SUPPLIER PERFORMANCE MANAGEMENT:

A BEHAVIORAL STUDY

by

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To my parents,

my siblings,

and my beloved wife.

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This dissertation studies supplier performance management and explores practical approaches to improve supplier performance. We use the theoretical model prediction as a benchmark and we test our analytical findings using behavioral experiment. The result typically is a strategy or policy recommendation to OEM in order to induce desirable performance of its suppliers. This dissertation analyzes three important problems in supplier performance management in three essays, Chapter 2 to 4. Below, we briefly summarize each problem:

In the first essay, Chapter 2, we study the coordination problem in a setting with multiple contractors working on a project. Specifically, we analyze the risk-sharing contract in which the payment to the contractors depending on the minimum effort among the contractors. Following the conventional wisdom of minimum effort games, we show that the contractors may fail to coordinate their efforts. For a project with parallel tasks, there exist multiple Pareto-ranked equilibria, where all contractors exert the same efforts, and the lowest equilibrium efforts are observed when the contractors play the secure equilibrium. To mitigate this coordination failure,

we propose an information feedback policy, and show that the contractors' efforts in the secure equilibrium increase in the information feedback frequency. Therefore, the OEM may induce the contractors to increase their effort by providing feedback with frequency that increases linearly in the number of contractors. To test our analytical findings, we conducted a behavioral experiment that varies the feedback frequency and the number of contractors. Our experimental result confirms that a higher information feedback frequency leads to a better project outcome and a higher contractors' payoff. In addition, coordination among contractors gets more difficult with more contractors working on the project and in turn results in a lower contractors' payoff.

In the second essay, Chapter 3, we considered supplier's scorecard system which is a tool for manufacturers to track supplier performance. We investigate the effectiveness of two approaches for a manufacturer to incentivize desirable performance of suppliers based on the evaluation of their scorecard, the Absolute and Relative approaches. Under the Absolute approach, the manufacturer incentivizes the supplier if the supplier achieves a prespecified targeted score. Under the Relative approach, the manufacturer incentivizes suppliers based on the suppliers' scorecard ranking in the supplier base. We consider a two-period supplier-manufacturer contractual agreement where the manufacturer evaluates and reviews supplier performance (acceptable or unacceptable) at each period. Supplier performance outcome at each period is determined by its binary effort decision (high or low) where acceptable performance is more likely to be resulted from exerting the costly high effort than from exerting low effort. We derive the optimal targeted score and the optimal reward scheme that results in the highest supplier performance under the Absolute and Relative approach respectively. We derive that under the Relative approach allocating the whole reward pie to the supplier with the highest overall score maximizes supplier performance. Comparing the suppliers' resultant performance under the two approaches, we characterize conditions on which each approach is preferable. To test our theoretical findings, we conducted a human-subject experiment that varies the reward as well as the incentive approach. We observe that subjects over-provide effort compared to the theoretical model benchmark under both approaches. We further observe that subjects exert more effort under the Relative approach compared to the Absolute approach indicating that in the Relative approach, competition motivates suppliers to provide more effort. The result shows that the manufacturer incurs less cost for each unit of effort it receives from the supplier under the Relative approach compared to the Absolute approach.

Finally, in the third essay, Chapter 4, we study a long-term contractual agreement following the Absolute approach. We derive that supplier's optimal effort decision at each period follows a threshold strategy where exerting high effort is optimal when its score is between a lower and upper threshold, and exerting low effort is optimal otherwise. We experimentally test the theoretical findings using human-subject in the role of supplier. The result shows that subjects overexert effort compared to the theoretical model prediction. The data are explained well by a behavioral model that incorporates three behavioral concepts; joy of wining, perceived probability and bounded rationality. The result suggests that subjects gain psychological utility as they reach the target and win the reward. Second, subjects' perceived probability follows a function that is shaped like an inverted "S". We observe that subjects overweight small probability and underweight large probability. Finally, the behavioral model estimation shows that subjects make noisy decisions. The result suggests that likelihood of a decision increases in the expected utility of the decision.

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CHAPTER 1

INTRODUCTION

This dissertation analyzes three important problems in supplier performance management in three chapters. In this chapter, we start describing research problems studied in Chapters 2–4, discuss the relevant literature and summarize our contributions.

1.1. Coordination in Projects under Risk-Sharing Contracts

1.1.1. Overview

Manufacturing a complex product, such as a commercial airliner, is a complicated project with multiple parallel and sequential tasks that are outsourced to a large number of contractors. In these projects, the original equipment manufacturer (OEM) earns profit after all contractors have completed their tasks and the entire project has been completed. To improve cash flow, OEMs sometimes use a risk-sharing contract which stipulates that all contractors are paid only after all other contractors complete their tasks. The contract is feasible if the OEM possesses a strong bargaining power in the market. For example, when Boeing developed the Boeing 787 Dreamliner, this type of contract was used (Tang and Zimmerman 2009). More generally, the risk-sharing contract can be used when the project owner's payoff is determined by the minimum effort among the contractors. For example, when an OEM launches a new product, the total available quantity is determined by the minimum proportionated quantity among the components needed for assembly and the payment may be contingent upon this total quantity (Hu and Qi 2017). In milk supply chain in developing countries, the quality of the total mixed milk depends on the worst quality of the milk collected from each milk farmer, and the payment depending on the mixed quality is also used (Mu et al. 2015).

In contrast to a conventional contract in which the contractors are paid contingent upon their own efforts, the risk-sharing contract allows the risk of poorly-performed projects to be distributed between the OEM and the contractors. Taking the Dreamliner manufacturing for example, if a contractor delays its own progress, it may also delay the progress of the entire project, so the OEM does not pay any of the contractors during the delay. Forced to share in the cost of delay, the contractors should be motivated to avoid delaying their own tasks, and the OEM should enjoy the financial benefit from delayed payment to the contractors.

While the above intuition generally holds, a complication arises when contractors work on their tasks in parallel. In this case, if one contractor is known to procrastinate, then all other contractors will not benefit from completing their tasks early, so if delaying decreases their costs, all contracts are better off if they delay. This coordination issue may negatively affect the outcome of the project and even negate the financial benefits that the OEM may derive from the contract. In fact, among many factors, the coordination issue in the risk-sharing contract also contributes to the 40-month delay in the Boeing 787 project (Greising and Johnsson 2007).

Motivated by these observations, we investigate the following research questions regarding projects under the risk-sharing contracts. First, what are the potential project outcomes under the risk-sharing contract? Second, how can the OEM coordinate the efforts among the contractors to improve the project outcome? To answer these questions, we first build a game-theoretical model to understand the contractors’ equilibrium behavior, and then conduct a behavioral experiment to test the analytical predictions.

We consider a project with multiple symmetric and parallel tasks, with each task assigned to one contractor under the risk-sharing contract. We assume that contractors can exert costly effort in completing their assigned task, which determines their respective task outcome such as the completion time, final delivery quantity, or the quality of the product supplied. The contractors decide on their effort level simultaneously and without observing the decisions of the other contractors. The project outcome is determined by the minimum effort among all contractors, which in turn determines the payment from the OEM to each contractor. The contractor's payoff is the payment from the OEM minus the cost of efforts in completing its own task. We assume that the payment from the OEM increases concavely in the minimum effort among the contractors due to the diminishing marginal return of the minimum effort on the project outcome. On the other hand, each contractor's own costs increase linearly with its own effort. Therefore, there exists a maximum beneficial effort level under which the marginal revenue from earlier project completion is higher than the marginal cost of this effort.

We derive the equilibrium effort of the contractors and show that there exist multiple equilibria that are Pareto ranked. In any equilibrium, the contractors exert the same effort. When all the contractors exert the least effort, the equilibrium is the least efficient one, but it is the *secure equilibrium* (also called risk-dominant equilibrium) because it emerges when the contractor chooses the effort that would maximize its payoff in the worst possible scenario. Although which equilibrium actually emerges depends on the equilibrium selection rule, which is an empirical question that we investigate as well, we observe that the coordination failure in which all the contractors choose low efforts may occur as an inherent property of the risk-sharing contract. Moreover, the equilibrium structure of this game is the same, regardless of whether the contractors make their effort decisions for the entire project up-front, or over time, as long as the contractors are not informed about one another's progress.

In order to improve coordination among contractors, we introduce the risk-sharing contract with periodic *information feedback*. Contractors exert effort over time, and periodically decide on their effort levels. At the start of each decision period, the contracts can observe the progress of all other contractors before deciding on their own effort level for the current period. Same as in the base model, the project outcome depends on the minimum total efforts among all contractors.

We derive a subgame perfect secure equilibrium in the form of a *secure equilibrium threshold strategy*. Under this strategy, in each period, contractors compare their own cumulative effort to a threshold. If a contractor's cumulative effort is below the threshold, it will exert as much effort as possible to reach the threshold; if a contractor's cumulative effort is above the threshold, it will exert the lowest allowable effort. The threshold evaluates the maximum total effort each contractor can reach by the end of horizon under the secure equilibrium. Intuitively, providing information feedback motivates contractors who have fallen behind to catch up with the leading contractors, even in the most conservative case in which all contractors follow the secure equilibrium.

We show that information feedback is effective in motivating suppliers to exert more efforts under the secure equilibrium. We also show that the equilibrium total effort increases in the number of information feedback periods, and there exists a minimum number of such feedback periods that leads to the maximum beneficial effort, i.e., the effort level under which the marginal revenue is higher than the marginal cost of additional effort. Interestingly, this minimum number of information feedback periods increases linearly in the number of contractors, indicating that the coordination becomes increasingly difficult when there are more contractors working on the project. We also check the robustness of the findings in two scenarios, one in which there is random noise in the task outcome and the other in which the effort cost is convexly increasing. In both scenarios, we find information feedback is effective in improving coordination among the contractors under mild conditions.

We test the analytical model prediction in the laboratory using a behavioral experiment that varies the information feedback frequency and the number of contractors. We observe that the average minimum effort selected in treatments with no feedback is significantly lower than the maximum beneficial effort, and the coordination improves as more feedback opportunities are provided. These evidences attest to the effectiveness of the information feedback policy. We also observe that, consistent with our analytical model, an increase in the number of contractors leads to a lower total effort. Finally, the contractors' payoff weakly increases in the number of feedbacks and decreases in the number of contractors.

1.1.2. Literature Review

Our work is closely related to the behavioral economics literature on coordination games, in particular, the minimum-effort game in behavioral economics literature. The seminal work of Van Huyck et al. (1990) shows that there exist multiple Pareto-ranked equilibria in the minimum effort game and raises the issue of equilibrium selection in coordination games. They find that the secure equilibrium, in which all players exert the lowest effort, emerges in the laboratory. For an early review on equilibrium selection, we refer the readers to Harsanyi and Selten (1988) and Harsanyi (1995). To explain the subjects' behavior in the standard coordination game setting, Crawford (1995) present a learning model where the subject's effort choice in each period is linearly related to the previous periods effort, and Anderson et al. (2001) use a logit equilibrium framework and show that increasing the effort cost or the group size reduces the equilibrium effort. Camerer and Ho (1999) introduce experience-weighted attraction learning framework to explain decision making in normal form games including the coordination game.

The standard coordination game used in behavioral economics is static—that is, players make their effort decisions up-front. Since the initial Van Huyck et al. (1990) study, various interventions have been explored to help improve coordination among players under the standard coordination game setting. These interventions can be organized in two categories based on whether the subjects repeatedly interact with other subjects or not: in the single-shot setting subjects are randomly matched after each round while in the repeated-interaction setting, subjects play the game repeatedly throughout the experiment. Examples of literature studying the single-shot coordination game include pre-game communication (Cooper et al. 1992), varying the cost of efforts (Goeree and Holt 2005), social identity (Chen and Chen 2011), natural identity (Chen et al. 2014), and setting non-binding goals (Fan and Gómez-Miñambres 2016, Weber 2006).

