protection. When the opportunity cost is high (or the future profits are low), as described by $k > \min\{\pi(L), k^*\}$, the target firm will not invest in its own interest, and therefore it will be necessary to provide a protection scheme $\{r, T, M\}$ whose optimal form is defined as in equation (4.5).

A benevolent government maximises social welfare, the discounted sum of the producer's profit and consumers' surplus, with respect to $\{r, T, M\}$. First of all, it is assumed that protection will impose a shadow cost[105] to the society, that is, for each incremental profit $r_t(\tau)$, there will be a shadow cost $\lambda\ r_t(\tau)$. Hence for $t \leq T$, define $\pi(r)$ as the sum of current profit and the incremental profit from protection, that is, $\pi(r) := \pi(L) + r(T)$, and let $S(r)$ be the corresponding consumer surplus, i.e., $S(r) := S(L) - (1+\lambda)r(T)$. For an easier expression of the solution, we rewrite the protection scheme in equation (4.5) as $\{\pi(r), T, M\}$. For $t > T$, $\overline{\pi}$ is the post-investment compensation granted for a period of M and the consumer surplus is $S(H) - (1+\lambda)\hat{\pi}$. It can be checked that,

$$\frac{\partial[\pi(r) + S(r)]}{\partial r} < 0 \quad \text{and} \quad \overline{\pi} + S(H) - (1+\lambda)\hat{\pi} < \pi(\mathrm{H}) + \mathrm{S}(\mathrm{H}), \qquad (4.6)$$

implying that a higher r and a higher M will cause more welfare loss.

For a given scheme $\{\pi(r), T, M\}$, the principal's discounted utility for a successful investment is:

[105] The shadow cost may come from public internal funding which is assumed by Laffont and Tirole (1993).

$$\sum_{t=1}^{T}\delta^{t-1}[\pi(r)+S(r)]+\sum_{t=T+1}^{\infty}\delta^{t-1}[\pi(H)+S(H)]-(1+\lambda)\delta^{T}\rho(M),$$

where $\delta^{T}\rho(M)$ is the discounted sum of the components in $\Pi(T,M)$ (where $\rho(M)$ is increasing in M) and $\lambda\delta^{T}\rho(M)$ denotes the total shadow costs for the post-investment protection[106]. Since the target firm's effort is not observable, there is a moral hazard problem with the design of the optimal scheme. Moreover, the following discussion concentrates on implementing a successful investment, and to make the following discussion reasonable, we assume the welfare gain from a successful investment to be sufficiently high to cover the cost of the protection scheme.

Given the target firm's best response, the equilibrium requires that the protection scheme must be consistent with the agent itself acting rationally. In other words, in the principal's programming problem, except for Constraints 4.1-3, we need the following constraints to ensure that the target firm will accept the offer of the protection scheme and finish the investment.

Given a scheme $\{\pi(r),T,M\}$, the target firm's utility for a successful investment is:

$$\sum_{t=1}^{T}\delta^{t-1}\pi(r)-\sum_{t=T-\Delta+1}^{T}\delta^{t-1}k+\delta^{T}P(M).$$

Recall the definition of $\rho(M)$ from the principal's utility function and $P(M):=\sum_{t=1}^{\infty}\delta^{t-1}\pi(H)+\rho(M)$, which is also increasing in M. The interpretation of this function is: for each time before the deadline T, a unit profit $\pi(r)$ is granted, and after T, $\bar{\pi}$ is granted for a period of M. From $T+M+1$ on, no protection will be granted and hence

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[106] $(1+\lambda)\delta^{T}\rho(M)$ is put as a separate term since M is not necessarily an integer.

the target firm has $\pi(H)$ each period. Lemma 4.2 says that for a given T, it is optimal for the target firm to delay putting in effort till the last Δ periods. Hence, the opportunity cost only happens in the last Δ periods of T: $\sum_{i=T-\Delta+1}^{T} \delta^{i-1} k$.

The first constraint is the Individual Rationality (IR) constraint, which says that the whole protection scheme will give the target firm at least the same utility as rejecting the scheme, that is,

$$\sum_{i=1}^{T} \delta^{i-1} \pi(r) - \sum_{i=T-\Delta+1}^{T} \delta^{i-1} k + \delta^{T} P(M) \geq \sum_{i=1}^{\infty} \delta^{i-1} \pi(L)$$ [107].

(IR)

The reservation utility is the autarky profit level $\sum_{i=1}^{\infty} \delta^{i-1} \pi(L)$, as the investment will not be undertaken. Recall that we are discussing only the cases with $k > \min\{\pi(L), k^*\}$.

Secondly, the Protection Rationality (PR) constraint says that taking the whole scheme will give the target firm at least the same utility as taking the first part of the scheme and staying in autarky henceforth, that is,

$$- \sum_{i=T-\Delta+1}^{T} \delta^{i-1} k + \delta^{T} P(M) \geq \sum_{i=T+1}^{\infty} \delta^{i-1} \pi(L). \qquad \text{(PR)}$$

When Δ is known and $k > \min\{\pi(L), k^*\}$, PR means that the target firm will not benefit by taking the protection program but shirking throughout T, which gives the profit

[107] It is noted in Kreps(1992) that the assumption of weak inequality is "to assume that ties are broken in a fashion that favours the first mover" (the government), in order to ensure the existence of equilibrium (p. 604).

$\sum_{i=1}^{T} \delta^{i-1}\pi(r) + \sum_{i=T+1}^{\infty} \delta^{i-1}\pi(L)$. Clearly if it does not pay to shirk from $T-\Delta+1$, it will not pay to start shirking later.

Furthermore, Lemma 4.2 shows that the capacity constraint must be satisfied for a successful investment:

$$T \geq \Delta. \qquad \text{(capacity constraint)}$$

Rewriting Constraint 4.2 in terms of $\pi(r)$, we have the Cost Limit (CL) constraint, i.e.,

$$\pi(r) \geq k. \qquad \text{(CL)}$$

Together with the non-negativity constraints: $r, T, M \geq 0$, we have the programming problem (*P1*):

$$\max_{\{\pi(r), T, M\}} \left\{ \sum_{i=1}^{T} \delta^{i-1}[\pi(r) + S(r)] + \sum_{i=T+1}^{\infty} \delta^{i-1}[\pi(H) + S(H)] - (1+\lambda)\delta^{T}\rho(M) \right\}. \qquad \textbf{(\textit{P1})}$$

St $\quad T \geq \Delta, \qquad$ (capacity constraint)

$$\pi(r) \geq k, \qquad \text{(CL)}$$

$$\sum_{i=1}^{T} \delta^{i-1}\pi(r) - \sum_{i=T-\Delta+1}^{T} \delta^{i-1}k + \delta^{T}P(M) \geq \sum_{i=1}^{\infty} \delta^{i-1}\pi(L), \qquad \text{(IR)}$$

$$-\sum_{i=T-\Delta+1}^{T} \delta^{i-1}k + \delta^{T}P(M) \geq \sum_{i=T+1}^{\infty} \delta^{i-1}\pi(L). \qquad \text{(PR)}$$

In addition, we have to check that the solution of (*P1*) satisfies Constraints 4.1 and 4.3.

According to the relative sizes of k, $\pi(L)$ and k^*, we can classify three cases: $k^* < k \leq \pi(L)$, $\pi(L) < k \leq k^*$, and $k > \max\{\pi(L), k^*\}$. Since different cases involve different constraints binding, we need to discuss each case separately to avoid confusion.

4.2.1 $k^* < k \leq \pi(L)$

This is the case where the target firm can afford the investment cost each period (that is, there is no liquidity problem), but the future profits of the investment are not high enough to cover the overall cost. To solve the problem, firstly, by the assumption of $k \leq \pi(L)$, the CL constraint is satisfied for any $r \geq 0$. Secondly, let us guess that the capacity constraint is biding, i.e., $T = \Delta$ (the lowest possible deadline that might induce efficient investment). Later we will check if this setting is optimal. Substituting $T = \Delta$ into the PR constraint, we have:

$$-\sum_{i=1}^{\Delta} \delta^{i-1} k + \delta^{\Delta} P(M) \geq \sum_{i=\Delta+1}^{\infty} \delta^{i-1} \pi(L). \tag{4.7}$$

Equation (4.7) will be violated if we set $M = 0$, since for $k > k^*$,

$$-\sum_{i=1}^{\Delta} \delta^{i-1} k + \sum_{i=\Delta+1}^{\infty} \delta^{i-1} \pi(H) < \sum_{i=\Delta+1}^{\infty} \delta^{i-1} \pi(L), \tag{4.8}$$

or equivalently,

$$\delta^{\Delta}[-\delta^{-\Delta} \frac{1-\delta^{\Delta}}{1-\delta} k + \frac{1}{1-\delta}(\pi(H) - \pi(L))] < 0.$$

Keeping $M = 0$, we can check that the value[108] of the PR constraint:

[108] "Value" here refers to the value of LHS minus RHS of the equation.

$$-\sum_{i=T-\Delta+1}^{T}\delta^{i-1}k+\sum_{i=T+1}^{\infty}\delta^{i-1}[\pi(H)-\pi(L)]$$

or equivalently,

$$\delta^{T}[-\delta^{-\Delta}\frac{1-\delta^{\Delta}}{1-\delta}k+\frac{1}{1-\delta}(\pi(H)-\pi(L))],$$

is increasing in T (since δ^{T} is decreasing in T). As equation (4.8) says that PR is not satisfied with the shortest possible deadline $T=\Delta$, we could possibly solve the problem in two ways: one is to increase T, so that the value of PR will be increased up to zero to satisfy the constraint. However, this setting will still violate Constraint 4.3, and therefore we cannot solve the problem by increasing T[109]. The other solution is to increase M, which then implies that a single during-investment scheme cannot implement a successful investment for this case.

Let $T=\Delta$ and define $\overline{M}$ as the smallest M to satisfy PR2:

$$-\sum_{i=1}^{\Delta}\delta^{i-1}k+\delta^{\Delta}P(\overline{M})=\sum_{i=\Delta+1}^{\infty}\delta^{i-1}\pi(L). \tag{4.9}$$

The existence of $\overline{M}$ is defined, since $\overline{\pi}>\pi(H)$. Moreover, since the post-investment protection is granted conditional on the observation of a successful investment at the end of time T, no more effort will be needed and therefore there is no moral hazard problem in the setting of M. Given this setting, we have to compare CL and IR to find out the optimal $\pi(r)$. Given T, the only way to increase the target firm's utility is to increase

[109] This is shown in the proof for Lemma 4.2. The same argument will be applied to all the following cases, and hence will not be replicated.

$\pi(r)$ or M, but a higher $\pi(r)$ or M will decrease the principal's utility. To maximise utility, the government has to minimise the target firm's utility. Therefore, given $T = \Delta$ and $M = \overline{M}$, let us firstly guess that only IR is binding and define $\bar{r}$ as:

$$\sum_{i=1}^{\Delta} \delta^{i-1}\pi(\bar{r}) - \sum_{i=1}^{\Delta} \delta^{i-1}k + \delta^{\Delta}P(\overline{M}) = \sum_{i=1}^{\infty} \delta^{i-1}\pi(L). \tag{4.10}$$

Equation (4.10) implies $\pi(\bar{r}) = \pi(L)$. As noted, the CL constraint will be satisfied for any $r \geq 0$.

Furthermore, we need to check if Constraints 4.1 and 4.3 are satisfied with $\{\pi(r), T, M\} = \{\pi(L), \Delta, \overline{M}\}$. Constraint 4.1 is obviously satisfied and by manipulating equation (4.9), we have

$$\delta^{\Delta}\left[P(\overline{M}) - \sum_{i=1}^{\infty} \delta^{i-1}\pi(L)\right] = \sum_{i=1}^{\Delta} \delta^{i-1}k.$$

By using the notation from the proof for Lemma 4.2, we have $\mathrm{H} - \mathrm{L} \geq \frac{[1 + \delta + \ldots + \delta^{\Delta-1}]}{\delta^{\Delta}}\mathrm{k}$, and hence Constraint 4.3 is satisfied.

Finally, we need to check whether $T = \Delta$ is the optimal setting. Note that both T and M are costly to the government, since if we set T and M to be zero, the welfare would be maximal. Since T is set at the lowest possible value Δ and a higher T will still violate Constraint 4.3, we can conclude that $T = \Delta$ is the optimal setting. Therefore, the optimal protection scheme for this case is $\{\pi(L), \Delta, \overline{M}\}$. This scheme says that the government will not provide any extra protection before the deadline Δ, since the target firm does not have a liquidity problem. However, if the target can complete the investment before or on the deadline, it will be granted the post-investment protection up to $\overline{\pi}$ for a period of $\overline{M}$. The setting of $\overline{M}$ is to provide enough incentive for the target firm to undertake the investment, and it corresponds to most patent designs, whose purposes are to create enough future profits for R&D activities. In other areas, for example, $\overline{M}$ could be interpreted as the tax-exempt period granted to an infant industry firm.