Examples of literature studying the coordination games with repeated interactions among the players include entry competition for the right to play the coordination game (Van Huyck et al. 1993), the use of entry fees (Cachon and Camerer 1996), varying group sizes (Knez and Camerer 1994), effect of prior experiences in other games on coordination (Devetag 2005), varying incentives and the availability of information from previous rounds (Brandts and Cooper 2006), gradual growth of group size (Weber 2006), varying numbers of repeated interactions (Berninghaus and Ehrhart 1998), competition between two groups of subjects (Riechmann and Weimann 2008), and flexibility in dissolving relationships in repeated interactions (Hyndman and Honhon 2015). In addition to the repeated interactions, Deck and Nikiforakis (2012) consider allowing monitoring of other subjects' effort adjustment in a round. In their experiment, a subject is able to adjust its efforts up or down in a round while the cost only depends on the final decision, making the monitoring a form of cheap talk. For a literature review on the coordination failure and other ways to engineer coordination in the standard coordination game in laboratory, we refer the readers to Devetag and Ortmann (2007).

Our work differs from the aforementioned behavioral economics studies in two ways. First, we consider a *dynamic* decision-making process instead of the one-shot decision making in the standard coordination game in all the interventions above. This is because a project is a process with a relatively long duration, contractors exert efforts over time rather than in one shot, and their payoffs are determined by the *cumulative* efforts rather than one of the efforts decisions. In our base model and treatment, subjects periodically make effort decisions without observing others' efforts until the end of the project. The experimental result showing the coordination failure is in line with the literature on the single-shot coordination game, in particular, Goeree and Holt (2005), confirming the robustness of the coordination failure results in the new setting when the decisions are made dynamically but not observable to others.

Second and more importantly, the new intervention in our work—providing *within round* information feedback by enforcing communication among the contractors—should be distinguished from the *between round* information feedback from repeated interactions. In all our treatments, subjects are randomly assigned to a project in each round *without* observing the history of their group members in the past projects. Besides this main difference, our work is also different from Deck and Nikiforakis (2012) in that the efforts are cumulative in a round following the practice of a project in our setting, making the game not a cheap talk as in their experiment.

Our study is also related to literature on project management. Project management is the planning, scheduling, and directing of the certain amount of resources to achieve the project objective, i.e., producing deliverables such as products or services. For a comprehensive review on project management, we refer the readers to Tavares (2002) and Williams (2003). Among different areas in the project management literature, our study is closely related to the *contract management*. Contract management is the process of aligning the objective of contractors with that of the project through contractual agreement between the OEM and contractors (Kerzner 2013, PMI 2013). While the incentive contract is an important component of project management, the literature is relatively sparse. Bayiz and Corbett (2005) design optimal contracts to motivate subcontractors' efforts when the efforts are not observable and therefore may result in moral hazard. Chen et al. (2015) consider a general form of incentive contacts for sequential tasks and show that the performance of such contracts is better than a fixed price contract. Chen and Lee (2016) propose a delivery-schedule-based contract in a project supply chain such that contractors' payment is split to a down payment and a balance paid at the maximum of supplier's actual delivery time and a due date set by the OEM, and show that this contract coordinates the channel. Rahmani et al. (2015) consider a project with co-production between a client and vendor and show that simple contracts such as the fixed-fee and time-and-material contracts improve collaboration.

To the best of our knowledge, Kwon et al. (2010) and Xu and Zhao (2012) are the only two pioneer studies of the risk-sharing contract (also referred to as the delayed payment contract) when the tasks are in parallel. Kwon et al. (2010) compare the effectiveness of delayed and non-delayed payment contracts and show that when suppliers' work rates are adjustable, the manufacturer is better off under the delayed payment contract in a project with either a small revenue or a large number of suppliers. Xu and Zhao (2012) propose the use of the fair-sharing contract to align the incentive of the contractors working on the project governed by the delayed payment. In both studies, it is assumed that the Pareto dominant equilibrium effort is selected in the presence of multiple equilibria. In our work, we consider different equilibrium selection rules which result in selections of different equilibrium efforts. For example, when the secure equilibrium is selected, contractors may exert minimum efforts. We then show that a mitigation strategy featuring information feedback improves coordination of contractors' efforts in theory. Finally, we conduct a controlled laboratory experiment and empirically test the equilibrium selection rule as well as the effectiveness of the proposed mitigation strategy.

1.2. Incentivizing Suppliers Using Scorecard: A Behavioral Study

1.2.1. Overview

Using *supplier's scorecard* to manage supplier performance has been reported from many different companies such as Home Depot (Bowman 2006), Boeing, and Wal-Mart and P&G (Choice 2012); All design their supplier's scorecard system to meet their business needs. Supplier's scorecard is a tool that keeps track of supplier performance based on key performance indicators. Each indicator carries a separate weight and the supplier overall score is computed based on the weighted average of the performance indicators. Metalcraft is a supplier to large automakers that demand zero defects (Kulp et al. 2004). To comply with this business need, Metalcraft rates its supplier performance based on quality, timing and delivery and categorizes the supplier into three color coded threshold: Green, Yellow, and Red when the supplier quality performance rating is higher than 70, between 50 and 69, and below 50 respectively. Metalcraft uses this rating to avoid outsourcing to Red suppliers and Red suppliers are placed in the No-Quote list.

Sun Microsystem, a leading supplier of enterprise computing products, rates its electronic components suppliers based on four indicators: quality, lead time/delivery/flexibility, technology, and support (Farlow et al. 1996). Each of these indicators contribute up to 30, 30, 25, and 15 points toward the total 100 possible points respectively. Sun updates and reviews suppliers' score with each of its suppliers quarterly to keep them on the track. Sun uses the scorecard to influence supplier behavior; Sun's Tier-1 suppliers are awarded 10-40% of major Sun's outsourcing program. According to Dick Allen, Sun's global commodity manager, "competition keeps people honest".

To manufacturers the main use of scorecard is to incentivize desirable performance of its suppliers. We refer to the approaches used by Metalcraft and Sun Microsystem as *Absolute* and *Relative* approach respectively. Under the Absolute approach a supplier with an overall score below a prespecified score becomes ineligible to win a future business. Under the Relative approach the manufacturer incentivizes the supplier with a higher score with a larger size of the future business.

Under both Absolute or Relative approaches, a higher overall score is incentivized by the manufacturer but through a different mechanism. To comply with manufacturer's requirement and in turn gain these incentives, suppliers need to exert costly effort. Suppliers exert costly effort to improve their performance through the contract life span while the scorecard system periodically evaluates and reviews suppliers' performance. We investigate the effectiveness of these approaches in incentivizing the desirable behavior of suppliers. We therefore formally state the following research questions. How do suppliers make effort decision under each approach? Does suppliers' effort decision changes over time depending on the reviewed score by the manufacturer? Which approach can incentivize a higher supplier performance and therefore is preferred by the manufacturer? To address these questions, we first build a game-theoretical model to understand the suppliers' equilibrium effort decision, and then conduct a behavioral experiment to test the theoretical predictions.

We develop a game-theoretical model to study supplier performance under the Absolute approach by considering a manufacturer who outsources a product to a supplier over a two-period contract. The manufacturer inspects supplier delivered good at each period and informs the supplier about its performance (acceptable or unacceptable). Supplier performance at each period is determined by its binary effort decision, high or low; exerting high effort is more expensive than exerting low effort, but it provides a higher chance to pass the manufacturer's inspection. At the end of the contract the manufacturer rewards the supplier if its final score is above a prespecified target. The manufacturer objective is to set a target that results in a highest supplier performance. We first derive supplier's optimal effort decision as a function of the targeted score and then derive manufacturer's optimal target that maximizes supplier effort. We show that under the optimal target, supplier's optimal effort increases in the reward value and decreases in the per-unit cost of high effort.

To study the impact of the Relative approach on suppliers' performance we consider a setting similar to the Absolute approach with two main differences. First, here the manufacturer outsources a product to two suppliers. Second, the manufacturer rewards supplier with a higher final score with larger slice of the reward pie and share the reward pie between the two suppliers in case of tie. Under the Relative approach the manufacturer objective is to set a reward scheme that results in the highest supplier performance. We derive supplier equilibrium action as a function of reward scheme. We show that suppliers high effort proportion increases in the difference between suppliers' reward. Using this result, we derive the optimal reward scheme. Under the optimal reward scheme, the manufacturer rewards the whole reward pie to the supplier with the highest final score. We showed that under the optimal reward scheme, the high effort proportion increases in the reward value and decreases in the per-unit cost high effort.

Comparing the resultant suppliers' optimal effort decision under both approaches, we derive a threshold such that the Absolute approach is preferred to the Relative approach when the *relative reward* is less than the threshold and Relative approach is preferred otherwise. Relative reward is defined as the reward divided by the per-unit cost of high effort and shows that how large the reward is compared to the per-unit cost of high effort.

We test the theoretical model prediction in the laboratory using a behavioral experiment that varies the reward as well as the rewarding approach. We observe that under both approaches suppliers over-provide effort compared to the theoretical model prediction. The experimental results show that in contrast to the theoretical prediction the Relative approach leads to a higher supplier performance even when the relative reward is less than the theoretical threshold. We observe that suppliers are more likely to follow the theoretical model prediction when the theoretical prediction is to exert high effort compared to the case when the theoretical prediction is to exert low effort. Additionally, suppliers are less prone to follow the theoretical model prediction under Absolute approach compared to the Relative approach. These two factors behind deviations from the theoretical model prediction result in a higher effort observed in the Relative approach treatments compared to the Absolute approach treatments. We show that suppliers on average earn less for each unit of high effort they exert under the Relative approach compared to the Absolute approach.

1.2.2. Literature Review

Many research projects on supplier performance management study supplier incentive contract, which is an important aspect of the problem that we are studying. Davis and Hyndman (2017) study supplier performance management in a two-tier supply chain where the retailer offers fixed payment at the beginning of contract and a bonus if a high-quality product is delivered. The supplier then decides on its effort which can be high, or low. The product is of high quality with probability one when the supplier exerts high effort and low quality with probability less than one if the supplier exerts low effort. They study how the monetary incentives affect overall quality and supply chain efficiency. Lee and Li (2017) study three approaches in managing quality of supplier's delivery: Investing directly in suppliers to improve its performance, incentivizing supplier quality-improvement effort, and inspecting quality of incoming parts from the supplier. Benjaafar et al. (2007) investigate the effect of *supplier selection* and *supplier allocation* on the suppliers' performance. Under the supplier selection, the manufacturer allocates all demand to one supplier and the probability that a supplier is selected increases in the service level that the supplier commits. Under the supplier allocation, the manufacturer allocates a proportion of demand to each supplier such that the proportion allocated to a supplier increases in the service level that the supplier commits. They showed that the supplier selection policy motivates supplier to provide a higher service quality. In their setting suppliers commit to provide service level and suppliers' service level is observable to the manufacturer, however in our setting suppliers' effort is not observable by the manufacturer and manufacturer evaluate supplier performance to make the allocation decision. Li et al. (2013) investigate supplier relationship management by considering infinite repeated interaction between a manufacturer and two suppliers. They characterize the optimal contract that motivates better performance of suppliers. Baiman et al. (2000) analyze a setting where supplier effort to improve the quality of the product and the manufacturers' inspection effort are unobservable and derive the conditions of contractibility (e.g., on internal or external failures) to implement the first-best and second-best outcomes. (Cachon and Zhang 2007) investigate the impact of several performance-based allocation policies that assign incoming jobs to two strategic servers who choose their processing rates and faster service is costly. Katok et al. (2008) consider a finite-horizon service level agreement that supplier gains bonus when achieves or exceeds a targeted service level. They investigate the impact of the length of review period and the bonus size on the supplier stocking level. They observed that longer review period are more effective than shorter review period in motivating higher stocking level by the supplier. (Klotz and Chatterjee 1995) considered a dual-sourcing model where each supplier receives a fixed share of total production volume and compete on the rest in a second-price auction. For a literature review on supplier selection problem, we refer the readers to (Elmaghraby 2000, Ware et al. 2012).

Our work differs from the aforementioned studies in that we investigate the impact of competition on suppliers' performance and we compared the result with suppliers' performance under the Absolute approach. In our setting, we also considered a dynamic decision-making where suppliers are making decision about provision of effort in two periods. Moreover, our work sheds light on human behavior under competition and Absolute approach and goes beyond the theoretical model prediction.

Several studies have reported overexertion of effort in the rank-based tournaments and contests. These studies have shown that the subjects gain some extra psychological utility when they win, and this extra utility of wining (joy of wining) leads to overexertion of effort compared to the theoretical model prediction. Chen et al. (2011) study asymmetric tournaments where contestants have different levels of initial endowments. Through experimental analysis they showed that contestants overexert effort due to the psychological utility from winning and losing in the tournaments. Lim (2010) apply behavioral economics model to study the impact of social aversion on the contestants' performance. They consider a contest where contestants are ranked based on their outcome and all contestants ranked lower than a threshold share a monetary prize. They experimentally show that contestants overexert effort in contests with higher proportion of winner to losers if the contest outcome is publicly announced. Chen and Lim (2013) study contestants' performance in individual-based and the team-based contest. In the individual-based contest, each contestant competes over a prize against all the other contestants and the contestant with the higher outcomes wins the prize. In the team-based contest, all contestants in the same team competes over the prize against the other teams and prize is split equally among the teammates with higher total outcomes. Their observation from the experimental study show that overexertion of effort in the team-based contests is driven by the contestants' aversion of letting their team down. Kräkel (2008) study the impact of psychological emotion from winning and losing in tournaments and they show that the psychological utility from winning and losing in a tournament can explain the overexertion of effort in tournaments. Charness et al. (2013) experimentally investigate the status-seeking behavior of contestants in tournaments with possibility of sabotaging contestants' performance in the second stage. They show contestants overexert effort when relative performance is publicly announced. They also observe that ranking feedback motivate contestants to sabotage others' performance in the second stage. Gill et al. (2015) investigate the effect of rank feedback on subject performance in a real-effort experiment and they show that subject over-provide effort when rank feedback is available. Moreover, they observe that high and low rank subjects in each round overexert effort in the next round. (Sheremeta 2010) experimentally studies multi-stage and one-stage contests and analyzes the non-monetary utility of wining in a four-player contest. He shows that even in a contest with prize of zero subjects exert effort higher than zero. His analysis shows that the impact of non-monetary utility of wining on subjects' behavior is significant. Price and Sheremeta (2011) study the impact of per-period or per-treatments endowment on contests. They show that the non-monetary utility of wining can explain the overexertion of effort in their experiment. Berger and Pope (2011) empirically investigate the impact of halftime performance on wining in contests. They observe that being slightly behind in halftime can increase the chance of winning. Buser (2016) studies the impact of early outcome of a competition on subjects' future performance. considers a two-stage game where the first stage consists of a two-person real-task tournament followed by public announcement of subjects' rank, and in the second stage subjects decide on the performance target in the second stage. The higher the target, the higher the reward. Subjects who did not achieve the target gain nothing. They observe that losers set a more challenging target. For a literature review on the experimental study of contests, all-pay auctions and tournaments, we refer the readers to (Dechenaux et al. 2015).

Our work differs from the aforementioned papers in two ways. First, we consider a dynamic setting where suppliers make decisions on their effort in two periods rather that a single shot decision making process. This new setting is coming from the application of supplier scorecard that the manufacturer review supplier performance after each period. Second, in our work we compare the supplier performance under Relative approach with supplier performance under the Absolute approach.

Our research is also related to the literature on *moral hazard*. Moral hazard studies investigate principal-agent problem where the outcome of agents' conditional on their decisions are uncertain and therefore not observable by the principal. Moral hazard problem is common in insurance, labor contracting, and anywhere that decision making responsibility is assigned to an independent agent. To the best of our knowledge Zeckhauser (1970) is the first who formally modeled the moral hazard problem. He investigates the impact of insurance policies on insurant expenditure where the payment to the insurant is proportional to its health expenditure and the insurant select medical expenditure that best suits himself. Bolton et al. (2004) investigate the impact of feedback mechanism moral hazard problem associated with trading among strangers in market with online feedback. They experimentally study three markets, market with feedback, market without feedback as well as market with repeated interaction among same individuals. They observe that feedback improves efficiency in the whole market. Douthit et al. (2012) study the impact of pre-contract cheap talk in principal agent problem where the agent decides on the production effort. they experimentally observed that pre-communication is effective in mitigating moral hazard and therefore subjects exert higher effort. Lazear and Rosen (1981) study agent's investment of effort under piece rates contracts and compensation based on rank order tournaments. They showed that the worker investment effort is identical under both compensation scheme when workers are risk neutral. Mishra and Prasad (2004) study the impact of delegating of pricing authority to the salesforce under information asymmetry. They derive that the centralized pricing where the firm sets the price performs at least as good as pricing delegation when the agent private information can be revealed to the firm through contracting.

In contrast with the existing literature, our study investigates agent's effort decisions in response to remaining time of the contract and its score at any given period. We consider this dynamic setting as in the supplier scorecard setting suppliers decide on their provision of effort over time after manufacturer reviews their score. We are contributing to this area by comparing the suppliers' performance under two approaches: Relative approach and Absolute approach.

1.3. How Supplier Scorecards Affect Procurement Quality: A Behavioral Study

1.3.1. Overview

Most manufacturing firms sign long-term contracts with their key suppliers. In the automotive industry, for example, the length of long-term supply contracts averages about 1.5 years with a standard deviation of 2.5 years (Sako and Helper 1998). Long-term supply contracts are by their nature incomplete, meaning that the buyer cannot perfectly dictate the suppliers' actions during the life span of the contract, and instead must rely on monitoring the outcome of those actions, often through regular inspections. Such regular monitoring of supplier performance provides timely and constructive feedback to keep suppliers on track. Typically, supplier performance management is accomplished by utilizing the supplier scorecard. The supplier scorecard is a tool for manufacturers to track supplier performance based on performance attributes such as delivery reliability, product quality, and customer service.

The main use of supplier scorecard for a manufacturer is to regulate its sourcing decisions by generating a *Non-Quote List* (Kulp et al. 2004). A supplier will be included into a Non-Quote List if its overall score falls below a pre-specified target. In such a case, the supplier will become ineligible for winning the buying firm's new contracts, and the buyer often declines to renew an ongoing contract. Therefore, the manufacturer can use the scorecard system to incentivize desirable behaviors of suppliers by linking their performance with their chance to gain renewed contracts.

We analyze supplier performance within the context of supplier scorecard system. We consider a supplier who exerts effort during the life span of a long-term contract, while the scorecard system periodically evaluates its performance. Supplier's score at each period stochastically depends on supplier's effort decision; where exerting a higher effort results in a higher chance of achieving satisfactory performance. The supplier receives a reward if its overall score exceeds a prespecified targeted score; otherwise, it loses the reward. We show that at each period the supplier "*gives up*" (i.e., stopping to aggressively pursue contract reward by exerting the costly effort) if his current score is too low to give him a good chance of meeting the buyer's targeted score, and he "*takes a break*" (i.e., economically saving effort cost while maintaining high contract reward probability) if his current score is so high that he can risk losing the score in the current period.

To test our theoretical findings, we conducted behavioral experiments that varies the targeted score and the success probability of high effort on supplier performance. Our experiments show that the average effort is significantly above the optimal effort predicted by the theoretical model. We establish a behavioral model to analyze this systematic deviation from the theoretical prediction. The behavioral model provides a psychologically plausible explanation for the higher effort observed in the experiment compared with the optimal effort predicted by the theoretical model. Incorporating various behavioral factors and comparing the behavioral models, we show that subject's psychological utility of wining results in overexertion of effort.

As my contribution to this research project is in establishing and analyzing the behavioral model, and additionally the theoretical model setting is similar to the Absolute approach, here we focus on analyzing the experimental observation.

CHAPTER 2

COORDINATION IN PROJECT UNDER-SHARING CONTRACT

In what follows, we introduce our model in Section 2.1. We then describe the experiment design, hypotheses, and results in Sections 2.2 and 2.3. We finally check the robustness of our analytical findings in three extensions in Section 2.4. All proofs can be found in Appendix A. All experimental instructions are provided in Appendix B, and additional results on the experimental outcomes are provided in Appendix C.

2.1. Analytical Model

We develop a game theoretic model to analyze a project under the risk-sharing contract — the payment to the contractors depends on the minimum effort among all contractors. There are G parallel and homogeneous tasks and each task is assigned to a risk-neutral contractor. Each contractor determines the amount of effort (such as full-time equivalent labor hours) for the assigned task. We denote contractor i's total effort by e_i and the per-unit cost of effort by C. The feasible effort is within a range between the lowest effort $\underline{e}$ and the highest effort $\bar{e}$. The lowest effort $\underline{e}$ defines a contractor's minimal committed effort on the task, which can be 0. The highest effort $\bar{e}$ reflects the contractor's limited resource in exerting effort. The project output is determined by the least effort among all the contractors.[1] We denote the effort vector of all contractors by $\boldsymbol{e} = (e_1, \dots, e_G)$ and the least effort among all the contractors by $P(\boldsymbol{e}) \triangleq \min_{i=1,..,G}\{e_i\}$.

[1] For example, in the airliner manufacturing case, the higher effort exerted by a contractor, the sooner the contractor can complete the assigned task. However, it will have to wait until the last contractor completes its task before getting paid. The completion time of the last task is determined by the least effort among all the contractors.

The contractor's payoff $\pi_i(\boldsymbol{e})$ is the revenue generated from the payment of the OEM, $R\left(P(\boldsymbol{e})\right)$, minus the cost of efforts in completing its own task, Ce_i. We assume the contractor's revenue increases in the least effort among all the contractors, i.e., $\frac{\partial R}{\partial P(\boldsymbol{e})} \geq 0$, while there exists diminishing marginal return of effort, i.e., $\frac{\partial^2 R}{\partial P(\boldsymbol{e})^2} \leq 0$. It follows that there exists a maximum beneficial effort e^* beyond which the marginal revenue of increasing the least effort by one unit is lower than the marginal cost, i.e., $e^* = \inf\left\{e \colon \frac{\partial R}{\partial P(\boldsymbol{e})}\Big|_{P(\boldsymbol{e}) = e} \leq C, e \in \left[\underline{e}, \bar{e}\right]\right\}$. The payoff function is summarized as follows. All the parameters and payoff functions are common knowledge.

$$\pi_i(\boldsymbol{e}) = R\big(P(\boldsymbol{e})\big) - Ce_i, \qquad e_i \in \left[\underline{e}, \bar{e}\right], \qquad i = 1, \ldots, G, \tag{1}$$

From the perspective of contractor i, the least effort among all the contractors is the minimum of its own exerted effort e_i and the least effort among the others, denoted by e_{-i}. That is, we can alternatively denote the least effort among all contractors by $P(\boldsymbol{e}) = \min\{e_i, e_{-i}\}$. It follows that contractor i's payoff depends on the minimum of its own effort and the least effort among the others. When the contractor decides its effort level, it should take the least effort among other contractors into consideration. We show the contractors' equilibrium effort in Proposition 2.1. All the proofs are relegated to the Appendix A.