4.2.2 $\pi(L) < k \leq k^*$

In this case, the target firm's current profit cannot cover each period's opportunity cost, but the investment can bring higher future profits than the current status. To solve the problem, first note that since $\pi(L) < k$, CL will be violated for some values of *r*. Second, let us guess that the capacity constraint is binding, that is, $T = \Delta$, and hence the PR constraint has the form of equation (4.7). The difference from the previous case is that if we set $M = 0$, equation (4.7) will be satisfied, since $k \leq k^*$. Substitute $T = \Delta$ and $M = 0$ into the IR constraint, and let us first guess that IR is binding. Define $\pi(r^*)$ as the smallest value such that:

$$\sum_{i=1}^{\Delta} \delta^{i-1}\pi(r^*) - \sum_{i=1}^{\Delta} \delta^{i-1}k + \delta^{\Delta}P(0) = \sum_{i=1}^{\infty} \delta^{i-1}\pi(L). \tag{4.11}$$

Since $k \leq k^*$, equation (4.11) says that $\pi(r^*) \leq \pi(L)$, which will violate the CL constraint. Alternatively, we can let CL bind, which gives $\pi(r) = k > \pi(L)$, where IR is satisfied with inequality. Finally, it can be checked in a similar way that Constraints 4.1 and 4.3 are satisfied and the setting of $T = \Delta$ is optimal.

To conclude, for this case we have $\{\pi(r), T, M\} = \{k, \Delta, 0\}$, which gives the target firm extra protection for the during-investment periods and stops the protection afterwards. This form corresponds to most infant or injured industry protection. In infant industries, the target firms suffer most from the shortage of funding, even though their prospects are promising.

4.2.3 $k > \max\{\pi(L), k^*\}$

In this case, the target firm has no ability or willingness to invest. One can think of most basic industries such as steel and cement industries. Investment in these industries is capital consuming and future profits are not very high under foreign competition. To find the solution, firstly, as in the previous case, CL will be violated for some values of r, since $\pi(L) < k$ by assumption. In addition, if we set $T = \Delta$ and $M = 0$, the PR constraint will be violated as shown in equation (4.8). Proceed as with case 4.2.1 in setting $M = \overline{M}$, as defined in equation (4.9).

Given $T = \Delta$ and $M = \overline{M}$, let us start by guessing IR to be binding which gives $\pi(r^{*\prime})$:

$$\sum_{i=1}^{\Delta} \delta^{i-1} \pi(r^{*\prime}) - \sum_{i=\Delta-\Delta+1}^{\Delta} \delta^{i-1} k + \delta^{\Delta} P(\overline{M}) = \sum_{i=1}^{\bar{\Delta}} \delta^{i-1} \pi(L).$$

By equation (4.9), this means that $\pi(r^{*\prime}) = \pi(L)$, which again violates the CL constraint since $\pi(L) < k$. On the other hand, allowing CL to be binding gives $\pi(r) = k > \pi(L)$ and IR will be satisfied with inequality. Finally, we can check that Constraints 4.1 and 4.3 are satisfied and the setting of $T = \Delta$ is optimal.

To conclude, for this case we have $\{\pi(r), T, M\} = \{k, \Delta, \overline{M}\}$. The optimal protection scheme solves the target firm's liquidity problem during the investment period, and further rewards it with the profit $\overline{\pi}$ for a period of $\overline{M}$ after the completion.

Notice that the during-investment protection basically has no beneficial incentive effect but is for the credit constraint problem. The main result of this section is summarised as Proposition 4.2.

Proposition 4.2

Depending on the cost and revenue environments, the optimal protection could involve no protection, one-part protection or two-part protection.

This proposition can provide an answer to the controversy in empirical results, some of which agree that protection has a positive effect, for example Baldwin and Krugman (1988) conclude that "Japanese import protection aided the growth of their semiconductor industry"; but some disagree, for example Krueger and Tuncer (1982) use data from Turkish manufacturing industries to show that "there is no systematic tendency for more protected firms or industries to have had higher growth of output per unit of input than less protected firms or industries". Luzio and Greenstein (1995) report the result of the Brazilian government's strong protection on the electronic goods: "most observers argue that Brazilian firms did not come close to reaching parity with their potential international competitors in most markets". Our result suggests that not all cases fit into one protection form, and efficient protection should take into account the target firm's investment ability as well as investment willingness. If the wrong form is applied, the protection will probably fail to achieve its purpose in inducing the investment.

4.3 Δ is unknown to the government

In this section, we discuss the case where the target firm has private information about the time needed to complete the investment. The private information comes from, for example, business secrecy or expertise. The main issues of this section are: How will the protection scheme change after taking into account the agent's private information? More specifically, will the principal give excess protection (in both during- and post-investment periods) to ensure incentive compatibility? Will the principal be better off offering a non-screening protection scheme? Can the protection scheme maintain investment efficiency? To answer these questions, we need to find the optimal screening protection scheme in the presence of incomplete information.

Keeping the assumptions of profits and opportunity cost as in the previous section, this section further assumes that the target firm knows the value of Δ, and the principal[110] anticipates that this value can take two possible levels Δ_1 and Δ_2 with respective probabilities υ and $(1-\upsilon)$. The information structure is common knowledge.

Firstly, denote k_i* as the critical investment cost where the target firm i is indifferent between investing and not investing under the current profit[111], that is,

$$k_i* = \frac{\sum_{i=\Delta_i+1}^{\infty} \delta^{i-1}[\pi(H)-\pi(L)]}{\sum_{i=1}^{\Delta_i} \delta^{i-1}}.$$

[110] The discrete (instead of continuous) setting is better for understanding the different subcases in this section.

[111] In other words, k_i* is such that $\sum_{i=1}^{\Delta_i} \delta^{i-1}\pi(L) - \sum_{i=1}^{\Delta_i} \delta^{i-1}k_i* + \sum_{i=\Delta_i+1}^{\infty} \delta^{i-1}\pi(H) = \sum_{i=1}^{\infty} \delta^{i-1}\pi(L)$.

Since $\Delta_1 < \Delta_2$, we know that $k_2{}^* < k_1{}^*$. Together with the relative sizes of $k_1{}^*$ and $\pi(L)$, concerning the target firm's ability and willingness to invest, we can classify six cases: $k \le \min\{\pi(L), k_2^*\}$, $k_2^* < k \le \min\{\pi(L), k_1^*\}$, $k_1^* < k \le \pi(L)$, $\pi(L) < k \le k_2^*$, $\max\{\pi(L), k_2^*\} < k \le k_1^*$ and $\max\{\pi(L), k_1^*\} < k$. As in the previous section, the case with $k \le \min\{\pi(L), k_2^*\}$ will be ignored because the solution is trivially not to provide protection. Recall that the following design is intended to look for a screening protection scheme and we will discuss later whether it is better than a non-screening scheme. Moreover, since the target firm has private information, the derivation of the optimal protection scheme mainly relies on applying the *revelation principle*, proposed by Gibbard (1973), Green and Laffont (1977), Dasgupta et al. (1979) and Myerson (1979), which says that any efficient outcome of any Bayesian game can be represented by a truth-telling incentive compatible direct mechanism. A mechanism is a method to allocate resources among players. For example, the optimal protection could be determined through a bargaining process. The revelation principle says that we can restrict our attention to a direct mechanism, which requests the privately informed player to report its type to the uninformed player. The allocation of resources is then dependent on what is reported. Of course, the informed player could mis-report in its own interest. An incentive compatible direct mechanism requires that the allocation among resources is designed in such a way that it will be a best response for the privately informed player to report truthfully. To make the following discussion reasonable, we restrict our attention to the case where the welfare improvement is sufficiently high to have both types finish the investment.

Let $\hat{\Delta}_1$ and $\hat{\Delta}_2$ be the reported values from types Δ_1 and Δ_2 respectively. By the revelation principle, we can concentrate on looking for a truth-telling equilibrium, i.e., $\hat{\Delta}_i = \Delta_i$, $i = 1,2$. Denote the respective protection schemes for Δ_1 and Δ_2 as $\{\pi(r_1), T_1, M_1\}$ and $\{\pi(r_2), T_2, M_2\}$.

Given $\{\pi(r_1), T_1, M_1\}$ and $\{\pi(r_2), T_2, M_2\}$, the government's expected utility for a successful investment is:

$$\{\upsilon[\sum_{i=1}^{T_1} \delta^{i-1}(\pi(r_1) + S(r_1)) + \sum_{i=T_1+1}^{\infty} \delta^{i-1}[\pi(H) + S(H)] - (1+\lambda)\delta^{T_1}\rho(M_1)]$$
$$+(1-\upsilon)[\sum_{i=1}^{T_2} \delta^{i-1}(\pi(r_2) + S(r_2)) + \sum_{i=T_2+1}^{\infty} \delta^{i-1}[\pi(H) + S(H)] - (1+\lambda)\delta^{T_2}\rho(M_2)]\},$$

where each term has the same meaning as in the complete information case, and the total utility is the weighted sum over two types. For each type, the agent's utility for completing the investment is:

$$\sum_{i=1}^{T_i} \delta^{i-1}\pi(r_i) - \sum_{i=T_i-\Delta_i+1}^{T_i} \delta^{i-1}k + \delta^{T_i}P(M_i).$$

The interpretation for every term is similar to the complete information case. For each type to finish the investment, the protection scheme must first satisfy:

$$T_1 \geq \Delta_1,$$
$$T_2 \geq \Delta_2.$$

For those whose investment abilities are limited (i.e., $\pi(L) < k$), these are "capacity constraints", since if the during-investment protection length cannot cover Δ_i, the best response of type i is not to invest (Lemma 4.2). However, for those whose investment abilities are not limited (i.e., $\pi(L) \geq k$), these constraints need to be satisfied as well. The reason is: T_i is an inspection date and the compensation henceforth depends on the performance at T_i. If $T_i < \Delta_i$, the investment will not be completed on the inspection date, hence by Lemma 4.1 the target firm will get zero protection after the deadline. If $k \leq k_i$ *, the firm will still invest, as it would in the first place. For this case, there is no loss to require $T_i \geq \Delta_i$, because no protection $r_i = 0$ is always feasible. If $k > k_i$ *, the target firm will be better off shirking throughout the funding period, and hence the investment will not be finished. Overall, the constraint of $T_i \geq \Delta_i$ is necessary even if $\pi(L) \geq k$.

Secondly, the cost limit constraints must be satisfied:

$$\pi(r_1) \geq k, \qquad \text{(CL1)}$$

$$\pi(r_2) \geq k. \qquad \text{(CL2)}$$

Thirdly, remember that each protection scheme actually consists of two parts. The Individual Rationality (IR) constraints say that by taking the whole scheme, each type will have at least the same utility as staying in autarky[111]. Since the autarky profits vary with cases[112], to generalise the notation, an index is defined as:

$$X = 1 \qquad \text{if } \pi(L) < k$$
$$= 0 \qquad \text{otherwise.}$$

and

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[111]"Autarky" means the situation when there is no protection.
[112]In some cases, the target firm will invest without protection, but mimicking the other type will give it at least the same utility.

$$R^{IR}(X,\Delta_i) = X\sum_{t=1}^{\infty}\delta^{t-1}\pi(L)$$

$$+(1-X)\max\left\{\sum_{t=1}^{\Delta_i}\delta^{t-1}\pi(L)-\sum_{t=1}^{\Delta_i}\delta^{t-1}k+\sum_{t=\Delta_i+1}^{\infty}\delta^{t-1}\pi(H),\ \sum_{t=1}^{\infty}\delta^{t-1}\pi(L)\right\}.$$

$R^{IR}(X,\Delta_i)$ denotes the target firm's autarky payoff. The meaning of $R^{IR}(X,\Delta_i)$ is as follows: if $\pi(L)<k$, the target firm certainly will not put in effort without protection and hence it keeps the current profits; if $\pi(L)\geq k$, depending on whether $k\leq k_i{*}$ or $k>k_i{*}$, the target firm will or will not undertake the investment, and therefore the reservation utility is the maximum over these two profits. The IR constraints are written as:

$$\sum_{t=1}^{T_1}\delta^{t-1}\pi(r_1)-\sum_{t=T_1-\Delta_1+1}^{T_1}\delta^{t-1}k+\delta^{T_1}P(M_1)\geq R^{IR}(X,\Delta_1), \tag{IR1}$$

$$\sum_{t=1}^{T_2}\delta^{t-1}\pi(r_2)-\sum_{t=T_2-\Delta_2+1}^{T_2}\delta^{t-1}k+\delta^{T_2}P(M_2)\geq R^{IR}(X,\Delta_2). \tag{IR2}$$