Proposition 2.1. *There exist multiple equilibria in which all contractors exert the same effort between the lowest effort* $\underline{e}$ *and the maximum beneficial effort* e^*.

The multiple equilibria are inherent in the contractual structure of the risk-sharing contract. First of all, we observe that none of the contractors have incentive to exert any effort beyond e^* as it is dominated by exerting e^*. In what follows, we consider the scenario where all contractors exert an effort between $\underline{e}$ and e^*. Recall that contractors' payment is determined by the least effort among all the contractors. Take contractor i for example, given the least effort among all other contractors e_{-i}, this contractor does not have incentive to exert a different effort. If the contractor increases its effort beyond e_{-i}, it pays a higher cost while the payment, determined by the least effort of others, remains the same. Therefore, the revenue remains constant as the project output is still determined by e_{-i} while incurring a higher cost, leading to a loss in profit. On the other hand, if the contractor lowers its effort below e_{-i}, it will become the contractor who determines the project output. In this case, although the contractor has decreased its cost, the payment from the project decreases even more, leading to a loss in its profit. By symmetry, all contractors prefer to exert the same effort as the least effort among others.

The existence of multiple equilibria reveals an inherent possibility for contractors to fail to coordinate their efforts under the risk-sharing contract. We note that these equilibria are Pareto ranked, among which all contractors exerting the lowest effort $\underline{e}$ leads to the lowest payoff for the contractors while exerting the maximum beneficial effort e^* leads to the highest payoff for the contractors. Among all the equilibria, the OEM prefers the contractors to coordinate on the most beneficial effort e^*. In fact, this is one reason why Boeing adopted the risk-sharing contract in the first place. However, due to the special incentive structure of the risk-sharing contract, in equilibrium the contractors may exert an effort level which is significantly lower than e^*. Therefore, it is important to investigate which equilibrium emerges as the focal one.

There are two special equilibria among these multiple equilibria: the *payoff-dominant* equilibrium and the *secure* equilibrium (Van Huyck et al. 1990). The *payoff-dominant* equilibrium is an equilibrium which is not strictly Pareto dominated by any other equilibria. Therefore, everyone exerting the maximum beneficial effort e^* is the payoff-dominant equilibrium because all contractors obtain the highest payoff in this equilibrium. On the other hand, the *secure* equilibrium is an equilibrium in which all contractors are assured to achieve the highest payoff in the worst case. Since there exist multiple equilibria, contractors are uncertain about the strategies of the other contractors, and therefore may find it risky to exert any effort above the lowest effort. To mitigate the risk, a contractor may adopt the maxmin strategy which maximizes the worst-case payoff, resulting in the secure equilibrium identified in Corollary 2.1 below.

Corollary 2.1. *There exists a unique secure equilibrium in which all contractors exert the lowest effort* $\underline{e}$.

Exerting the lowest effort $\underline{e}$ assures contractor i of achieving the highest payoff in the worst case when all other contractors exert $\underline{e}$. In this scenario, exerting any effort above $\underline{e}$ is costly to contractor i and does not affect the revenue contractor i receives because the completion time of the project is determined by the least effort of other contractors, $\underline{e}$. Therefore, contractor $i's$ payoff is maximized at the lowest effort $\underline{e}$.

Finally, we consider the contractors' effort level as if it is a one-shot decision for ease of exposition in the discussions above. In the scenario where the effort is exerted in a sequence of periods, the equilibrium outcomes remain the same when the contractors cannot observe each other's progress. In that case, there still exist multiple Pareto-ranked equilibria regarding the total effort of contractors and exerting the lowest effort is the secure equilibrium as shown in Proposition 2.1 and Corollary 2.1. In the next Section, we introduce a simple policy that results in a higher equilibrium effort when the effort is exerted over time, even in the conservative scenario in which the secure equilibrium is selected.

2.1.1. The Risk-Sharing Contracts with Information Feedback

The model setting is similar to the base model, except that the contractors simultaneously decide their efforts in each of the N periods with *information feedback* on the progress of all contractors. The *information feedback* includes all contractors' efforts in the previous periods and therefore their cumulative efforts up to the current period. In each period, contractors simultaneously decide their own effort after obtaining the information feedback and incur a unit cost of C. We denote the effort of contractor i in period n by $e_{i,n}$, its cumulative effort at the beginning of period n by $\hat{e}_{\mathrm{i},n-1} \triangleq \sum_{t=1}^{n-1} e_{i,t}$, and the cumulative effort vector of all contractors by $\hat{\boldsymbol{e}}_{\boldsymbol{n}} \triangleq (\hat{e}_{1,n}, \dots, \hat{e}_{G,n})$. We also note that the feasible effort in any period is between the lowest effort $\underline{e}_N \triangleq \frac{\underline{e}}{N}$ and the highest effort $\bar{e}_N \triangleq \frac{\bar{e}}{N}$ and therefore a contractor's total effort in the N periods is between $\underline{e}$ and $\bar{e}$, which are the lowest and highest efforts respectively in the base model. The completion time of a contractor's own task is determined by its total effort. The higher the contractor's total effort is, the sooner it finishes its task. The project completion time is determined by the completion time of the last task, which in turn is determined by the least total effort among all the contractors. We denote the least total effort among all the contractors by $P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) \triangleq \min_{i=1,..,G}\{\hat{e}_{\mathrm{i},N}\}$.

Contractor i's payoff is determined by the revenue, which depends on the least total effort among all contractors, and its cost, which depends on its own total effort. Therefore, we have contractor i's payoff $\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}})$ as follows.

$$\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) = R\big(P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})\big) - C\hat{e}_{i,N} \tag{2}$$

In what follows, we analyze the impact of information feedback by considering the most conservative case in which the contractors adopt the maxmin rule and select the secure equilibrium, which leads to the longest delay in the absence of information feedback as shown in Corollary 1. Intuitively, if the information feedback improves coordination even in this most conservative case, it should lead to an even higher coordination levels in other cases. We also note that there exist multiple effort paths which lead to the same total effort for contractor i in this multi-period game. To simplify the analysis, in what follows, we focus on the set of threshold strategies such that contractors exert as much effort as they can to reach a threshold in any period. We also define $x^+ \triangleq \max\{x, 0\}$. Formally a threshold strategy is defined as follows.

Definition 2.1 (The threshold strategy.) *For any period n, given cumulative efforts $\hat{\boldsymbol{e}}_{n-1}$, the action of contractor i following a threshold T_n is*

$$e_{i,n} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T_n - \hat{e}_{i,n-1}\right)^+\right\} \tag{3}$$

Intuitively, the threshold strategy stipulates that contractor i should only exert the lowest effort $\underline{e}_N$ if its cumulative effort is larger than the target threshold, i.e., $\hat{e}_{i,n-1} \geq T_n$; otherwise it should exert as much effort as possible to reach the threshold. The following lemma characterizes the subgame perfect secure equilibrium threshold strategy in period n, where $e^*_{i,n}$ denotes contractor i's equilibrium action and $\hat{\boldsymbol{e}}^*_N = \left(\hat{e}^*_{1,N}, \dots, \hat{e}^*_{G,N}\right)$ denotes the equilibrium total effort vector of all contractors.

Lemma 2.1 (Subgame perfect secure equilibrium threshold strategy.) *Relabel the contractor with the* i^{th} *smallest cumulative effort at the beginning of period* n *as contractor* i. *For any period* n, *given cumulative efforts* $\hat{\boldsymbol{e}}_{n-1}$, *the subgame perfect secure equilibrium action of contractor i is*

$$e_{i,n}^{*} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T_n^{*} - \hat{e}_{i,n-1}\right)^{+}\right\}, \tag{4}$$

where $T_n^{*} = \min\{T_n^1, T_n^2\}$ *is the subgame perfect secure equilibrium threshold with* $T_n^1 \triangleq \min_{j=1,\ldots,\min\{G,N-n+2\}} \left(\hat{e}_{j,n-1} + (N-n+2-j)\left(\bar{e}_N - \underline{e}_N\right)\right)$ *and* $T_n^2 \triangleq e^{*} - (N-n+1)\underline{e}_N$. *Moreover, the resulting equilibrium least total effort is* $P(\hat{\boldsymbol{e}}_N^{*}) = (N-n+1)\underline{e}_N + T_n^{*}$.

We illustrate the intuition of the subgame perfect secure equilibrium threshold strategy by considering a project with two contractors, i.e., $G = 2$. As it is trivial to show that the contractors should never exert an effort above the maximum beneficial effort e^{*}, we focus on discussing the case where the total effort is not limited by e^{*}, i.e., $T_n^{*} = T_n^1$.

At the beginning of the last period, assume that contractor 2 has exerted more efforts than contractor 1, i.e., $\hat{e}_{2,N-1} \geq \hat{e}_{1,N-1}$. As a contractor's payoff is determined by the minimum of the two total efforts and its own total effort, in any equilibrium, the two total efforts should be as close as possible if not equal. Among all possible equilibria, the worst case for contractor 1 occurs when contractor 2 exerts the lowest effort $\underline{e}_N$. In this case contractor 1's payoff increases in its effort if its total effort is less than $\hat{e}_{2,N-1} + \underline{e}_N$ and decreases in its effort otherwise. It is immediate that the best action for contractor 1 is to exert the highest effort to reach $\hat{e}_{2,N-1} + \underline{e}_N$, i.e., $e_{1,N}^{*} = \min\left\{\bar{e}_N, \hat{e}_{2,N-1} - \hat{e}_{1,N-1} + \underline{e}_N\right\}$. On the other hand, the worst case for contractor 2 occurs when contractor 1 exerts $e^*_{1,N}$, and the corresponding best response for contractor 2 is to exert $e^*_{2,N} = \underline{e}_N$. This is the equilibrium satisfying the maxmin criteria, as both contractors maximize their payoff considering the worst possible case. In short, in the secure equilibrium, in the last stage, contractor 2, the leading contractor, exerts the lowest effort while contractor 1 exerts the right amount of effort to close the gap in the cumulative efforts between the two.

Rolling back to period $N-1$, contractor 1's secure equilibrium action is to exert the highest effort $\bar{e}_N$ regardless of contractor 2's effort in this period, because if contractor 1 ends up with a higher cumulative effort at the beginning of period N, the other contractor will match the difference between the two cumulative efforts; if it ends up with a lower cumulative effort, it will be able to further shrink the effort gap between the two contractors in period N. In both cases, the least total effort is the same as contractor 1's total effort, and therefore contractor 1's secure equilibrium effort is to exert the highest effort $\bar{e}_N$ in period $N-1$.

On the other hand, knowing that contractor 1 will exert the highest effort in this period as well as the equilibrium actions in the next period, contractor 2 will choose an effort level that results in the highest least total effort yet the smallest effort gap at the end of period N. If the current effort gap is large, contractor 2 will exert an effort to induce contractor 1 to exert the highest effort $\bar{e}_N$ as well in the next period, resulting in a least total effort of $\hat{e}_{1,N-2} + 2\bar{e}_N$. If the current effort gap is small, contractor 2 will exert the highest effort $\bar{e}_N$ that induces contractor 1 to exert the right amount of effort to close the gap between the two in the next period, resulting in a least total effort of $\hat{e}_{2,N-2} + \bar{e}_N + \underline{e}_N$. It follows that in the secure equilibrium, contractor 2 should choose an action that yields the lower of the two payoffs, i.e., a threshold action with the threshold defined as $T^1_{N-1} = \min\{\hat{e}_{1,N-2} + 2(\bar{e}_N - \underline{e}_N), \hat{e}_{2,N-2} + (\bar{e}_N - \underline{e}_N)\}$ (recall that the minimum effort for each period is $\underline{e}_N$.) We note that the threshold evaluates the maximum total effort each contractor can reach by the end of horizon considering the worst possible scenario. The explanation is similar for period n where $n < N - 1$.

We next extend our explanation to the general case of G contractors by considering two scenarios: the last $G - 1$ periods which resemble the discussion of the last period in the two contractors case, and the first $N - G + 1$ periods which resemble the discussion of period $N - 1$ above.

We consider the scenario in the last $G - 1$ periods starting from period N. In this period, contractor 2 should exert $\underline{e}_N$ to maximize the payoff in the worst case following the same logic in the two contractors case. It then follows that all the contractors who have exerted more efforts than contractor 2 should exert $\underline{e}_N$ as well. Rolling back to period $N - 1$, knowing that only the difference between contractor 1 and 2 will be matched in the last period in the secure equilibrium, contractor 3 does not have incentive to exert an effort above $\underline{e}_N$, because any additional effort beyond $\underline{e}_N$ may not be matched by contractor 1 and 2 in the worst case for contractor 3. It follows that all the contractors who have exerted more efforts than contractor 3 should exert $\underline{e}_N$ as well while contractor 1 and 2 evaluate the maximum total effort that they can reach at the end of the horizon. Following the same logic, at any period $n \geq N - G + 2$, contractor $N - n + 2$ as well as any contractors with a higher cumulative effort should exert $\underline{e}_N$ while contractors 1 to $N - n + 1$ should evaluate the maximum total effort that they can reach at the end of the horizon and exert efforts according to the specified equilibrium threshold.

We then consider the scenario in the first $N - G + 1$ periods. In period $n \leq N - G + 1$, we label contractor k as the contractor who determines the potential least maximum total effort that can be reached at the end of the horizon, considering the strategic behaviors in the last $G-1$ periods. We note that contractor k is analogous to contractor 1 in period $N-1$ with two contractors because all other contractors will decide their equilibrium actions based on the maximum effort contract k can achieve, and contractor k's secure equilibrium effort is to exert the highest effort $\bar{e}_N$ in period n. On the other hand, considering contractor G who has exerted the most effort among all contractors, when this contractor's cumulative effort is less than the potential specified by contractor k, it should have incentive to exert an effort above $\underline{e}_N$ because the additional effort will be matched by other contractors similar to the intuition for contractor 2 in period $N-1$ with two contractors. It follows that all other contractors will have incentive to exert an effort above $\underline{e}_N$ to close the gap between their cumulative efforts and the potential that is determined by contractor k's cumulative efforts.

Now we have fully characterized the subgame perfect secure equilibrium action, and we next identify the contractors' secure equilibrium paths in the following proposition. We use $\lceil x \rceil$ to denote the smallest integer above x.

Proposition 2.2. (**Secure equilibrium path)** *The secure equilibrium action of contractor i is*

$$e_{i,n}^{*}=\begin{cases}\min\{\bar{e}_N, e^{*}-(n-1)\bar{e}_N-(N-n)\underline{e}_N\} & n=1,\dots,n^{*}\\ \underline{e}_N & n=n^{*}+1,\dots,N\end{cases} \tag{5}$$

where $n^{*}=\min\left\{\left\lceil\frac{e^{*}-N\underline{e}_N}{\bar{e}_N-\underline{e}_N}\right\rceil,(N-G+1)^{+}\right\}$ *denotes the number of periods with an effort above* $\underline{e}_N$.

Consider the case with two contractors. Following Lemma 2.1, both contractors exert efforts according to the secure equilibrium threshold strategy defined by T_n^{*}. In addition, we note that at the beginning of the first period both contractors have not exerted any efforts yet, i.e., $\hat{e}_{1,0} = \hat{e}_{2,0} = 0$. Therefore, following the secure equilibrium threshold strategy, they will exert as much as possible to reach the threshold in the first n^* periods, and exert the lowest effort afterwards.

It follows from Proposition 2.2 that all contractors should reach the same total effort in equilibrium, and this total effort increases in the number of information feedback N, and decreases in the number of contractors G. This indicates that the more numbers of information feedback opportunities that the OEM enforces, the higher total efforts the contractors will achieve. We next specify the minimum number of information feedback to induce contractors to exert the maximum beneficial effort in Proposition 2.3.

Proposition 2.3. $N^* = \left\lceil (G-1)\frac{\bar{e}-\underline{e}}{\bar{e}-e^*} \right\rceil$ *is the minimum number of information feedback to induce contractors to exert the maximum beneficial effort* e^*.

It follows from Proposition 2.3 that the minimum number of information feedback increases linearly in the number of contractors. This observation shows that coordination among contractors is getting harder with more contractors working on the project. Therefore, the OEM should enforce more information feedback opportunities to induce a higher effort level with more contractors. We also note that the minimum number of information feedback increases in e^* because contractors need to coordinate to reach a higher total effort. Finally, the minimum number of information feedback decreases in the highest effort $\bar{e}$ and the lowest effort $\underline{e}$. In both cases, contractors are able to exert more efforts per period, resulting in less need of information feedback.

We note that the information feedback policy is attractive as it increases the contractors' efforts without changing the OEM's payment to the contractors. By specifying appropiate numbers of information feedback, even in the most conservative case where the equilibrium is a secure equilibrium, the contractors should exert the maximum beneficial effort e^* in total. This is in sharp contract with Corollary 2.1 where all contractors exert the lowest efforts in the secure equilibrium. To test our theoretical findings, we conduct a behavioral experiment as described in the next Section.

2.2. Experimental Design

Our experiment varies the number of within round feedback and the number of contractors, for a 3×2 full factorial design. These treatments are labeled as I_G^{N-1} where the superscript N indicates the number of information feedbacks and in turn $N-1$ indicates the number of within round feedbacks and the subscript G indicates the number of contractors. Table 2.1 summarizes the six treatments, their labels, and the number of independent cohorts in each treatment.

Table 2.1. Summary of the Experimental Design

		Number of Contractors	
		2	4
Number of Within Round Feedbacks[2]	0	I_2^0 (3 cohorts of 10, 6 cohorts of 8 and 1 cohort of 6)	I_4^0 (8 cohorts of 12)
	1	I_2^1 (5 cohorts of 10 and 1 cohort of 8)	I_4^1 (4 cohorts of 12)
	5	I_2^5 (4 cohorts of 8)	I_4^5 (4 cohorts of 12)

Note. Each cohort is considered as one independent observation in the statistical test. The number of cohorts are in the parentheses. In total, we included 366 human subjects in our study.

[2] Treatment I_2^0 (I_4^0) includes two settings. In the first setting subjects make decision in one period. In the second setting subjects make decision on their effort level in 2 (6) periods similar to treatment I_2^1 (I_4^5), except the other contractors' efforts are not revealed until the end of the last period in each round. Note that in both settings no within round feedback is provided. We pooled the observations of these two settings as there is not significant difference in the average least effort observed in the experiment (corresponding t-tests are not significant under 5% significance level). Note that this result is in line with Proposition 2.2.

We simplify a general revenue function in (2), and use a piecewise linear function in which the per-unit cost of effort is C as shown in (6) below:

$$\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) = \min\{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}), e^*\} - C\hat{e}_{i,N}, \qquad e_{i,n} \in [\underline{e}_N, \bar{e}_N], \qquad i = 1, \ldots, G \tag{6}$$

We keep the per-unit cost of effort $C = 0.75$ constant and consider the lowest effort of $\underline{e} = 110$, the highest effort of $\bar{e} = 230$, and the maximum beneficial effort of $e^* = 170$. Our parameters are comparable to those in Goeree and Holt (2005) study.

Treatment I_G^{N-1} follow the information feedback policy in Section 2.1.1. We vary the number of within round feedbacks to be below and above the minimum required number of within round feedbacks to achieve full coordination e^*. We provide 1 and 5 within round feedbacks in treatment I_2^1 and I_4^5 respectively. Because these are the minimum number of within round feedbacks to induce contractors to achieve the maximum beneficial effort $e^* = 170$. Following Proposition 2.3, in treatment I_2^1 with 2 contractors $N^* = \left\lceil (2-1)\frac{230-110}{230-170} \right\rceil = 2$ (i.e., 1 within round feedback) and in treatment I_4^5 with 4 contractors $N^* = \left\lceil (4-1)\frac{230-110}{230-170} \right\rceil = 6$ (i.e., 5 within round feedbacks).

In treatment I_G^{N-1}, we set the lowest effort per-period $\underline{e}_N = \frac{110}{N}$ and the highest effort per-period $\bar{e}_N = \frac{230}{N}$ (e.g., in treatment I_2^1, $\underline{e}_2 = 55$ and $\bar{e}_2 = 115$). In the first period of each round, subjects are asked to simultaneously make a decision on their own effort in the first period. After all subjects made decisions in the first period, the information feedback about their efforts is revealed to all, and they are asked to make decisions on their effort in the next period. This continues until the last period. Subjects' payoff from their actions follows (6).

All experimental sessions follow the same protocol. Upon arrival to the laboratory, subjects are seated in separated computer terminals, and given a copy of the instruction. All the instructions are written to frame the task in the project management setting, and Appendix B contains compendium instructions. The experimenter read instructions aloud to the subjects to make sure the description of the game is common knowledge. Subjects are matched randomly in each round for 20 rounds. In addition to a $5 show up fee, subjects are paid their earnings privately and in cash at the end of the session.

We programmed all six treatments using the software Z-Tree Fischbacher (1999), and conducted the sessions in the Center and Laboratory for Behavioral Operations and Economics (LBOE) at The University of Texas at Dallas. Subjects were recruited from the graduate students of The University of Texas at Dallas with the help of the recruitment software SONA, and each person participated in one session only.

2.3. Hypotheses and Results

2.3.1. Research Hypotheses

The Analytical model in Section 2.1 provides two empirically testable predictions. First, coordination among contractors (contractors' payoff) weakly increases in the frequency of within round feedback. Second, coordination among contractors (contractors' payoff) weakly decreases in the number of contractors. Therefore, our analytical model implies the following two sets of hypotheses:

Hypothesis 2.1.A. (The effect of information feedback frequency) *Coordination among contractors weakly increases in the number of within round feedback.*

Hypothesis 2.1.B. (The effect of information feedback frequency) C*ontractors' payoff weakly increases in the number of within round feedback.*

The analytical model predicts that contractors achieve the maximum beneficial effort of $e^* = 170$ in treatments I_2^1, I_2^5 and I_4^5 and in turn earn the maximum payoff of 42.5 ECU (i.e., $170 - 0.75 \times 170$). On the other hand, the analytical model predicts that contractors will exert the lowest effort of $\underline{e} = 110$ in treatments I_2^0, I_4^0 and I_4^1 and in turn contractors gain the payoff of 27.5 ECU (i.e., $110 - 0.75 \times 110$) (Proposition 2.2). Specifically, the observed least total effort (contractors' payoff) should weakly increase from treatments I_2^0 (I_4^0) to I_2^1 (I_4^1) to I_2^5 (I_4^5).

Hypothesis 2.2.A. (The effect of the number of contractors). *Coordination among contractors weakly decreases in the number of contractors working on the project.*

Hypothesis 2.2.B. (The effect of the number of contractors). *Contractors' payoff weakly decreases in the number of contractors working on the project.*

The analytical model predicts that contractors will exert the maximum beneficial effort of $e^* = 170$ in treatments I_2^1, I_2^5 and I_4^5 and in turn earn the maximum payoff of 42.5 ECU and contractors will exert the lowest effort of $\underline{e} = 110$ in treatment I_2^0, I_4^0 and I_4^1 and in turn gain the payoff of 27.5 ECU (Proposition 2.2). Specifically, the observed least total effort (contractors' payoff) should weakly decrease from I_2^0, I_2^1, and I_2^5 to I_4^0, I_4^1 and I_4^5 respectively.