Next, the Protection Rationality (PR) constraints require that by taking the whole scheme, each type will have at least the same utility as taking just the first part of the scheme and staying in autarky henceforth. For example, when $\pi(L)<k$, this means that the target firm will not take the scheme but shirk throughout T. Following the same procedure in defining IR, define $R^{PR}(X,\pi(r_i),T_i,\Delta_i)$ as:

$$R^{PR}(X,\pi(r_i),T_i,\Delta_i) = X\sum_{t=T_i+1}^{\infty}\delta^{t-1}\pi(L)$$

$$+(1-X)\max\left\{\overline{PR}(\pi(r_i),T_i,\Delta_i),\ \sum_{t=T_i+1}^{\infty}\delta^{t-1}\pi(L)\right\}, \tag{4.12}$$

where $\overline{PR}(\pi(r_i), T_i, \Delta_i)$ [113]

$$= \begin{cases} -\sum_{i=1}^{\Delta_i} \delta^{i-1} k_i + \sum_{i=T_i+1}^{\Delta_i} \delta^{i-1} \pi(L) + \sum_{i=\Delta_i+1}^{\infty} \delta^{i-1} \pi(H), \ \text{if } T_i < \Delta_i, \\ \max\left\{ - \sum_{i=T_i-\Delta_i+1}^{T_i} \delta^{i-1} k_i, -\sum_{i=1}^{\Delta_i} \delta^{i-1} k_i + \sum_{i=\Delta_i+1}^{T_i} \delta^{i-1} (\pi(H) - \pi(r_i)) \right\} + \sum_{i=T_i+1}^{\infty} \delta^{i-1} \pi(H), \ \text{if } T_i \geq \Delta_i. \end{cases}$$

$R^{PR}(X, \pi(r_i), T_i, \Delta_i)$ is the utility from taking just the first part of scheme and then staying in autarky. Note that the discounted utility from the first part of the scheme appears on both sides of the constraint and will be cancelled out. When $\pi(L) < k$, the autarky decision is not to invest and hence we have the first term in equation (4.12). The second term is the maximum between $\overline{PR}(\pi(r_i), T_i, \Delta_i)$ and $\sum_{i=T_i+1}^{\infty} \delta^{i-1} \pi(L)$. The latter means the utility for $k > k_i{}^*$, where the autarky decision is not to invest. The former means the utility for $k \leq k_i{}^*$, where the target firm will invest in autarky. But depending on the relative sizes of the during investment protection and $\pi(H)$, $\overline{PR}(\pi(r_i), T_i, \Delta_i)$ has three possible values: when $T_i < \Delta_i$, the target firm has higher profits (since $\pi(r_i) \geq \pi(L)$ by Constraint 4.1) for the first T_i periods. However, since the time needed for completion is longer than T_i, the investment will not be completed on the deadline but the firm will still continue its investment and finish at Δ_i. When $T_i \geq \Delta_i$, it is possible that the target firm will finish earlier than the deadline. For delaying till T_i, the target firm's utility is: $\sum_{i=1}^{T_i} \delta^{i-1} \pi(r_i) - \sum_{i=T_i-\Delta_i+1}^{T_i} \delta^{i-1} k_i + \sum_{i=\Delta_i+1}^{\infty} \delta^{i-1} \pi(H)$, and the utility for finishing earlier at Δ_i is

[113] The case with $T_i < \Delta_i$ will be excluded by the capacity constraints, however, to exhaust each possibility of the target firm's autarky decision, we need to write it down here.

$\sum_{i=1}^{T_i} \delta^{i-1}\pi(r_i) - \sum_{i=1}^{\Delta_i} \delta^{i-1}k_i + \sum_{i=\Delta_i+1}^{T_i} \delta^{i-1}(\pi(H) - \pi(r_i)) + \sum_{i=\Delta_i+1}^{\infty} \delta^{i-1}\pi(H)$. The reservation utility is hence the maximum of these two utilities. The PR constraints are:

$$-\sum_{i=T_1-\Delta_1+1}^{T_1} \delta^{i-1}k + \delta^{T_1}P(M_1) \geq R^{PR}(X, \pi(r_1), T_1, \Delta_1), \tag{PR1}$$

$$-\sum_{i=T_2-\Delta_2+1}^{T_2} \delta^{i-1}k + \delta^{T_2}P(M_2) \geq R^{PR}(X, \pi(r_2), T_2, \Delta_2). \tag{PR2}$$

Similar to the IR constraints, the right hand side of the PR constraints also vary with types.

Finally, we need further constraints to screen the types. First of all, the Incentive Compatibility (IC) constraints say that taking the whole scheme that is meant for each type gives him at least the same utility as taking the whole scheme that is meant for the other type, that is,

$$\sum_{i=1}^{T_1} \delta^{i-1}\pi(r_1) - \sum_{i=T_1-\Delta_1+1}^{T_1} \delta^{i-1}k + \delta^{T_1}P(M_1) \geq \sum_{i=1}^{T_2} \delta^{i-1}\pi(r_2) - \sum_{i=T_2-\Delta_1+1}^{T_2} \delta^{i-1}k + \delta^{T_2}P(M_2), \tag{IC1}$$

and

$$\sum_{i=1}^{T_2} \delta^{i-1}\pi(r_2) - \sum_{i=T_2-\Delta_2+1}^{T_2} \delta^{i-1}k + \delta^{T_2}P(M_2) \geq \sum_{i=1}^{T_1} \delta^{i-1}\pi(r_1) - \sum_{i=T_1-\Delta_2+1}^{T_1} \delta^{i-1}k + \delta^{T_1}P(M_1)$$

$$\text{if } T_1 \geq \Delta_2. \tag{IC2}$$

When $T_1 < \Delta_2$, type Δ_2 will not finish the investment at T_1 and this case will be considered in the IPR constraints defined as follows. The IPR constraints say that the whole scheme for each type should give him at least the same utility as taking only the first part of the scheme *for the other type* and staying in autarky henceforth, i.e.,

$$\sum_{i=1}^{T_1}\delta^{i-1}\pi(r_1)-\sum_{i=T_1-\Delta_1+1}^{T_1}\delta^{i-1}k+\delta^{T_1}P(M_1)\geq R^{PR}(X,\pi(r_2),T_2,\Delta_1)+\sum_{i=1}^{T_2}\delta^{i-1}\pi(r_2)\,, \qquad \text{(IPR1)}$$

and

$$\sum_{i=1}^{T_2}\delta^{i-1}\pi(r_2)-\sum_{i=T_2-\Delta_2+1}^{T_2}\delta^{i-1}k+\delta^{T_2}P(M_2)\geq R^{PR}(X,\pi(r_1),T_1,\Delta_2)+\sum_{i=1}^{T_1}\delta^{i-1}\pi(r_1)\,. \qquad \text{(IPR2)}$$

Together with the non-negativity constraints: $r_i, T_i, M_i \geq 0$, we have the programming problem (***P2***):

$$\max_{\{\pi(r_1),T_1,\Delta_1\},\{\pi(r_2),T_2,\Delta_2\}}\{\upsilon[\sum_{i=1}^{T_1}\delta^{i-1}(\pi(r_1)+S(r_1))+\sum_{i=T_1+1}^{\infty}\delta^{i-1}[\pi(H)+S(H)]-(1+\lambda)\delta^{T_1}\rho(M_1)]$$
$$+(1-\upsilon)[\sum_{i=1}^{T_2}\delta^{i-1}(\pi(r_2)+S(r_2))+\sum_{i=T_2+1}^{\infty}\delta^{i-1}[\pi(H)+S(H)]-(1+\lambda)\delta^{T_2}\rho(M_2)]\}$$

subject to capacity constraints, CL1, CL2 IR1, IR2, PR1, PR2, IC1, IC2, IPR1 and IPR2. Constraints 4.1 and 4.3 also need to be satisfied by the solution. (***P2***)

Since the constraints are case contingent, we need to check each case separately to avoid confusion.

4.3.1 $k_2^* < k \leq \min\{\pi(L), k_1^*\}$

Since r_i, T_i, M_i are costly[114] to the government, these variables should be set at the lowest possible values without violating any constraint. In this case, there is no liquidity problem for both types, but the investment cost is too high for the inefficient type to cover the overall cost. Hence the efficient type will invest and the inefficient type will not invest without protection, and both CL constraints will be satisfied for any feasible $r \geq 0$. To

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[114]The reason follows the complete information case.

find the solution, suppose first that both capacity constraints are binding: $T_1 = \Delta_1$ and $T_2 = \Delta_2$ (i.e., the lowest possible deadlines that induce produce efficient investment). Later we will check if it is the optimal setting. Substituting the settings of T_i, we can simplify the PR constraints as:

$$\begin{aligned}
&-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(M_1)\geq-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(H),\\
&-\sum_{i=1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(M_2)\geq\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}\pi(L).
\end{aligned}\tag{4.13}$$

If only taking the first part of the scheme, the efficient type has a higher profit each period till T_1 ($=\Delta_1$). Afterwards, his autarky utility is the value from completing the investment. As $k_2^* < k$, PR1 will be satisfied for any $M_1 \geq 0$, but PR2 will be violated if we set $M_2 = 0$. Define $\overline{M}_2$ as the smallest M_2 to satisfy the PR2 constraint[115]:

$$-\sum_{i=1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(\overline{M}_2)=\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}\pi(L).\tag{4.14}$$

Since we only know that $M_1 = 0$ can satisfy PR1, we will leave the setting of M_1 as general. Temporarily, we have $\{T_1, M_1\} = \{\Delta_1, M_1\}$ and $\{T_2, M_2\} = \{\Delta_2, \overline{M}_2\}$. Substituting this setting into the other constraints, we can further simplify first the IR constraints:

$$\begin{aligned}
&\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(M_1)\geq\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(L)-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(H),\\
&\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)-\sum_{i=1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(\overline{M}_2)\geq\sum_{i=1}^{\infty}\delta^{i-1}\pi(L).
\end{aligned}\tag{4.15}$$

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[115] Recall from the complete information case where we argue that the increase of T will not solve the problem.

From the IR constraints, it is difficult to tell which type will mimic the other because the reservation utilities vary with types. However, we have the IPR constraints:

$$\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(M_1)$$

$$\geq\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)+\max\left\{-\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2}\delta^{i-1}k,\ -\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\sum_{i=\Delta_1+1}^{\Delta_2}\delta^{i-1}(\pi(H)-\pi(r_2))\right\}+\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}\pi(H). \tag{4.16}$$

$$\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)-\sum_{i=1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(\overline{M}_2)\geq\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(L). \tag{4.17}$$

To satisfy Constraint 4.1[116], it must be true that IPR2 (4.17) implies IR2 (4.15). Manipulating equation (4.17) by using the definition of $\overline{M}_2$ yields:

$$\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)\geq\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)+\sum_{i=\Delta_1+1}^{\Delta_2}\delta^{i-1}\pi(L). \tag*{(4.17)'}$$

Constraint 4.1 says that IR1 will be satisfied if IPR1 is satisfied. Overall, if Constraint 4.1 is satisfied, then both IR constraints can be replaced by the IPR constraints. Finally since $T_1=\Delta_1$, IC2 is not valid and IC1 is simplified to:

$$\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(M_1)\geq\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)-\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(\overline{M}_2). \tag{4.18}$$

The relationship between IPR1 (4.16) and IC1 (4.18) is not yet clear. If $\pi(r_2)>\pi(H)$, together with $\overline{M}_2>0$ we know that equation (4.18) will imply equation (4.16) because

[116] That is, $\pi(r_1)\geq\pi(L)$.