2.3.2. Experimental Results

The left graph in Figure 2.1 shows the average least total effort in the two-contractor treatments and the right graph shows the average least total effort in the four-contractor treatments in settings with 0, 1 and 5 within round of feedbacks. Each gray point represents the per-cohort average least total effort and each black point represents average least total effort of all cohorts in the same treatment. The figure provides a sense of how effort levels vary over time in response to the information feedback frequency, as well as number of contractors.

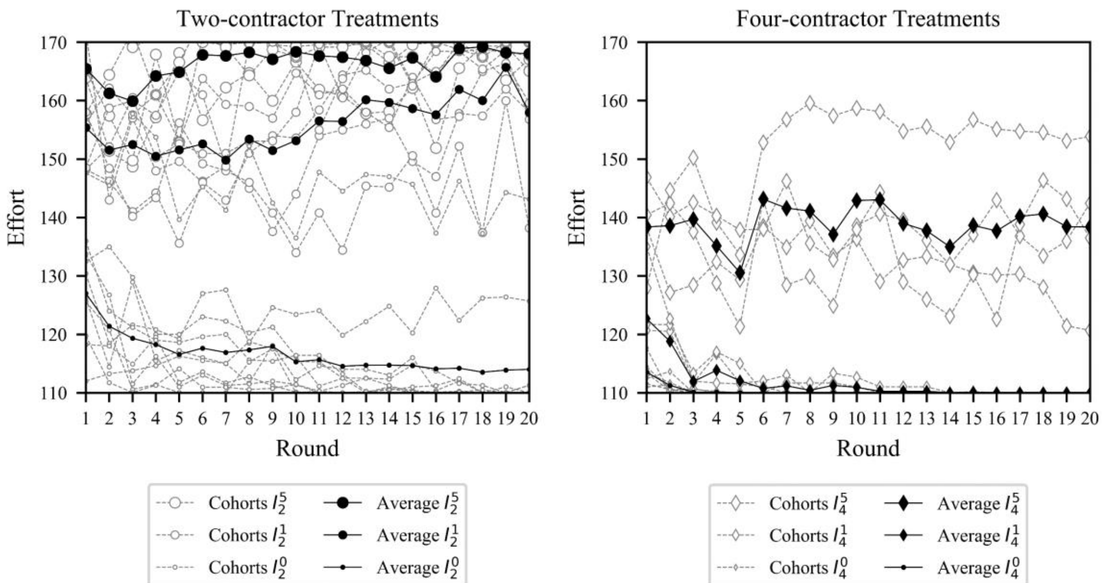

Figure 2.1. Average Least Total Effort in Treatments with Two Contractors (Left) and Four Contractors (Right)

Figure 2.1 illustrates two findings. First, the average least total effort in treatment I_2^5 (I_4^5) (the large circles (diamonds) on the top) is higher than the average least total effort in treatment I_2^1 (I_4^1) (the medium circles (diamonds) in the middle). Similarly, the average least total effort in treatment I_2^1 (I_4^1) (the medium circles (diamonds) in the middle) is higher than the average least total effort in treatment I_2^0 (I_4^0) (the small circles (diamonds) on the bottom). Note that in treatments $I_2^0(I_4^0)$, I_2^1 (I_4^1) and I_2^5 (I_4^5), the number of contractors are the same (i.e., $G = 2(4)$) and the number of within round feedbacks varies from 0 to 1 to 5. This observation is in line with Hypothesis 2.1.A and confirms that coordination among contractors weakly increases in the number of within round feedbacks. Second, the average least total effort in treatment I_2^0, I_2^1, and I_2^5 are less than average least total effort in treatment I_4^0, I_4^1 and I_4^5 respectively. This result is in line with Hypothesis 2.2.A and validates that coordination among contractors gets more difficult with more contractors working on the project. We formally compare effort between treatments using a one-sided t-test, and the alternative hypothesis as implied by Hypothesis 2.1.A and Hypothesis 2.2.A and summarize these results in Table 2.2.

Table 2.2. Summary of the Experimental Results on H 2.1.A and H 2.2.A

		Two Contractors			Four Contractors			
	Treatments	I_2^0	I_2^1	I_2^5	I_4^0	I_4^1	I_4^5	
	Avg. Effort	117.94	156.08	166.40	110.17	111.72	138.83	
	Std. Error	3.22	2.87	2.04	0.04	0.50	4.38	
Hypothesis	Alternative Hypothesis							*p*-Value
Effect of Information Feedback Frequency on Coordination (H 1A)	$I_2^0 < I_2^1$	x	x					0.000
	$I_2^1 < I_2^5$		x	x				0.009
	$I_4^0 < I_4^1$				x	x		0.026
	$I_4^1 < I_4^5$					x	x	0.004
Effect of Number of Contractors on Coordination (H 2A)	$I_4^0 < I_2^0$	x			x			0.019
	$I_4^1 < I_2^1$		x			x		0.000
	$I_4^5 < I_2^5$			x			x	0.001

Next, we explain the dynamics under the information feedback policy by analyzing the average effort at the periods' level. Figure 2.2 summarizes average effort per-period of treatments with 1 within round feedback, i.e., I_2^1 (Black bars) and I_4^1 (Gray bars), while Figure 2.3 summarizes average effort per-period of treatments with 5 within round feedbacks, i.e., I_2^5 (Black bars) and I_4^5 (Gray bars). Note that in both figures the vertical axis is from bottom to top. These figures illustrate two main findings. First, in line with the analytical prediction in Proposition 2.2, here we observe that subjects exert weakly higher effort in the earlier periods than in the later periods. Exerting effort in the earlier periods induces subjects with lower cumulative effort to match the effort of the leading contractor in the following periods. Note that in treatment I_2^5 we cannot reject that the average per-period effort in period 1 and 2, and similarly 2 and 3 are the same under 5% significant level and this is in line with the analytical model prediction that contractors should exert the same amount of effort in period 1 to 3. Second, in each period subjects exert less effort in the four-contractor treatments compared to the two-contractor treatments (all corresponding one-sided t-tests are significant under 5% significance level). This result is in line with Hypothesis 2.2.A and shows that more contractors working on the project makes coordination more difficult among contractors. These results are supported by the statistical tests presented in Table 2.3 and Table 2.4. Note that in Table 2.3 and Table 2.4, $P_i > P_j$ states that the average effort in period i is greater than the average effort in period j and $P_i \neq P_j$ states that the average effort in period i is not equal to the average effort in period j.

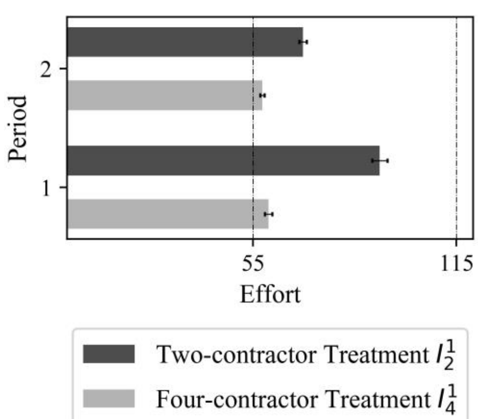

Figure 2.2. Average Effort Per-Period (1 Within Round Feedback)

Table 2.3. Summary of the Experimental Results (1 Within Round Feedback)

Avg. Effort	Std. Erro	Alternative Hypothesis	
		$P_2 < P_1$	$P_2 < P_1$
69.71	1.06	x	
57.71	0.63		x
92.39	2.26	x	
59.56	1.10		x
p-Value (I_2^1)		0.0002	
p-Value (I_4^1)			0.0155

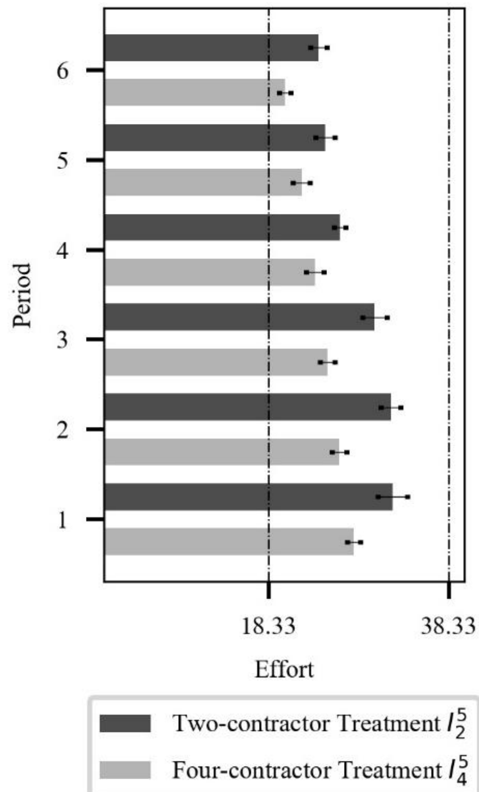

Figure 2.3. Average Effort Per-Period (5 Within Round Feedbacks)

Table 2.4. Summary of the Experimental Results (5 Within Round Feedbacks)

Avg. Effort	Std. Err.	Alternative Hypothesis $P_1 > P_2$	$P_2 > P_3$	$P_3 > P_4$	$P_4 > P_5$	$P_5 > P_6$
23.85	0.90					x
20.07	0.66					x
24.56	1.07				x	x
21.93	0.93				x	x
26.19	0.66			x	x	
23.41	0.96			x	x	
30.05	1.36		x	x		
24.81	0.82		x	x		
31.85	1.11	x	x			
26.08	0.79	x	x			
32.05	1.61	x				
27.73	0.74	x				
p-Value (I_2^5)		0.4227	0.0822	0.0720	0.0185	0.1551
p-Value (I_4^5)		0.0198	0.0088	0.0036	0.0001	0.0051

Next, through regression analysis we study how subjects make effort decisions conditional on group's highest cumulative effort at each period, i.e., $\max_j\{\hat{e}_{j,t-1}\} - \hat{e}_{i,t-1}$. The dependent variable is subject's effort and the independent variables are listed in the first column of Table 2.5. In the regression analysis we include observation from treatments I_2^1, I_4^1, I_2^5 and I_4^5. Regression analysis reveals three main points. First, the positive and significant coefficient of $\max_j\{\hat{e}_{j,t-1}\} - \hat{e}_{i,t-1}$ shows that subjects tend to follow the leading subject with the highest cumulative effort in their group and try to catch up and close the gap by exerting more effort. Second, the negative and significant coefficient of *Group Size* shows that subjects tend to exert less effort in project with larger group. This result is in line with Hypothesis 2.2.A and validates that coordination becomes more difficult in project with larger group size. Third, the negative and significant coefficient of *Periods* shows that subjects exert more effort in the earlier periods compared to the later period. Table 2.5 presents the regression summary.