$\bar{\pi} > \pi(H)$. However, if $\pi(r_2) \leq \pi(H)$, then whether (4.18) implies (4.16) will depend on the size of $\pi(r_2)$. To determine $\pi(r_2)$, we need to check the IPR2 constraint (equation (4.17)). By letting equation (4.17)' bind, we can see that $\pi(r_2)$ and $\pi(r_1)$ are linearly dependent, i.e.,

$$\sum_{i=1}^{\Delta_2} \delta^{i-1}\pi(r_2) = \sum_{i=1}^{\Delta_1} \delta^{i-1}\pi(r_1) + \sum_{i=\Delta_1+1}^{\Delta_2} \delta^{i-1}\pi(L). \tag{4.17)''}$$

As $\pi(r_2)$ and $\pi(r_1)$ will be cancelled from both sides of IC1, there is no further constraint on $\pi(r_i)$ except for Constraint 4.1. Hence, let us firstly suppose that Constraint 4.1 binds for $\pi(r_1)$, that is, $\pi(r_1) = \pi(L)$, which further implies $\pi(r_2) = \pi(L)$ by equation (4.17)". By this setting, we can see that IC1 (4.18) implies IPR1 (4.16), since $\overline{M}_2 > 0$ and $\bar{\pi} > \pi(H)$. Finally, let $\overline{M}_1^0$ be the smallest M_1 that satisfies IC1:

$$\sum_{i=1}^{\Delta_1} \delta^{i-1}\pi(r_1) - \sum_{i=1}^{\Delta_1} \delta^{i-1}k + \delta^{\Delta_1}P(\overline{M}_1^0) = \sum_{i=1}^{\Delta_2} \delta^{i-1}\pi(r_2) - \sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2} \delta^{i-1}k + \delta^{\Delta_2}P(\overline{M}_2).$$

To compare the relative sizes of $\overline{M}_1^0$ and $\overline{M}_2$, rewrite the above equation by substituting the setting of $\pi(r_i)$:

$$-\sum_{i=1}^{\Delta_1} \delta^{i-1}k + \delta^{\Delta_1}P(\overline{M}_1^0) = \sum_{i=\Delta_1+1}^{\Delta_2} \delta^{i-1}\pi(L) + \delta^{\Delta_2-\Delta_1}[-\sum_{i=1}^{\Delta_1} \delta^{i-1}k + \delta^{\Delta_1}P(\overline{M}_2)]. \tag{4.18)'}$$

It can be checked that $\overline{M}_1^0 < \overline{M}_2$. To prove this, suppose $\overline{M}_1^0 = \overline{M}_2$ and let $X := -\sum_{i=1}^{\Delta_1} \delta^{i-1}k + \delta^{\Delta_1}P(\overline{M}_1^0)$. (4.18)' implies $(1-\delta^{\Delta_2-\Delta_1})X = \sum_{i=\Delta_1+1}^{\Delta_2} \delta^{i-1}\pi(L)$

$(=\delta^{\Delta_1}\frac{1-\delta^{\Delta_2-\Delta_1}}{1-\delta}\pi(L))$ or equivalently, $X=\delta^{\Delta_1}\frac{1}{1-\delta}\pi(L)$, which will violate PR1[117].

Now, suppose $\overline{M}_1^0<\overline{M}_2$ and let $-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(\overline{M}_2)=X+\varepsilon$, where ε is the utility difference from setting $\overline{M}_1^0$ and $\overline{M}_2$ (since $P(.)$ is increasing and $\overline{M}_1^0<\overline{M}_2$, we have $\varepsilon>0$). Therefore, from (4.18)' we have $X=\delta^{\Delta_1}\frac{1}{1-\delta}\pi(L)+\frac{\varepsilon}{1-\delta^{\Delta_2-\Delta_1}}$, which depending on the size of ε, will possibly satisfy the PR1 constraint. Hence, it must be that $\overline{M}_1^0<\overline{M}_2$. Furthermore, whether $\overline{M}_1^0\geq 0$ is dependent on the relative sizes of $\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(L)-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(H)$ (the RHS of IR1) and $\sum_{i=1}^{\Delta_2-\Delta_1}\delta^{i-1}k+\sum_{i=1}^{\infty}\delta^{i-1}\pi(L)$ (the RHS of IC1). If the former is bigger, then IR1 should be binding and hence we set $M_1=0$; If the latter is bigger, then we set $M_1=\overline{M}_1^0>0$, which simultaneously satisfies PR1 and IC1. So far, we have $\{\pi(r_1),T_1,M_1\}=\{\pi(L),\Delta_1,\overline{M}_1^0\}$ or $\{\pi(L),\Delta_1,0\}$ and $\{\pi(r_2),T_2,M_2\}=\{\pi(L),\Delta_2,\overline{M}_2\}$. It can be checked that IR, IPR, IC, capacity and cost limit constraints are satisfied. Finally, since PR2 and Constraint 4.1 are binding, following the same argument as in Section 4.2, it can be checked that Constraint 4.3 is satisfied with the scheme for type 2. Constraint 4.3 is satisfied with type 1's scheme by assumption. By the same argument in Section 4.2, we can argue that the setting of $T_i=\Delta_i$ is optimal to the government. The result says that if type Δ_1 mimics Δ_2, it stands to get a reward $\overline{M}_2$ and the benefit from delaying the investment cost; but to get this mimicking benefit, the efficient type will have to delay completion until Δ_2 which is costly (since it doesn't get $\pi(H)$ until later). So there may or may not be an incentive to

[117] PR1 has a reservation utility higher than the current profits.

mimic Δ_2; if there is, $\overline{M}_1^0$ is needed to ensure incentive compatibility. It is assumed feasible[118] to have $\overline{M}_1^0 > 0$, which is interpreted as the information rent paid to the efficient type.

4.3.2 $k_1^* < k \leq \pi(L)$

In this case, the investment cost is too high for both types to cover the overall cost, hence neither of them will invest in autarky. However, as there is no liquidity problem, the CL constraints will be satisfied for any feasible r by assumption. Suppose first that both capacity constraints are binding, which gives $T_1 = \Delta_1$ and $T_2 = \Delta_2$. Together with the assumptions of $\pi(L) \geq k$ and $k_1^* < k$, we can shorten the PR1 constraint as:

$$-\sum_{i=1}^{\Delta_1} \delta^{i-1} k + \delta^{\Delta_1} P(M_1) \geq \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1} \pi(L), \tag{4.19}$$

and the PR2 constraint as in equation (4.13) from the previous case. If we set $M_1 = 0$ and $M_2 = 0$, both PR1 and PR2 will be violated. Hence, except for $\overline{M}_2$ defined in equation (4.14), we can define $\overline{M}_1$ to be the smallest M_1 to satisfy PR1:

$$-\sum_{i=1}^{\Delta_1} \delta^{i-1} k + \delta^{\Delta_1} P(\overline{M}_1) = \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1} \pi(L). \tag{4.20}$$

Any $M_1 \geq \overline{M}_1$ and $M_2 \geq \overline{M}_2$ will satisfy the PR constraints. As in the previous case, we leave the setting of M_1 as general and hence we temporarily have $\{T_1, M_1\} = \{\Delta_1, M_1\}$ and

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118 There is no other consideration, such as political pressure, on the setting of protection scheme.

$\{T_2, M_2\} = \{\Delta_2, \overline{M}_2\}$. Substituting this setting into the other constraints, we can further simplify first the IR1 constraint as:

$$\sum_{i=1}^{\Delta_1} \delta^{i-1}\pi(r_1) - \sum_{i=1}^{\Delta_1} \delta^{i-1}k + \delta^{\Delta_1} P(M_1) \geq \sum_{i=1}^{\infty} \delta^{i-1}\pi(L), \tag{4.21}$$

and the IR2 constraint as equation (4.15). Moreover, we have IPR1:

$$\sum_{i=1}^{\Delta_1} \delta^{i-1}\pi(r_1) - \sum_{i=1}^{\Delta_1} \delta^{i-1}k + \delta^{\Delta_1} P(M_1) \geq \sum_{i=1}^{\Delta_2} \delta^{i-1}\pi(r_2) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}\pi(L), \tag{4.22}$$

and IPR2 as equation (4.17). By applying Constraint 4.1, we know that IPR constraints imply IR constraints and hence we only need to consider IPR constraints. Since $T_1 = \Delta_1$, IC2 is not valid and we need only consider IC1, which is described in equation (4.18). Comparing IPR1 (4.22) and IC1 (4.18), we know that IC1 implies IPR1, which can be checked by substituting the definition of $\overline{M}_2$ and the fact that $-\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2} \delta^{i-1}k > -\sum_{i=1}^{\Delta_1} \delta^{i-1}k$. Hence, the various constraints can be summarised by IC1 (which implies IPR1 and hence IR1), and IPR2 (which implies IR2).

To derive $\pi(r_i)$ and M_1, we need to check IC1, IPR2 and Constraints 4.1 and 4.3. First of all, by the definition of $\overline{M}_2$, equation (4.17)' (from IPR2) is valid with equality. By letting equation (4.17)' bind, we can see that $\pi(r_2)$ and $\pi(r_1)$ are linearly dependent. As $\pi(r_2)$ and $\pi(r_1)$ will be cancelled out from both sides of IC1, there are no further constraints on $\pi(r_i)$ except for Constraint 4.1. Hence let us suppose that Constraint 4.1 binds for $\pi(r_1)$, that is, $\pi(r_1) = \pi(L)$, which therefore implies $\pi(r_2) = \pi(L)$ by equation (4.17)''. Substituting these values into IC1 gives:

$$-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(M_1)\geq\sum_{i=\Delta_1+1}^{\Delta_2}\delta^{i-1}\pi(L)-\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(\overline{M}_2) \qquad (4.18)''$$

To find the optimal M_1, let $\tilde{\overline{M}}_1$ be the value of M_1 such that equation (4.18)" is binding. We need to compare the relative sizes of $\tilde{\overline{M}}_1$ and $\overline{M}_1$. Note that, if $M_1 = \overline{M}_1$, the left hand side of equation (4,18)" will be $\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(L)$ by the definition of $\overline{M}_1$. This value is smaller than the right hand side of (4.18)", which is $\sum_{i=1}^{\Delta_2-\Delta_1}\delta^{i-1}k+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(L)$ by using the definition of $\overline{M}_2$ and the assumption of $\pi(L)\geq k$. Hence it must be $\tilde{\overline{M}}_1 > \overline{M}_1$. To simultaneously satisfy PR1 and IC1, we need to choose the bigger value, that is, $M_1 = \tilde{\overline{M}}_1$. The intuition is: $\overline{M}_1$ only gives the efficient type the reservation utility which is the same as that of the inefficient type, but mimicking can give him at least the benefit from delaying to put in the investment cost. To ensure incentive compatibility, M_1 must be bigger than $\overline{M}_1$ to compensate this mimicking benefit. Furthermore, following the argument in the pervious case, we can show that if $\tilde{\overline{M}}_1 = \overline{M}_2$, the value of $-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(\tilde{\overline{M}}_1)$ will be $\delta^{\Delta_1}\frac{1}{1-\delta}\pi(L)$ (hence the expected utility will be $\sum_{i=1}^{\infty}\delta^{i-1}\pi(L)$), but this will not satisfy the IC1 constraint, whose RHS is $\sum_{i=1}^{\Delta_2-\Delta_1}\delta^{i-1}k+\sum_{i=1}^{\infty}\delta^{i-1}\pi(L)$. Hence it must be $\tilde{\overline{M}}_1 < \overline{M}_2$. Therefore, the optimal scheme is $\{\pi(r_1), T_1, M_1\} = \{\pi(L), \Delta_1, \tilde{\overline{M}}_1\}$, and $\{\pi(r_2), T_2, M_2\} = \{\pi(L), \Delta_2, \overline{M}_2\}$. Following the same checking process as in the previous case, this solution satisfies Constraints 4.1 and 4.3 and the setting $T_i = \Delta_i$ is optimal to the government. This solution shows that even when both types are liquidity constrained, it is still optimal to give the efficient type a shorter period of post-investment protection, as the efficient type has less incentive to mimic the inefficient type whose higher profits from a successful investment will not be realised until later.

4.3.3 $\pi(L) < k \leq k_2^*$

In this case, both types have liquidity problems and hence neither of them will invest without protection, although both types' future profits from a successful investment are sufficiently high. The cost limit constraints will be violated under the current profit for both types. By setting $T_1 = \Delta_1$ and $T_2 = \Delta_2$, we can simplify the respective PR constraints as equation (4.19) and equation (4.13). Unlike the previous cases, the PR constraints will be satisfied if $M_i = 0$, and therefore any $M_i \geq 0$ will satisfy the PR constraints. Furthermore, we have IR1 and IR2 as equations (4.21) and (4.23):

$$\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1) - \sum_{i=1}^{\Delta_1}\delta^{i-1}k + \delta^{\Delta_1}P(M_1) \geq \sum_{i=1}^{\infty}\delta^{i-1}\pi(L), \tag{4.21}$$

$$\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2) - \sum_{i=1}^{\Delta_2}\delta^{i-1}k + \delta^{\Delta_2}P(M_2) \geq \sum_{i=1}^{\infty}\delta^{i-1}\pi(L). \tag{4.23}$$

Similarly, we have IPR1 and IPR2 constraints as:

$$\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1) - \sum_{i=1}^{\Delta_1}\delta^{i-1}k + \delta^{\Delta_1}P(M_1) \geq \sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2) + \sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}\pi(L), \tag{4.22}$$

$$\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)-\sum_{i=1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(M_2)\geq\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(L). \tag{4.24}$$

By applying Constraint 4.1, we know that IPR1 implies IR1 and IPR2 implies IR2. Therefore, we only need to consider equations (4.22) and (4.24). However, it is difficult to tell from equations (4.22) and (4.24) which type will mimic the other. We go on to check the IC constraints. Since $T_1 = \Delta_1$, IC2 is not valid and only IC1 is valid:

$$\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)-\sum_{i=1}^{\Delta_1}\delta^{i-1}k+\delta^{\Delta_1}P(M_1)\geq\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)-\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(M_2). \tag{4.25}$$

It can be checked that IC1 implies IPR1: as any $M_2 \geq 0$ will satisfy PR2 and $-\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2}\delta^{i-1}k > -\sum_{i=1}^{\Delta_1}\delta^{i-1}k$, the RHS of IC1 is bigger than the RHS of IPR1. We now have constraints IPR2 (4.24) and IC1 (4.25) to decide four variables: $\pi(r_i)$ and M_i, $i = 1,2$. We certainly need more information to find the solution. Recall that any $M_i \geq 0$ will satisfy the PR constraints and the cost limit constraints will be violated for the current profit $\pi(L)$. Given $T_i = \Delta_i$, we know from the agent's utility function that the only way to increase utility is to increase $\pi(r_i)$ or M_i. However, a higher $\pi(r_i)$ or M_i will decrease the principal's utility, hence (4.24) and (4.25) should be set at the lowest possible values. Let us firstly guess (4.24) to be binding and let $M_2 = 0$. By manipulating equation (4.24) after assuming binding, we have:

$$\sum_{i=1}^{\Delta_2}\delta^{i-1}\pi(r_2)=\sum_{i=1}^{\Delta_1}\delta^{i-1}\pi(r_1)+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(L)-[-\sum_{i=1}^{\Delta_2}\delta^{i-1}k+\delta^{\Delta_2}P(0)]. \tag{4.24'}$$

As there are no further restrictions on $\pi(r_i)$ except for the cost limit constraints, we can guess that type 1's cost limit constraint is binding, that is, $\pi(r_1) = k$. Denote $\pi(r_2{*})$ as the value that satisfies equation (4.24)', it must be $\pi(r_2{*}) < k$ (since $-\sum_{i=1}^{\Delta_2}\delta^{i-1}k + \delta^{\Delta_2}P(0) \geq \sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}\pi(L)$ by assumption). Since the cost limit constraint will be violated by $\pi(r_2{*})$, we set instead $\pi(r_2) = k$ (CL2 binding). By this setting, IPR2 is satisfied with inequality. After substituting $M_2, \pi(r_1)$ and $\pi(r_2)$ with *0*, *k* and *k*, we can rewrite IC1:

$$\delta^{\Delta_1}P(M_1)) \geq \sum_{i=1}^{\Delta_2}\delta^{i-1}k - \sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2}\delta^{i-1}k + \delta^{\Delta_2}P(0). \qquad (4.25)'$$

Let $\overline{M_1}'$ be the value such that (4.25)' is binding. Whether $\overline{M_1}' > 0$ is dependent on the relative size of k[119]: if $\delta^{\Delta_1}\pi(H) \geq k$, then the LHS of (4.25)' is greater than the RHS. To have it binding, it must be that $\overline{M_1}' \leq 0$; if $\delta^{\Delta_1}\pi(H) < k$, it must be that $\overline{M_1}' > 0$. For the case when $\overline{M_1}' > 0$, setting $M_1 = \overline{M_1}'$ can satisfy both IC1 and PR1; if $\overline{M_1}' \leq 0$, then set $M_1 = 0$ as required by the non-negative constraint. Following the same checking process as in the previous case, this solution satisfies Constraints 4.1 and 4.3, and the setting of $T_i = \Delta_i$ is optimal to the government.

To conclude, in this case both types have liquidity problems and will not invest without protection. The optimal scheme $\{\pi(r_1), T_1, M_1\} = \{k, \Delta_1, \overline{M_1}'\}$ or $\{k, \Delta_1, 0\}$ and $\{\pi(r_2), T_2, M_2\} = \{k, \Delta_2, 0\}$ provides both types extra protection during the investment

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[119] Let $M_1 = 0$ and rearrange (4.25)', we have $\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}\pi(H) - \sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}\pi(H) \geq \sum_{i=1}^{\Delta_2-\Delta_1}\delta^{i-1}k$, or in short, $\delta^{\Delta_1}\pi(H) \geq k$.

period so that they can afford the opportunity cost. There is no protection to the inefficient type after the completion, however, depending on the relative profits from finishing the investment earlier (Δ_1) (which it has to forgo the extra protection $k-\pi(L)$ from taking the inefficient type's scheme) and finishing later (Δ_2), there will be no protection or protection up for a period of $\overline{M}_1'$ to the efficient type after the completion.

4.3.4 $\max\{\pi(L),k_2^*\}<k\le k_1^*$

Similar to the previous case, both types are liquidity constrained and will not invest in autarky. In addition, the inefficient type's future profits from the investment in this case are not sufficiently high either. By assumption of parameters, the cost limit constraints will be violated under the current profit. After setting $T_1=\Delta_1$ and $T_2=\Delta_2$, we have PR1 and PR2 constraints as equations (4.19) and (4.13). Different from the previous case is that if we set $M_2=0$, PR2 will be violated. Hence let us set $M_2=\overline{M}_2$ as defined in equation (4.14) and we know that $\overline{M}_2>0$.

The other constraints are the same as in the previous case, that is, we have equations (4.21) and (4.23) for IR1 and IR2, and equations (4.22) and (4.24) for IPR1 and IPR2. By applying Constraint 4.1, we can replace both IR constraints by IPR constraints. Since $T_1=\Delta_1$, we know that IC2 is not valid and IC1 is as equation (4.25). The only difference in this case is the first guess about M_2. As argued, we can firstly set $M_2=\overline{M}_2$ since M_2 must be at least $\overline{M}_2$ to satisfy PR2. Manipulating IPR2 (4.24) gives equation (4.17)', which will be valid with equality. To satisfy the cost limit constraint, let $\pi(r_1)=k$ which by equation (4.17)" implies that $\pi(r_2)<k$, but this will violate the cost limit constraint.

Instead, if we set $\pi(r_1)=\pi(r_2)=k$, (4.17)' will be satisfied with inequality. Substitute $\pi(r_i)=k$ and $M_2=\overline{M}_2$ into IC1 (4.25), and let $\overline{M}_1*$ be the smallest value to satisfy IC1. Rearranging IC1, we have:

$$\delta^{\Delta_1}P(\overline{M}_1*)-\sum_{i=1}^{\Delta_2-\Delta_1}\delta^{i-1}k \geq \delta^{\Delta_2-\Delta_1}[\delta^{\Delta_1}P(\overline{M}_2)]. \tag{4.26}$$

From equation (4.26), we have $\overline{M}_1*>\overline{M}_2$. To prove, suppose $\overline{M}_1*=\overline{M}_2$ and let Y:=$\delta^{\Delta_1}P(\overline{M}_1*)$. From (4.26), we have $(1-\delta^{\Delta_2-\Delta_1})Y=\sum_{i=1}^{\Delta_2-\Delta_1}\delta^{i-1}k$ $(=\frac{1-\delta^{\Delta_2-\Delta_1}}{1-\delta}k)$, which implies $Y=\frac{1}{1-\delta}k$. Now suppose $\overline{M}_1*>\overline{M}_2$, then we have $\delta^{\Delta_1}P(\overline{M}_2)=Y-\varsigma$, where ς is the utility difference for changing from $\overline{M}_1*$ to $\overline{M}_2$ (since $P(.)$ is increasing and $\overline{M}_1*>\overline{M}_2$, $\varsigma>0$). Depending on ς, the efficient type's rent could possibly decrease and still satisfy IC1. Therefore, it must be that $\overline{M}_1*>\overline{M}_2$. Since $\overline{M}_2>0$, it must be that $\overline{M}_1*>0$.

To sum up, in this case we have $\{\pi(r_1),T_1,M_1\}=\{k,\Delta_1,\overline{M}_1*\}$ and $\{\pi(r_2),T_2,M_2\}$ $=\{k,\Delta_2,\overline{\mathrm{M}}_2\}$. We can check that this solution satisfies all the constraints and $T_i=\Delta_i$ is optimal to the government. Since, in this case both types are liquidity constrained, the optimal scheme provides the during-investment protection to both types to pay the investment cost. Moreover, since the inefficient type is lacking in willingness to invest, there will be post-investment protection for a period of $\overline{\mathrm{M}}_2$. For the efficient type to mimic, it can benefit from the extra during-investment protection $\mathrm{k}-\pi(\mathrm{L})$ for $\Delta_2-\Delta_1$

period and the post-investment protection $\overline{M}_2$. Hence, the screening scheme has to give the efficient type longer post-investment protection to ensure incentive compatibility.

4.3.5 $\max\{\pi(L), k_1^*\} < k$

In this case, both types have liquidity problems and lack willingness to invest. By assumption, the cost limit constraints will be violated under the current profit. After setting $T_1 = \Delta_1$ and $T_2 = \Delta_2$, we have PR1 and PR2 as equations (4.19) and (4.13). The difference from the previous case is: both PR constraints will be violated if we set $M_1 = M_2 = 0$. Therefore, in addition to setting $M_2 = \overline{M}_2$ as defined in equation (4.14), we define $\overline{M}_1$ as described in equation (4.20). That is, $\overline{M}_1$ and $\overline{M}_2$ are the values that cause the PR constraints to be binding. The other constraints are the same as in the previous case. Let us temporarily set $M_2 = \overline{M}_2$. Substituting T_1, T_2, M_2 by $\Delta_1, \Delta_2, \overline{M}_2$, we know that IPR2 (equation (4.24)) and IC1 (equation (4.25)) will imply IR2 and IR1. We further guess equation (4.24) to be binding and set $\pi(r_1) = k$. As argued in the previous case, we know that $\pi(r_2) = k$ (the cost limit constraint is binding) will be higher than the value of $\pi(r_2)$ which makes equation (4.24) binding. Therefore, we set $\pi(r_1) = \pi(r_2) = k$. Substitute $\pi(r_i)$ into IC1 and denote $\bar{\bar{M}}_1$ as the smallest value to satisfy IC1, that is,

$$\sum_{i=1}^{\Delta_1} \delta^{i-1} k - \sum_{i=1}^{\Delta_1} \delta^{i-1} k + \delta^{\Delta_1} P(\bar{\bar{M}}_1) = \sum_{i=1}^{\Delta_2} \delta^{i-1} k - \sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2} \delta^{i-1} k + \delta^{\Delta_2} P(\overline{M}_2)$$

or equivalently,

$$\delta^{\Delta_1} P(\overline{\overline{M}}_1) - \sum_{i=1}^{\Delta_2-\Delta_1} \delta^{i-1} k = \delta^{\Delta_2-\Delta_1} [\delta^{\Delta_1} P(\overline{M}_2)]. \tag{4.26)'$$

First of all, following the same argument as in the previous case, we know that $\overline{\overline{M}}_1 > \overline{M}_2$. Next, it must be that $\overline{\overline{M}}_1 > \overline{M}_1$, since by the definition of $\overline{M}_2$, the right hand side of IC1 is higher than $\sum_{t=1}^{\infty} \delta^{t-1}\pi(L)$ (as $\sum_{i=\Delta_2-\Delta_1+1}^{\Delta_2} \delta^{t-1}k < \sum_{t=1}^{\Delta_2} \delta^{t-1}k$). It can also be checked that $\overline{\overline{M}}_1 = \overline{M}_1^*$. We can check that this solution satisfies all the constraints and $T_i = \Delta_i$ is optimal to the government.

To conclude, in this case both types have liquidity problems and lack willingness to invest. The optimal scheme $\{\pi(r_1), T_1, M_1\} = \{k, \Delta_1, \overline{\overline{M}}_1\}$ and $\{\pi(r_2), T_2, M_2\} = \{k, \Delta_2, \overline{\mathrm{M}}_2\}$ provides both types the during-investment protection to pay the investment cost. As in the previous case, by mimicking, the efficient type can have extra during-investment protection and the post-investment protection of period $\overline{\mathrm{M}}_2$. Since $\overline{\mathrm{M}}_1 < \overline{\mathrm{M}}_2$ (by the assumption of $\Delta_1 < \Delta_2$), although the efficient type also lacks willingness to invest, the mimicking benefit is still higher than its autarky utility. Hence we have the same solution as in the previous case.

Having derived the screening protection scheme, we now turn to the addressed question: "Will the government be better off offering a non-screening protection scheme?" Proposition 4.3 provides the answer:

Proposition 4.3

(1) The screening protection scheme could possibly coincide with the efficient scheme when only the inefficient type is lacking in investment willingness, or when there are only

liquidity problems; (2) The screening scheme is strictly better than the pooled scheme of the efficient type; however, whether it is better than the pooled scheme of the inefficient type is dependent on parameter values; (3) Whenever there is a liquidity problem, the efficient type's post-investment protection will be longer than that of the inefficient type; otherwise, the reverse result applies.

The welfare comparison for various schemes is routine and hence is presented in Appendix 4.2. The first part of the proposition can be seen from cases 4.3.1 and 4.3.3, where the screening schemes could possibly coincide with the efficient scheme. The intuition is: for both cases the efficient type has higher profits after completing the investment (if possible). Hence, depending on the size of future profits, the efficient type will not necessarily have the incentive to mimic the inefficient type, and hence we have the first result.