Table 2.5. Summary of the Regression Analysis

	Model			
Independent Variables	(1)	(2)	(3)	(4)
$\max_j\{\hat{e}_{j,t-1}\} - \hat{e}_{i,t-1}$	0.228*** (0.008)	0.228*** (0.008)	0.255*** (0.008)	0.255*** (0.008)
Group Size $\in \{2,4\}$	--	-6.956*** (1.302)	-6.617*** (0.428)	-6.617*** (0.428)
Period $\in \{2, \dots ,6\}$	--	--	-2.095*** (0.053)	-2.163*** (0.099)
Round $\in \{1, \dots ,20\}$	--	--	-0.026** (0 .011)	-0.049 (0.030)
Round×*Period*	--	--	--	0.006 (0.007)
Constant	45.557*** (1.380)	66.645*** (4.159)	71.299*** (1.385)	71.542*** (1.41)
R-squared	0.065	0.111	0.288	0.288

Note. in Table 2.5, In each cell, the first, and second row presents the coefficient estimation, and standard error (in parenthesis), respectively. Additionally, *p*-Value <0.01 ***, <0.05 **, and <0.1*

Figure 2.4 represents subjects' payoff in treatments with two contractors (black bars) and four contractors (gray bars), with 0, 1 and 5 within round feedbacks. Note that the average payoffs are in ECU (Experimental Currency Unit). The following figure illustrates two main findings. First, subjects' payoff weakly increases in within round feedback frequency. The analytical model predicts that contractors' payoffs are the same in treatments I_4^0 and I_4^1, and based on the experimental results we cannot reject that they are equal under 5% significance level. Note that a slightly lower payoff in I_4^1 compared to I_4^0 is coming from a higher variation observed in subjects' effort in treatment I_4^1. Second, subjects' payoff weakly decreases in the number of contractors working in the project. Note that we cannot reject that subjects' payoff are the same in treatments I_2^0 and I_4^0 under 5% significance level and this result is in line with the analytical prediction that contractors' payoffs are equal under these two treatments. These two findings are consistent with Hypothesis 2.1.B and Hypothesis 2.2.B, respectively. We formally compare payoff between treatments using a one-sided t-test, and the results are summarized in Table 2.6.

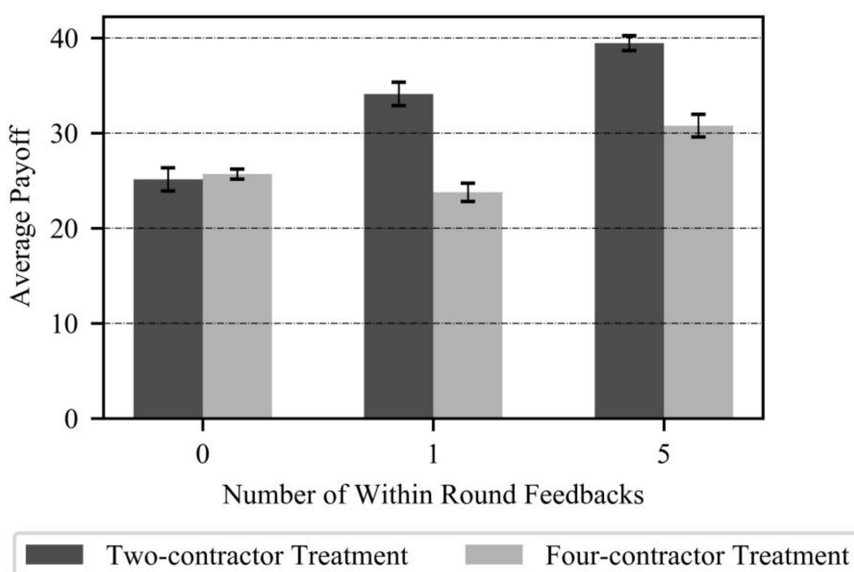

Figure 2.4. Average Payoff in Treatments with Two and Four Contractors

Table 2.6. Summary of the Experimental Results on H 2.1.B and H 2.2.B

		Two Contractors			Four Contractors			
	Treatments	I_2^0	I_2^1	I_2^5	I_4^0	I_4^1	I_4^5	
	Avg. Payoff	25.00	34.20	39.45	25.42	23.766	30.78	
	Std. Error	0.73	1.22	0.77	0.35	0.94	1.19	
Hypothesis	Alternative Hypothesis							p-Value
Effect of Information Feedback Frequency on Payoff (H 1B)	$I_2^0 < I_2^1$	x	x					0.0000
	$I_2^1 < I_2^5$		x	x				0.0035
	$I_4^0 < I_4^1$				x	x		0.9098
	$I_4^1 < I_4^5$					x	x	0.0021
Effect of Number of Contractors on Payof (H 2B)	$I_4^0 < I_2^0$	x			x			0.6883
	$I_4^1 < I_2^1$		x			x		0.0000
	$I_4^5 < I_2^5$			x			x	0.0007

2.4. Extensions on Analytic Model

In this Section, we discuss three extensions to our analytical model.

2.4.1. Uncertainty in Execution of Tasks

The model setting is similar to the information feedback setting in Section 2.1.1, except under this setting in period n contractor i's progress on its task $y_{i,n} = e_{i,n} + \epsilon_{i,n}$ is determined by its effort $e_{i,n}$ and an additive random noise $\epsilon_{i,n}$ with mean of zero and probability density function of $f_{\epsilon_{i,n}}(.)$. The stochastic term $\epsilon_{i,n}$, which is independent and identically distributed across the contractors and periods, reflects the component of progress that is resulted by environmental shocks that is out of the contractor's control. Under this setting the information feedback includes all contractors' progress in the previous periods and therefore their cumulative progress up to the current period.

We denote contractor i's cumulative progress at the beginning of period n by $\hat{y}_{\mathrm{i},n-1} \triangleq \sum_{t=1}^{n-1} y_{i,t}$ and the progress vector of all contractors by $\boldsymbol{y} = (y_1, \ldots, y_G)$ and the least progress among all the contractors by $P(\boldsymbol{y}_N) \triangleq \min_{i=1,..,G}\{\hat{y}_{\mathrm{i},N}\}$. Contractor i's payoff $\pi_i(\hat{\boldsymbol{y}}_N)$ is determined by the revenue $R\big(P(\hat{\boldsymbol{y}}_N)\big) = P(\hat{\boldsymbol{y}}_N)$ and it incurs a per-unit cost of C. Therefore, we have contractor i's payoff $\pi_i(\hat{\boldsymbol{y}}_N)$ as follows:

$$\pi_i(\hat{\boldsymbol{y}}_N) = P(\hat{\boldsymbol{y}}_N) - C\hat{e}_{i,N} \tag{7}$$

We consider a project with $G = 2$ tasks and we characterize contractors' equilibrium effort in two settings. First, in setting with no within round feedback we identify equilibrium effort in Proposition 2.4. Second, in setting with 1 within round feedback, we first derive the subgame perfect equilibrium effort in the second period in Lemma 2.2 and then we characterize the contractors effort in the first period in Proposition 2.5. As in a setting with no within round feedback when the per-unit cost of effort is less than $\frac{1}{2}$, contractors achieve full coordination, we explore how information feedback impacts coordination by focusing on a setting where the per-unit cost of effort is greater than $\frac{1}{2}$.

Proposition 2.4. (Proposition 2.1. of Carlsson and Ganslandt (1998)) *There exists unique pure strategy equilibrium where all contractors exert the lowest possible effort $\underline{e}$.*

Proposition 2.4 shows that contractors exert the lowest possible effort $\underline{e}$ in equilibrium resulting in the longest project delay. Next, we explore how providing 1 within round information feedback impacts contractors' effort decision in Lemma 2.1 and Proposition 2.5. For ease of exposition, we denote $\epsilon_n = \epsilon_{1,n} - \epsilon_{2,n}$ and we assume that $\epsilon_{i,n}$ follows a normal distribution with mean of 0 and standard deviation of $\frac{\sigma}{\sqrt{2}}$, i.e., $\epsilon_{i,n} \sim N\left(0, \frac{\sigma}{\sqrt{2}}\right)$ and in turn ϵ_n follows a normal distribution with mean of 0 and standard deviation of σ, i.e., $\epsilon_n \sim N(0, \sigma)$ with probability density function of $g_{\epsilon_n}(.)$ and cumulative density function of $G_{\epsilon_n}(.)$.

Lemma 2.2. (Subgame perfect equilibrium in the second period) *In the second period contractor i's subgame perfect equilibrium is* $e^*_{i,2} = \underline{e}_2 + \min\left\{\delta, \left(y_{-i,1} - y_{i,1} - G^{-1}_{\epsilon_2}(C)\right)^+\right\}$ *where* $y_{-i,1}$ *is the other contractor's progress at the end of period 1.*

It follows from Lemma 2.2 that contractors' subgame perfect equilibrium effort in the second period follows a threshold policy similar to Lemma 2.1, except here the threshold is subtracted by $G^{-1}_{\epsilon_2}(C)$. In the second period contractor that is ahead exerts the lowest possible effort $\underline{e}_2$ in equilibrium, and the other contractor closes the gap up to $G^{-1}_{\epsilon_2}(C)$. This inefficiency in matching effort in the second period is coming from the uncertainty and it increases in the standard deviation of the random noise σ.

Proposition 2.5. *When* $C < \frac{\sqrt{2}}{2}$ *there exists* $\bar{\sigma}(C, \delta)$ *such that when* $\sigma \leq \bar{\sigma}(C, \delta)$ *at least one contractor exerts the highest possible effort* $\bar{e}_2$ *in the first period.*

In the first period we show that under a sufficient condition at least one contractor exerts the highest possible effort $\bar{e}_2$. Proposition 2.5 shows that providing information feedback improves coordination among contractors and therefore mitigates project delay.

Next, we numerically investigate how contractor's effort decision in the first period is impacted by the per-unit cost of effort C and the standard deviation σ. In the numerical examples the effort bounds are the same as treatment I_2^1 (i.e., $\underline{e}_2 = 55$ and $\bar{e}_2 = 115$) and we vary the per-unit cost of effort C as well as the standard deviation σ.

Figure 2.5 shows the threshold $\bar{\sigma}$ (the solid black line) as a function of the per-unit cost of effort C. All the points (combinations of the C and σ) below the solid black line (the gray area) meet the sufficient condition where at least one contractor exerts the highest possible effort $\bar{e}_2$ in the first period. Next, we study how contractor's effort decision in the first period is impacted by the per-unit cost of effort C and the standard deviation σ beyond the sufficient condition shown in

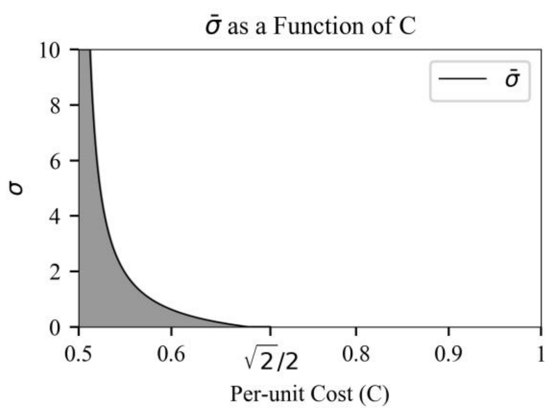

Figure 2.5. Threshold $\bar{\sigma}$ as a Function of the Per-unit Cost of Effort C

Figure 2.6 shows contractor 2's expected payoff in the first period as a function of its effort given that the other contractor exerts $e_{1,1} = 55$ in the first period, i.e., $\pi_{2,1}\left(e_{2,1} \middle| e_{1,1} = 55\right)$. In the second period, contractors follow the subgame perfect equilibrium identified in Lemma 2.2. In the left figure, we fixed the standard deviation at $\sigma = 1$ and we vary the per-unit cost of effort C from 0.5 to 0.999. In the right figure, we fixed the per-unit cost of effort at $C = 0.75$ and we vary the standard deviation σ from 0.001 to 30. In the left figure, we observe that when the per-unit cost of effort is less than 0.95, contractor two can maximize its payoff by exerting the highest possible effort $\bar{e}_2 = 115$, and otherwise it can maximize its payoff by exerting the lowest possible effort

$\underline{e}_2 = 55$. The right figure shows that when the standard deviation is less than 27 then contractor two can maximize its payoff by exerting the highest possible effort of $\bar{e}_2 = 115$ and otherwise it can maximize its payoff by exerting the lowest possible effort $\underline{e}_2 = 55$. This observation shows that even for the per-unit cost of effort C and the standard deviation σ beyond the sufficient condition defined in Proposition 2.5, providing 1 within round feedback improves coordination among contractors.