The argument for the second part of Proposition 4.3 is similar for each case, and hence we only explain case 4.3.1 here. From Appendix 4.2, we know that the welfare from the screening scheme is always higher than the pooled scheme of the efficient type, since there is a possibility $(1-\upsilon)$ that the investment is not completed in the latter. Recall that it is assumed optimal that the investment proceeds for both types. Whether the screening scheme is better than the pooled scheme of the inefficient type is dependent on the mixed effects of belief (υ) and the difference between types ($\Delta_2 - \Delta_1$). That is, if $\upsilon[\sum_{i=\Delta_1+1}^{\Delta_2}\delta^{i-1}(\pi(H)+S(H))-(1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1^0)]$ is higher than $(1-\upsilon)[\sum_{i=\Delta_1+1}^{\Delta_2}\delta^{i-1}(\pi(L)+S(L))$ $-(1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]$, then the screening scheme is better. For a higher belief or a smaller difference between two types, the screening scheme is more likely to be better than the pooled scheme of the inefficient type.

The intuition for the last part of the proposition is: whenever there is a liquidity problem, the efficient types mimicking incentive becomes higher, that is, type Δ_1 will have extra during-investment protection $k - \pi(L)$ for $\Delta_2 - \Delta_1$ more period by mimicking. If there is no post-investment protection for the inefficient type, the screening scheme could be the same as the efficient scheme; otherwise, the efficient type's post-investment protection is always higher, as it is not optimal to provide excessive protection during the investment period. When there is no liquidity problem, the efficient type's post-investment protection is always shorter, which is in contrast to most patent literature, for example Cornelli and Schankerman (1995), in asserting that a more efficient firm should be given a longer patent length to ensure incentive compatibility. Our model shows that this is true only when the target firm has a liquidity problem, otherwise, the efficient type's patent length can be shorter and still keep the incentive to finish earlier.

4.4 Conclusion and Further Research

Since various government interventions are still heavily applied by many developed and developing countries, a positive attitude is to provide a comprehensive guide to the design of protection scheme. More specifically, our model addresses two important but usually ignored dimensions: the protection form and the protection length. In the context of complete information, our model concludes that depending on parameters, the optimal protection could involve no protection, one-part protection or two-part protection. This result provides an explanation for the controversial empirical conclusions on protection effects. When there is incomplete information, we show that for some cases the screening always better than the pooled scheme of the efficient type. However, whether it is better than the pooled scheme of the inefficient type is dependent on parameters. More interestingly, our result suggests that when there is no liquidity problem, the efficient type's post-investment protection is shorter than the inefficient type. This is in contrast to the usual proposition in patent literature that a longer patent life should be given to the more efficient firm to ensure incentive compatibility.

As the model is simplified by considering only a monopoly firm, there is no discussion about the market structure effect. Further research can be extended to cover the interaction among firms. For example, granting the post-investment protection to a single firm, like a patent, could possibly save the incentive rent for the efficient type. Another important issue is the *time-inconsistency problem* in most government policies. As noted by Tornell (1994), "temporary protection has had to be renewed repeatedly or been transferred to permanent protection, if the government grants the protection in the present, it is unlikely that they will not grant it in the future." The present model can be extended by assuming an exogenous renewing rate, which may be determined by voting among parliament members from different interest groups[110]. As the producer's lobby power is limited by the single market profit, there will be some neutral voters whose attitude will depend on past protection experience. Therefore when protection is first introduced, we can expect an exogenous renewal rate in the future, and hence we can design a time-consistent protection scheme. However, the result is possibly similar to Tornell, i.e. the time consistent protection scheme could be too expensive to put in practice.

Appendix 4.1

[110] This belongs to another stream of protection analysis: political economy analysis.

Proof of Lemma 4.2: Firstly, for $T < \Delta$, at any time $t \leq T$, the protected firm's decision is to shirk, because any effort will not change the value at *T+1*, $V_{T+1} = \sum_{t=1}^{\infty} \delta^{t-1}\pi(L) = L$.

Secondly, for $T \geq \Delta$, the following is to decide at any $t \leq T$ how the target firm makes its decision between shirking and putting in effort, depending on history and the deadline. The proof is separated into two parts: for *t=* $T - \Delta + 1$ to T and for *t=1* to $T - \Delta$.

1. For *t=* $T - \Delta + 1$ to T, it is proved by strong induction that for an arbitrary number $\xi \leq \Delta - 1$, at time $t = T - \xi$, the protected firm will put in effort only when $n = \Delta - \xi - 1$. In the following, $\pi(L)$ and $r(\tau)$ are abbreviated as π and r for simplification . For $\xi = 0$, that is, $t = T$,

$$\text{if } n = \Delta - 1,\ V_T(n) = \max\{\pi + r + \delta V_{T+1}(\Delta - 1), \pi + r - k + \delta V_{T+1}(\Delta)\}$$
$$= \max\{\pi + r + \delta L, \pi + r - k + \delta H\}$$
$$= \pi + r - k + \delta H \quad \text{if} \quad \frac{k}{\delta} \leq [H - L].$$

$\frac{k}{\delta} \leq [H - L]$ is satisfied by Constraint 4.

$$\text{if } n \geq \Delta, \quad V_T(n) = \max\{\pi + r + \delta V_{T+1}(n), \pi + r - k + \delta V_{T+1}(n+1)\}$$
$$= \max\{\pi + r + \delta H, \pi + r - k + \delta H\}$$
$$= \pi + r + \delta H.$$
$$\text{if } n \leq \Delta - 2,\ V_T(n) = \max\{\pi + r + \delta V_{T+1}(n), \pi + r - k + \delta V_{T+1}(n+1)\}$$
$$= \max\{\pi + r + \delta L, \pi + r - k + \delta L\}$$
$$= \pi + r + \delta L.$$

Therefore, for $\xi = 0$ (i.e., *t=T*), the protected firm only puts in effort when $n = \Delta - 1$.

Next, let z be an arbitrary integer smaller than $\Delta - 1$. Suppose for every $j < z$, the protected firm's decision follows the rule

$$V_{T-j}(\Delta-j-1)=\max\{\pi+r+\delta V_{T-j+1}(\Delta-j-1),\pi+r-k+\delta V_{T-j+1}(\Delta-j)\}$$
$$=\pi+r-k+\delta V_{T-j+1}(\Delta-j),\qquad \text{if } \frac{(1+\delta+\ldots\delta^{j-2})}{\delta^{j-1}}k\leq[H-L].$$

and for all other number $n'\neq\Delta-j-1$,

$$V_{T-j}(n')=\max\{\pi+r+\delta V_{T-j+1}(n'),\pi+r-k+\delta V_{T-j+1}(n'+1)\}$$
$$=\pi+r+\delta V_{T-j+1}(n').$$

This supposition says that for any time $t=T-j$, if the protected firm has already put in investment for $\Delta-j-1$ times, it will find it optimal to put in effort in investment time *t*; otherwise, it will be better off with shirking.

For $\xi=z$, i.e. at time $t=T-z$, if $n=\Delta-z-1$, the firm's decision is :

$$V_{T-z}(\Delta-z-1)=\max\{\pi+r+\delta V_{T-z+1}(\Delta-z-1),\pi+r-k+\delta V_{T-z+1}(\Delta-z)\}$$

By supposition, this means:

$$V_{T-z}(\Delta-z-1)=\max\{\pi+r+\delta(\pi+r+\ldots\delta(\pi+r+\delta L)\ldots),$$
$$\pi+r-k+\delta(\pi+r-k+\delta(\ldots+\delta(\pi+r-k+\delta H\ldots))\}$$
$$=\max\{(\pi+r)(1+\delta+\ldots\delta^{z-2})+\delta^{z-1}L,.(\pi+r)(1+\delta+\ldots\delta^{z-2})-(1+\delta+\ldots\delta^{z-2})k+\delta^{z-1}H\}$$

Therefore, the protected firm will invest if $\frac{(1+\delta+\ldots\delta^{z-2})}{\delta^{z-1}}k\leq[H-L]$, which is satisfied under Constraint 4.3.

If $n>\Delta-z-1$, (note that $n+1>\Delta-z-1$ as well), by the supposition the protected firm will shirk till time $T-j$ (when $n=\Delta-j-1$), then start to put in effort and obtain the result of δH at *T+1*. The difference between investing and shirking at the moment is to choose to put in effort earlier or later. Since the former causes a higher discounted opportunity cost, shirking will be a better choice.

If $n < \Delta - z - 1$, if the protected firm chooses to work, causing opportunity cost of £k at the current stage, by supposition its next choices from *T-z+1* to *T* will be to shirk, and hence the effort status will remain $\Delta - z$. This will result in a final value of δL at *T+1*. However, if the protected firm chooses to shirk, without spending the investment cost, its next choices described by the supposition is to shirk from *T-z+1* to *T*. This will result in a final value of δL at time *T+1* as well. Thus, we can conclude that the best choice at $t = T - z$ is to shirk at this stage.

2. For *t=1* to $T - \Delta$, since the above discussion shows that at time $T - \Delta + 1$, the protected firm will put in effort only when *n=0*. It is argued that the protected firm will find it optimal to shirk from *t=1* till $T - \Delta$. Suppose it deviates once at time $s \le T - \Delta$, resulting in accumulated effort $n = 1$ at time $T - \Delta + 1$. The firm's value at time *s* is:

$$\pi + r - k + \delta(\pi + r + \ldots \delta(V_{T-\Delta+1}(1))\ldots)$$
$$= \sum_{i=s}^{T-\Delta} \delta^{i-1}(\pi + r) - k + \delta^{T-\Delta}[V_{T-\Delta+1}(1)] \qquad \text{(A4.1)}$$

The expected value to stick on shirking till time $T - \Delta$ is then

$$\pi + r + \delta(\pi + r + \ldots \delta(V_{T-\Delta+1}(0))\ldots)$$
$$= \sum_{i=s}^{T-\Delta} \delta^{i-1}(\pi + r) + \delta^{T-\Delta}[V_{T-\Delta+1}(0)] \qquad \text{(A4.2)}$$

The first part of the proof says that $V_{T-\Delta+1}(0) = \pi - k + \delta V_{T-\Delta+2}(1)$ and $V_{T-\Delta+1}(1) = \pi + \delta V_{T-\Delta+2}(1)$. Together with equation (A4.1) and (A4.2), we know that equation (A4.2) is greater than equation (A4.1), and therefore the protected firm will not deviate. *QED*

Appendix 4.2 Welfare effect comparison from different protection schemes

This appendix firstly summarises two different protection schemes: the efficient scheme (A) and the screening scheme (B). Next, the welfare effect (that is, the government's expected utility) is presented for: (1) the efficient protection scheme; (2) the screening protection scheme; (3) the pooled scheme of the efficient type; (4) the pooled scheme of the inefficient type.

4.3.1 $k_2^* < k \leq \min\{\pi(L), k_1^*\}$

A. The efficient protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{\pi(L), \Delta_1, 0\},\ \{\pi(r_2), T_2, M_2\} = \{\pi(L), \Delta_2, \overline{M}_2\}.$$

B. The screening protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{\pi(L), \Delta_1, \overline{M}_1^0\} \text{ or } \{\pi(L), \Delta_1, 0\}, \{\pi(r_2), T_2, M_2\} = \{\pi(L), \Delta_2, \overline{M}_2\}.$$

(1). Welfare for the efficient protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1}\delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2}\delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

(2). Welfare for the screening protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1}\delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1^0)]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2}\delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

,or the same as the efficient scheme.

(3). Welfare for the pooled scheme of the efficient type: $\{\pi(L), \Delta_1, 0\}$.

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(H)+S(H))] + (1-\upsilon)[\sum_{i=1}^{\infty} \delta^{i-1}(\pi(L)+S(L))]\}$$

(4). Welfare for the pooled scheme of the inefficient type: $\{\pi(L), \Delta_2, \overline{M}_2\}$.

$$\left\{\sum_{i=1}^{\Delta_2} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)\right\}$$

4.3.2 $k_1^* < k \leq \pi(L)$

A. The efficient protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{\pi(L), \Delta_1, \overline{M}_1\}, \ \{\pi(r_2), T_2, M_2\} = \{\pi(L), \Delta_2, \overline{M}_2\}.$$

B. The screening protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{\pi(L), \Delta_1, \tilde{\overline{M}}_1\}, \ \{\pi(r_2), T_2, M_2\} = \{\pi(L), \Delta_2, \overline{M}_2\}.$$

(1). Welfare for the efficient protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_1+1} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1)]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

(2). Welfare for the screening protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_1}\rho(\tilde{\overline{M}}_1)]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

(3). Welfare for the pooled scheme of the efficient type: $\{\pi(L), \Delta_1, \overline{M}_1\}$

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1)]$$
$$+(1-\upsilon)[\sum_{i=1}^{\infty} \delta^{i-1}(\pi(L)+S(L))]\}$$

(4). Welfare for the pooled scheme of the inefficient type: $\{\pi(L), \Delta_2, \overline{M}_2\}$

$$\left\{\sum_{i=1}^{\Delta_2} \delta^{i-1}(\pi(L)+S(L)) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)\right\}$$

4.3.3 $\pi(L) < k \le k_2^*$

A. The efficient protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{k, \Delta_1, 0\},\ \{\pi(r_2), T_2, M_2\} = \{k, \Delta_2, 0\}.$$

B. The screening protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{k, \Delta_1, \overline{M}_1'\} \text{ or } \{k, \Delta_1, 0\},\ \{\pi(r_2), T_2, M_2\} = \{k, \Delta_2, 0\}.$$

(1). Welfare for the efficient protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(k+S(k)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(H)+S(H))]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2} \delta^{i-1}(k+S(k)) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}(\pi(H)+S(H))]\}$$

(2). Welfare for the screening protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(k+S(k)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(H)+S(H)) - (1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1')]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2} \delta^{i-1}(k+S(k)) + \sum_{i=\Delta_2+1}^{\infty} \delta^{i-1}(\pi(H)+S(H))]\}$$

(3). Welfare for the pooled scheme of the efficient type: $\{k, \Delta_1, 0\}$

$$\{\upsilon[\sum_{i=1}^{\Delta_1} \delta^{i-1}(k+S(k)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(H)+S(H))]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_1} \delta^{i-1}(k+S(k)) + \sum_{i=\Delta_1+1}^{\infty} \delta^{i-1}(\pi(L)+S(L))]\}$$

(4). Welfare for the pooled scheme of the inefficient type: $\{k, \Delta_2, 0\}$

$$\left\{\sum_{i=1}^{\Delta_2}\delta^{i-1}(k+S(k))+\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))]\right\}$$

4.3.4 $\max\{\pi(L),k_2^*\}<k\le k_1^*$

A. The efficient protection scheme

$\{\pi(r_1),T_1,M_1\}=\{k,\Delta_1,0\}$, $\{\pi(r_2),T_2,M_2\}=\{k,\Delta_2,\overline{M}_2\}$.

B. The screening protection scheme

$\{\pi(r_1),T_1,M_1\}=\{k,\Delta_1,\overline{M}_1^*\}$, $\{\pi(r_2),T_2,M_2\}=\{k,\Delta_2,\overline{M}_2\}$.

(1). Welfare for the efficient protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1}\delta^{i-1}(k+S(k))+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2}\delta^{i-1}(k+S(k))+\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))-(1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

(2). Welfare for the screening protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1}\delta^{i-1}(\pi(L)+S(L))+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))-(1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1^*)]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2}\delta^{i-1}(\pi(L)+S(L))+\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))-(1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

(3). Welfare for the pooled scheme of the efficient type: $\{k,\Delta_1,0\}$

$$\{\upsilon[\sum_{i=1}^{\Delta_1}\delta^{i-1}(k+S(k))+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_1}\delta^{i-1}(k+S(k))+\sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(L)+S(L))]\}$$

(4). Welfare for the pooled scheme of the inefficient type: $\{k,\Delta_2,\overline{M}_2\}$

$$\left\{\sum_{i=1}^{\Delta_2}\delta^{i-1}(k+S(k))+\sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H)+S(H))-(1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)\right\}$$

4.3.5 $\max\{\pi(L), k_1^*\} < k$

A. The efficient protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{k, \Delta_1, \overline{M}_1\},\ \{\pi(r_2), T_2, M_2\} = \{k, \Delta_2, \overline{\mathrm{M}}_2\}.$$

B. The screening protection scheme

$$\{\pi(r_1), T_1, M_1\} = \{k, \Delta_1, \overline{\overline{M}}_1\},\ \{\pi(r_2), T_2, M_2\} = \{k, \Delta_2, \overline{\mathrm{M}}_2\}.$$

(1). Welfare for the efficient protection scheme

$$\{\upsilon[\sum_{i=1}^{\Delta_1}\delta^{i-1}(k + S(r_1)) + \sum_{i=\Delta_1+1}^{\infty}\delta^{i-1}(\pi(H) + S(H)) - (1+\lambda)\delta^{\Delta_1}\rho(\overline{M}_1)]$$
$$+(1-\upsilon)[\sum_{i=1}^{\Delta_2}\delta^{i-1}(\pi(L) + S(L)) + \sum_{i=\Delta_2+1}^{\infty}\delta^{i-1}(\pi(H) + S(H)) - (1+\lambda)\delta^{\Delta_2}\rho(\overline{M}_2)]\}$$

(2)~(4) are the same as in the previous case.

5. Conclusion

In closing, this chapter summarises the contributions of the thesis, including the findings for the addressed issues and some notes on mechanism design. Then we look at some applications of the three models.

This thesis consists of three individual models of research and development, addressing issues on technology adoption, funding contracts and protection schemes. The first model is motivated by the inconsistency of empirical results and theoretical models regarding the "firm size effects" upon the timing of adoption. To be specific, the empirical results show that large firms could adopt a certain technology earlier or later than small firms; however, previous theoretical models always assert that large firms will adopt earlier. Chapter 2 proposes a two-stage, endogenous learning, Stackelberg model to analyse firms' adoption decisions towards an innovation with uncertain profitability. It is shown that in a pure strategy equilibrium, the large firm may or may not tacitly delay its adoption to capture the information advantage, depending on production cost and belief parameters. In the comparative statics, we have an interesting conclusion concerning the after-adoption market concentration, that is, even for a successful innovation, if the large firm adopts earlier, the market concentration will decrease in the first stage and then return to the pre-adoption level in the second stage. The welfare analysis provides a justification for government intervention in firms' adoption decisions.

The second model is motivated by the fact that although more and more resources (personnel and money) have been devoted to R&D activities, there is little theoretical discussion regarding R&D funding issues. Chapter 3 provides a guideline to a rich class of funding contracts, especially for time-consuming projects confronted with moral hazard problems. As a benchmark of comparison, we first derive the optimal contract for a long-term project with only a moral hazard problem. The optimal contract form happens to be a multi-stage version of cost-plus-fixed-fee contracts, where the optimal fixed fee refers to the agent's shirking benefit from the contract. After considering the agent's private information, we derive the screening contracts for both discrete and continuous type settings. The screening contracts assign no efficiency loss to either type, which is in contrast to the usual conclusion in the literature. Moreover, within the continuous setting, we show that the principal will adopt a cut-off strategy in funding, and the cut-off point is affected by the fact that inefficient types (types greater than the cut-off point) will take the contract and shirk all through the funding period. Hence, the principal will fund the project for a shorter period in the presence of an opportunism problem. Furthermore, the discussion of the optimal auctioning contract shows that the principal will benefit from the competition among agents in two ways: First, the project is more likely to be completed by an efficient type under an auction. Second, competition reduces the incentive rent for the efficient type as he is less likely to mimic the inefficient type who might have less chance to win the auction, however, this rent reduction will vary with the difference between the two types. Comparing the optimal auction with a second-price auction, we show that bidding the principal's reservation price (rather than truth-bidding) will be the bidders' dominant strategies, and neither the revenue equivalence theorem nor the separation property will hold. Finally, when neither of the players has private information about the time needed for completion, we show that a longer funding period will actually induce more shirking, and the optimal funding length is determined as the point where the agent's shirking period is driven down to zero. With an additional assumption that neither of the involved parties can anticipate the contract renewal, we show that the lock-in effect persists under some constraints and a sequence of short-term contracts is preferable to a long-term contract.

The third model is motivated by the observation that various government interventions (protection) are still used by many developed and developing countries, but the empirical results do not always support the positive effect of protection. Considering a time-consuming investment, Chapter 4 first derives the optimal protection form, which consists of two often seen types of protection: during-investment and post-investment protection. When there is only a moral hazard problem, we show that the optimal protection scheme varies with the target firm's investment ability and willingness, and it hence could involve no protection, one-part protection or two-part protection according to the cost and revenue environments. This result suggests that not all cases fit into the same protection form, and the efficient protection should take into account the target firm's investment ability as well as investment willingness. In the context of incomplete information, we show that (1) The screening protection scheme could possibly coincide with the efficient scheme when only the inefficient type is lacking in investment willingness, or when there are only liquidity problems; (2) The screening scheme is strictly better than the pooled scheme of the efficient type; however, whether it is better than the pooled scheme of the inefficient type is dependent on parameter values; (3) Whenever there is a liquidity problem, the efficient type's post-investment protection will be longer than that of the inefficient type; otherwise, the reverse result applies.

Chapters 3 and 4 provide the following insights into mechanism design: Firstly, as a consequence of assuming unobservable effort and binary outcomes (success or failure), there will be no trade off between efficiency and rent extraction in the solution. In other words, the principal's fear that the whole project value will disappear in case of any shortage in funding has led the principal not to distort the production efficiency in the optimal mechanism. Furthermore, since there is no efficiency loss to any type, the solution will also be renegotiation proof after the revelation of the true value. However, there is a limitation in this setting, that is, throughout the thesis we are contented with the assumption that the principal can commit to not extend the scheme in the future. The time inconsistency problem has been a major concern in policy design, and although we have seen some discussion of the time inconsistency problem at the end of Section 3.6 and Chapter 4, this issue ought to be discussed in more detail. Secondly, the time-consuming (or equivalently limited liability) assumption draws our attention to long-term mechanism design, and to complete the object, the mechanism needs to make sure that the agent's effort decisions are best responses at each point within the mechanism. In terms of timing, although the principal's decision is to precommit to a mechanism (hence it does not belong to the dynamic context), the agent's effort decision will be dynamic. Thirdly, in Chapter 4 we consider the target firm's future profits after the completion of the investment, and as a result, the optimal compensation scheme is affected by this consideration. As we have seen the difference this makes in an example from the patent literature, we should be more cautious in providing incentive schemes when the agent's future value is taken into account.

We now consider possible applications of the three models. Firstly in the adoption model, technology adoption is basically an irreversible investment, and hence the model can be applied to various investment cases, such as the launch of McDonald into the Chinese market. The uncertainty associated with the investment may come from consumers' preferences, and natural or bureaucratic environments. Secondly, a natural and important application of the long-term mechanism design is to the area of regulatory economics. More specifically, instead of using a constant project value or constant welfare change, we can replace the value by a market demand function, and thus discuss issues of price or quality regulation. This is directly relevant to Chapter 4, as we can interpret different levels of protection rates in the forms of regulated prices. Moreover, the discussion of multiple agents will be more important as the regulated markets are usually oligopolies. Further research can also analyse the setting of two-sided private information, risk aversion, correlated types and (when there is an auction) collusion among bidders. Finally, we can extend the protection model to discuss the effects of interest groups. That is, since policies are usually decided by voting in the Parliament and the producer's lobby power will be limited by the single market profit, there will be some neutral voters whose attitude will depend on past protection experience. Hence when protection is first introduced, we can expect an exogenous renewal rate in the future, and therefore we can design a time-consistent protection scheme. But as explained, the time consistent protection scheme could be too expensive to put in practice.

References

Adams, W. J. (1970), Firm size and research activity, *Quarterly Journal of Economics* 84: 386-409.

Adams, W. J and Dirlam, J. B. (1966), Big steel, invention and innovation, *Quarterly Journal of Economics* 80: 167-189.

Addison, J. T. and Chilton, J. B. (1997), Nondisclosure as a contract remedy: explaining the advance notice puzzle, *Journal of Labor Economics*: 15(**1**), 143-64.

Aghion, P. and Tirole, J. (1994), The management of innovation, *Quarterly Journal of Economics* 109(**4**): 1185-1209.

Baily, M. (1974), Wages and employment under uncertain demand, *Review of Economic Studies* 41: 37-50.

Baldwin, R. E. and Krugman, P. R. (1988), Market access and international competition: a simulation study of 16 K random access memories, in R. Feenstra, Ed,. *Empirical Methods for International Trade*, 171-97.

Baldwin, W. L. and Scott, J. T. (1987), *Market Structure and Technological Change*, Harwood Academic Publishers, Switzerland.

Baldwin, R. (1969), The case against infant-industry tariff protection, *Journal of Political Economy* 77(**3**): 295-305.

Barcena-Ruiz, J. C. and Espinosa, M. P. (1996), Long-term or short-term managerial incentive contracts, *Journal of Economics and Management Strategy* 5(**3**): 343-59.

Becker, P. (1996), Defence Department sets R&D strategy, *Mechanical Engineering* 118(**12**): 38.

Bodman, P. M. and Devereux, M. B. (1993), A dynamic model of trade union contract duration, *Queen's Institute for Economic Research Discussion Paper* 882: 18.

Cantor, R. (1987), Work effort and contract length, *Economica* 55: 243-53.

Chemmanur, T. J. and John, K. (1996), Optimal incorporation, structure of debt contracts, and limited-recourse project financing, *Journal of Financial Intermediation* 5(**4**): 372-408.

Chiappori, P. A., Macho, I., Rey, P. and Salanie, B. (1994), Repeated moral hazard: the role of memory, commitment and the access to credit markets, *European Economic Review* 38(**8**): 1527-53.

Corden, M. (1974), *Trade Policy and Economic Welfare*, Oxford: Clarendon Press.

Cornelli, F. and Schankerman, M. (1995), Optimal patent renewals, Mimeo.

Cox, J. C., Isaac, R. M., Cech, P. and Conn, D. (1996), Moral hazard and adverse selection in procurement contracting, *Games and Economic Behavior* 17(**2**): 147-76.

Dasgupta, P., Hammond, P. and Maskin, E. (1979), The implementation of social choice rules: some general results on incentive compatibility, *Review of Economic Studies* 46(**2**): 185-216.

Daugherty, P. J., Germain, R. and Dorge, C. (1995), Predicting EDI technology adoption in logistics management: the influence of context and structure, *Logistics and Transportation Review* 31(**4**): 309-24.

David, P. (1969), A contribution of the theory of diffusion, memorandum 71, Stanford Centre of Economic Research in Economic Growth.

David, P. (1975), *Technical Choice, Innovation and Economic Growth,* Cambridge University Press.

Davies, S. W. (1979), *The Diffusion of Process Innovations*, Cambridge University Press.

Dye, R. (1985), Optimal length of contracts, *International Economic Review* 26(**1**): 251-70.

Freemantle, M. (1997), Turbulence roils German science, *Chemical and Engineering News* 75(**6**): 42-45.

Frey, B. (1993), Shirking and work morale? the impact of regulating. *European Economic Review* 37(**8**): 523-32.

Fudengberg, D. and Tirole, J. (1985), Preemption rent equalization in the adoption of new technology, *Review of Economic Studies* 52(**3**): 383-401.

Fudengberg, D. and Tirole, J. (1991), *Game Theory*, MIT Press.

Fung, K. C. (1994), Review of: empirical studies of strategic trade policy, *Journal of Economic Literature* 32(**4**): 1891-93.

Gallini, N. T. (1992), Patent policy and costly imitation, *Rand Journal of Economics* 23: 52-63.

Gaspar, V. and Leite, A. P. N. (1989/1990), Selection bias induced cost overruns, *Information Economics and Policy* 4: 175-187.

Gibbard, A. (1973), Manipulation of voting schemes: a general result. *Econometrica* 41(**4**): 567-601.

Gibbons, R. (1992), *A Primer in Game Theory*, Harvester Wheatsheaf.

Gilbert, R. J. and Newberry, D. M. G. (1982), Preemptive patenting and the persistence of monopoly, *American Economic Review* 72: 514-26.

Gilbert, R. J. and Shapiro, C. (1990), Optimal patent length and breadth, *Rand Journal of Economics* 21: 109-112.

Gorden, D. (1974), A neo-classical theory of Keynesian unemployment, *Economic Inquiry* 12: 431-59.

Green, J. and Laffont, J.-J. (1977), Characterisation of satisfactory mechanisms for the revelation of preferences for public goods. *Econometrica* 45: 427-438.

Green, G., Sunding, D., Eilerman, D. and Parker, D. (1996), Explaining irrigation technology choices: a microparameter approach, *American Journal of Agriculture Economics* 78(**4**): 1064-72.

Grossman, S. and Hart, O. (1986), The costs and benefits of ownership: a theory of lateral and vertical integration, *Journal of Political Economy* 94(**4**): 691-719.

Grossman, G. M. and Horn, H. (1988), Infant-industry protection reconsidered: the case of informational barriers to entry, *Quarterly Journal of Economics* 103(**4**): 767-87.

Hannan, T. H. and McDowell, J. M. (1990), The impact of technology adoption on market structure, *Review of Economics and Statistics* 72(**1**): 164-48.

Harrigan, J. (1993), OECD imports and trade barriers in 1983, *Journal of International Economics* 35: 91-111.

Harris, M. and Holmstrom, B. (1987), On the duration of agreements, *International Economic Review* 28(**2**): 389-406.

Harris, M. and Raviv, A. (1982), Allocation mechanisms and the design of auction, *Econometrica* 49(**6**): 1477-99.

Harris, C. and Vickers, J. (1987), Racing with uncertainty, *Review of Economic Studies* 54(**1**): 1-21.

Harsanyi, J. C. (1967), Games with incomplete information played by "bayesian" players, I-III, *Management Science* 14(3): 159-182.

Hart, O. and Holmstrom, B. (1987), The theory of contracts, *Advances in Economic Theory fifth world congress*, Edited by Bewley, T. F., Econometric Society Monographs No 12.

Head K (1994), Infant industry protection in the steel rail industry, *Journal of International Economics* 37: 141-165.

Hendricks, K. (1992), Reputations in the adoption of a new technology, *International Journal of Industrial Organisation* 10: 663-77.

Jesen, R. (1982), Adoption and diffusion of an innovation of uncertain profitability, *Journal of Economic Theory* 27: 182-193.

Jesen, R. (1988), Information capacity and innovation adoption, *International Journal of Industrial Organisation* 6: 335-350.

Jung, C., Krutilla, K. and Boyd, R. (1996), Incentives for advanced pollution abatement technology at the industry level: an evaluation of policy alternatives, *Journal of Environmental Economics and Management* 30(1): 95-111.

Kapur, S. (1992), Technological diffusion with endogenous learning, *University of Cambridge Economic Theory Discussion Paper.*

Katz, M. L. and Shapiro, C. (1985), On the licensing of innovation. *Rand Journal of Economics* 16:504-20.

Klemperer, P. (1990), How broad should the scope of patent protection be? *Rand Journal of Economics* 21: 113-130.

Kreps, P. M. (1990), *A Course in Microeconomics Theory*, Harvester Wheatsheaf.

Krueger, A. O. and Tuncer, B. (1982), An empirical test of the infant industry argument, *American Economic Review*, 72(5): 1142-52.

Krugman, P. and Smith, A. (1994), *Empirical Studies of Strategic trade Policy*, Chicago: University of Chicago Press.

Laffont, J. J. and Tirole, J. (1993), *A Theory of Incentives in Procurement and Regulation*, MIT Press, Cambridge and London.

Laffont, J. J. and Tirole, J. (1987), Auctioning incentive contract, *Journal of Political Economy* 95: 921-937.

Lee, T. and Wilde, L. L. (1980), Market structure and innovation: a reformulation, *Quarterly Journal of Economics* 94: 429-36.

Levin, D. and Smith, J. L. (1996), Optimal reservation prices in auction, *Economic Journal* 106: 1271-83.

Lucas, Jr., R. E. (1971), Optimal management of a research and development project, *Management Science* 17: 679-97.

Luzio, E. and Greenstein, S. (1995), Measuring the performance of a protected infant industry: the case of Brazilian microcomputers, *Review of Economic Statistics*: 622-33.

Mansfield, E. (1961), Technical change and the rate of imitation, *Econometrica* 29: 741-766.

Mansfield, E. (1963), Size of firm, market structure, and innovation, *Journal of Political Economy* 71: 556-576.

Mansfield, E. (1967), *Econometric Studies of Industrial Research and Technological Innovation*, New York.

Maskin, E. S. and Riley, J. G. (1984), Optimal auctions with risk averse buyers, *Econometrica* 52: 1473-1518.

Matthews, S. (1983), Selling to risk-averse buyers with unobservable tastes, *Journal of Economic Theory* 30: 370-400.

Matsuyama, K. (1990), Perfect equilibria in a trade liberalization game, *American Economic Review* 80(**3**): 480-92.

McCardle, K. F. (1985), Information acquisition and the adoption of new technology, *Management Science* 34: 1372-1389.

McAfee, R. P. and McMillan, J. (1987), Auctions and bidding, *Journal of Economic Literature* 25(**2**): 699-738.

Milgrom, P. R. (1987), Auction theory, Edited by Bewley, T. F., *Advances in Economic Theory: Fifth World Congress*. Econometric Society Monographs Series 12: 1-32, Cambridge University Press.

Milgrom, P. R. and Weber, R. J. (1982), A theory of auctions and competitive bidding, *Econometrica* 50(**5**): 1089-1122.

Miyagiwa, K. and Ohno, Y. (1995), Closing the technology gap under protection, *American Economic Review* 85(**4**): 755-70.

Myerson, R. B. (1979), Incentive compatibility and the bargaining problem, *Econometrica* 47(**1**): 61-73.

Myerson, R. B. (1981), Optimal auction design, *Mathematical Operations Research* 6: 58-73.

Nabseth, L. (1973), The diffusion of innovation in Swedish industry, *Science and Technology in Economic Growth*, Edited by Williams, B. R., Macmillan.

Nabseth, L. and Ray, G. F. (1974), *The Diffusion of New Industrial Process: An International Studies*, Cambridge University Press.

Nooteboom, B. (1993), Adoption, firm size and risk of implementation, *Economics of Innovation and New Technology* 2: 203-216.

Nooteboom, B. (1994), Innovation and diffusion in small firms: theory and evidence, *Small Business Economics* 6: 327-47.

Nordhaus, W. (1969), *Invention, Growth and Welfare*, MIT press, Cambridge.

Oster, S. (1982), The diffusion of innovation among steel firms: the basic oxygen furnace, *Bell Journal of Economics* 13: 45-56.

Piccione, M. and Tan, G. (1996), Cost-reducing investment, optimal procurement and implementation by auctions, *International Economic Review* 37(3): 663-85.

Quirk, J. P. and Terasawa, K. (1984), The winner's curse and cost estimation bias in pioneer projects, *Social Science Working Papers* 512: 25.

Reinganum, J. F. (1982), A dynamic game of R and D: patent protection and competitive behaviour, *Econometrica* 50: 671-85.

Reinganum, J. F. (1983), Technology adoption under imperfect information, *Bell Journal of Economics* 14(1): 57-69.

Reinganum, J. F.(1989), The timing of innovation: research, development, and diffusion, Chapter 14, *Handbook of Industrial Organisation*, 1, Edited by Schmalensee, R. and Willig, R. D., North Holland.

Rey, P., and Salanie, B. (1996), On the value of commitment with asymmetric information, *Econometrica* 64(6): 1395-1414.

Riley, J. G. and Sameulson, W. F. (1981), Optimal auctions, *American Economic Review* 71: 381-92.

Sadanand, V. (1989), Endogenous diffusion of technology, *International Journal of Industrial Organisation* 7: 471-487.

Safadi, R. and Laird, S. (1996), The Uruguay round agreements: impact on developing countries, *World Development* 24(7): 1223-42.

Scherer, F. M. (1964). *The Weapons Acquisition Process Economic Incentives*, Harvard University Press, Boston.

Schumpeter, J. (1943), *Capitalism, Socialism and Democracy*, Unwin University Books, London.

Singh, A. K. (1997), Layoffs and underwritten rights offers, *Journal of Financial Economics* 43(1): 105-30.

Solow, R. (1957), Technical change and the aggregate production function, *Review of Economics and Statistics* 39: 312-320.

Staiger, R. W. and Tabellini, G. (1987), Discretionary trade policy and excessive protection, *American Economic Review* 77(5): 823-837.

Stenbacka, L. R. (1991), Mergers and investments in cost reduction with private information, *International Journal of Industrial Organisation* 9: 397-405.

Stoneman, P. (1983), *The Economic Analysis of Technological Change*, Oxford University Press.

Stoneman, P. (1986), Technological diffusion: the viewpoint of economic theory, *Ricerche Economiche* 40(4): 585-606.

Stoneman, P. (1995), *Handbook of The Economics of Innovation and Technological Change*, Edited by Stoneman, P., Blackwell.

Sumrall, J. B. Jr. (1982), Diffusion of the basic oxygen furnace in the US steel industry, *Journal of Industrial Economics* 30: 421-447.

Tirole, J. (1988), *The Theory of Industrial Organization*, The MIT Press.

Toivanen, O., Diederen, P. and Stoneman, P. (1995), Investment, search and competition: innovation adoption as a real option, *Warwick Business School Working Paper*.

Tornell, A. (1994), On the Ineffectiveness of made-to-measure projectionist programs, *International Trade and Trade Policy*, Edited by Helpman E. and Razin, A., The MIT Press.

Varian, H. L. (1987), *Intermediate Microeconomics: a Modern Approach*, Norton, London.

Vickrey, W. (1961), Counterspeculation, auctions, and competitive sealed tenders, *Journal of Finance* 16: 8-37.

Vousden, N. (1990), *The Economics of Trade Protection*, Cambridge University Press.

Wright, D. J. (1995), Permanent versus temporary infant industry assistance, *Manchester School of Economic and Social Studies* 63(4): 426-34.