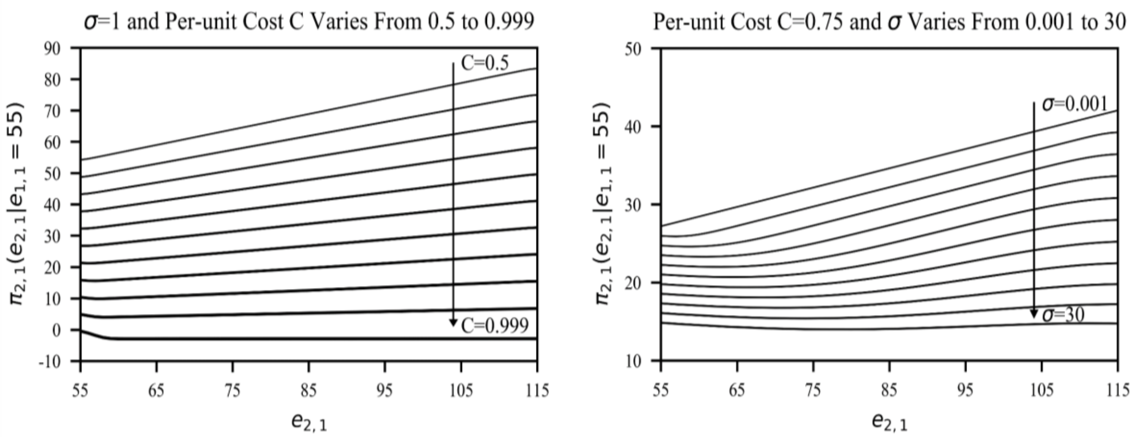

Figure 2.6. Contractor 2's Expected Payoff in the First Period as a Function of Its First Period Effort Given That Contractor 1's Effort of 55 in the First Period

Note that in the left figure the standard deviation is fixed at $\sigma = 1$ and the per-unit cost of effort varies in the direction of the arrow from $C = 0.5$ to $C = 0.999$ with step size of 0.05. In the right figure the per-unit cost of effort is fixed at $C = 0.75$ and the standard deviation σ varies in the direction of the arrow from $\sigma = 0.001$ to $\sigma = 30$ with step size of 3.

2.4.2. Assembly Systems with Uncertain Demand

We extend the analytical model presented in Section 2.1 and we consider an assembly system where the contractors' payment from OEM is contingent on the sales quantity. We consider an

OEM that assembles a product that consists of G modules and sources these G modules from G contractors. The model setting is similar to the information feedback setting in Section 3.1., except under this setting in each period, contractors simultaneously decide their production quantity in each of the N periods and incur a unit cost of C. We denote contractor i's production quantity at period n by $e_{i,n}$ and its cumulative production quantity by $\hat{e}_{\mathrm{i},n-1} \triangleq \sum_{t=1}^{n-1} e_{i,t}$. At each period, the production quantity can be anything between the lowest capacity $\underline{e}_N \triangleq \frac{\underline{e}}{N}$ and the highest capacity $\bar{e}_N \triangleq \frac{\bar{e}}{N}$. We assume that the final product requires equal quantity of each modules, and therefore the final production quantity is determined by the least total quantity among all the contractors denoted by $P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) \triangleq \min_{i=1,..,G}\{\hat{e}_{\mathrm{i},N}\}$. We assume that the final product faces uncertain demand that is realized at the end of period N denoted by D with probability density function of $f_D(.)$, cumulative density function of $F_D(.)$ and $\bar{F}_D(.) = 1 - F_D(.)$. The contractor i's revenue from OEM is generated from the unit price of p payed based on the sales quantity $\min\{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}), D\}$, i.e., $R\left(P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})\right) = p\min\{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}), D\}$. Note that the expected revenue $E_D\left[R\left(P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})\right)\right]$ increases in the final production quantity, i.e., $\frac{\partial E_D\left[R\left(P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})\right)\right]}{\partial P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})} = p\bar{F}_D\left(P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})\right) \geq 0$, and is concave in $P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})$, i.e., $\frac{\partial^2 E_D\left[R\left(P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})\right)\right]}{\partial P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})^2} = -pf_D(.) \leq 0$. It follows that there exists a maximum beneficial capacity e^* beyond which the expected marginal revenue of increasing the final production quantity by one unit is lower than the marginal cost, i.e., $e^* = \inf\left\{e: \frac{\partial \bar{F}}{\partial P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})}\Big|_{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) = e} \leq \frac{C}{p}, e \in \left[\underline{e}, \bar{e}\right]\right\}$. Contractor i's payoff $\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}})$ is summarized as follows:

$$\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) = p\min\{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}), D\} - C\hat{e}_{i,N} \tag{8}$$

In the following proposition we derive contractors' equilibrium production quantity in a setting without information feedbacks.

Proposition 2.6. *There exist multiple equilibria in which all contractors achieve the same total production quantity between the lowest capacity $\underline{e}$ and maximum beneficial capacity e^*.*

It follows form Proposition 2.6 that under this extension there still exist multiple equilibria in which all contractors achieve the same total production quantity between the lowest capacity $\underline{e}$ and e^* and the results remains intact to Proposition 2.1. It is trivial to show that all the results derived in Section 2.1 still holds under this extension with e^* defined as $e^* = \inf\left\{e: \frac{\partial \bar{F}}{\partial P(\hat{\boldsymbol{e}}_{\boldsymbol{N}})}\Big|_{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) = e} \leq \frac{C}{p}, e \in \left[\underline{e}, \bar{e}\right]\right\}$. In the absence of information feedback, contractors fail to coordinate their production quantity by playing the secure equilibrium. On the other hand, periodic information feedback is effective in improving coordination among contractors.

2.4.3. Convex Cost Function

In Section 2.1, we consider a linear cost function and we denote a per-unit cost effort by C. Here we extend the model by considering a quadratic cost function. We consider a project with $G = 2$ tasks that is governed under the risk-sharing contract with $N = 2$ periods following the same policy as in Section 2.1.1. Under this extension, contractor i's payoff is determined by the revenue $R\left(P(\hat{\boldsymbol{e}}_N)\right) = P(\hat{\boldsymbol{e}}_N)$, which depends on the least total effort among both contractors, and incurs cost based on quadratic cost function of the form of $\frac{C}{2} e_{i,n}^2$ in period n. Therefore, we have contractor i's payoff $\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}})$ as follows:

$$\pi_i(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) = P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}) - \sum_{n=1}^{N} \frac{C}{2} e_{i,n}^2 \tag{9}$$

When information feedback is not available, there still exist multiple equilibria in which both contractors exert the same amount of effort between the lowest possible effort $\underline{e}_2$ and $\min\left\{\underline{e}_2, \frac{1}{C}\right\}$ in each of the two periods. As there exist multiple equilibria, we derive the equilibrium that satisfies the maxmin strategy. Both contractors exert the lowest possible effort of $\underline{e}_2$ in both periods resulting in the longest project delay; Therefore, contractor's secure equilibrium still follows Corollary 2.1 and the result remains intact considering quadratic cost function when information feedback is not available. Next, when information feedback is available, we first characterize contractors' secure equilibrium path in Proposition 2.7. Then we discuss how the availability of information feedback impacts coordination among contractors. Recall that we relabel contractor with the lowest cumulative effort as contractor 1 and the other contractor as contractor 2 at the beginning of each period.

Proposition 2.7. (Secure equilibrium path) *In secure equilibrium, contractor 1 exerts* $e_{1,n}^* = \underline{e}_2 + \frac{\min\left\{\delta, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}}{2}$ *in the first and second period, i.e.,* $n \in \{1,2\}$ *and contractor 2 exerts* $e_{2,1}^* = \underline{e}_2 + \min\left\{\delta, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}$ *in the first period and* $e_{2,1}^* = \underline{e}_2$ *in the second period.*

Note that $\frac{1}{C}$ is the highest beneficial effort at each period and exerting any effort above $\frac{1}{C}$ is dominated by exerting $\frac{1}{C}$. Proposition 2.7 shows that in equilibrium one contractor exerts the highest beneficial effort when $\underline{e}_2 \leq \frac{1}{C}$ and the lowest possible effort $\underline{e}_2$ in the first period otherwise. On the other hand, the other contractor splits this effort equally into two periods. The contractor who exerts the highest beneficial effort incurs a higher cost to induce the other contractor to match whatever it is behind in the second period. It follows from Proposition 2.7 that both contractors achieve the total effort of $\underline{e} + \min\left\{\delta, \left(\frac{1}{c} - \underline{e}_2\right)^+\right\}$ under the secure equilibrium; Therefore, availability of information feedback improves coordination among contractors compared to the setting where information feedback is not available. Note that when $\frac{1}{c} \leq \underline{e}_2$ both contractors achieve $\underline{e}$ in equilibrium, as exerting effort more than $\frac{1}{c}$ costs more than its marginal revenue, and this is different from coordination failure inherent in the risk-sharing contract.

CHAPTER 3

INCENTIVIZING SUPPLIERS USING SCORECARD: A BEHAVIORAL STUDY

In what follows, we introduce the theoretical model in Section 3.1. We then describe the hypotheses, experiment design, and results in Sections 3.2. All proofs can be found in Appendix A. All experimental instructions are provided in Appendix B, and additional results on the experimental outcomes are provided in Appendix C.

3.1. Analytical Model

We first separately analyze supplier performance under Absolute and Relative approach in Section 3.1.1 and 3.1.2 respectively. Then we compare the effectiveness of Absolute and Relative approach on supplier performance in Section 3.1.3.

3.1.1. Absolute Approach

We consider a manufacturer-supplier contractual agreement such that the manufacturer evaluates supplier performance over a two-period contract. At any period $n \in \{1, 2\}$, the manufacturer evaluates supplier performance and assigns a score to the supplier. If supplier performance at period n is acceptable then the supplier gains 1 score, i.e., $s_n = 1$ and otherwise it receives no score, i.e., $s_n = 0$. We denote supplier cumulative score from periods 1 to n as $S_n = \sum_{t=1}^{n} s_t$. Manufacturer informs the supplier about its cumulative score S_{n-1} before the supplier decides on its effort at period n. We denote supplier effort at period n when its score is S_{n-1} as $e_n(S_{n-1})$ which can be either high effort denoted as H or low effort denoted as L. Supplier incurs cost of

$C > 0$ when it exerts high effort and 0 otherwise. Supplier performance at period n is considered as acceptable with probability p when it exerts high effort and with probability q when it exerts low effort. Acceptable performance is more likely to be resulted from exerting high effort than from exerting low effort, i.e., $q < p$.

The manufacturer initially announces a Targeted score T. Next, the supplier at each period decides on its effort after the supplier informs it about its cumulative score up to that period and the supplier incurs the cost of C when it exerts high effort and 0 otherwise. At the end of the contract, the manufacturer awards supplier which worth R if the supplier's final score S_2 is at least at some pre-determined target level T, and award 0 otherwise. We assume that supplier is risk-neutral and expected payoff maximizer. Given supplier cumulative score up to period n, S_{n-1}, supplier's objective is to choose his effort level $e_n(S_{n-1})$ to maximize his expected payoff from period $n \in \{1, \dots, N\}$ onward, denoted by $\pi_n(S_{n-1}) = \max_{e_n \in \{H,L\}} \{\pi_n(S_{n-1}, H), \pi_n(S_{n-1}, L)\}$ where $\pi_n(S_{n-1}, H) = p\pi_{n+1}(S_{n-1} + 1) + (1 - p)\pi_{n+1}(S_{n-1}) - C, \pi_n(S_{n-1}, L) = q\pi_{n+1}(S_{n-1} + 1) + (1 - q)\pi_{n+1}(S_{n-1})$ and $\pi_{N+1}(S_N) = \begin{cases} R & S_N \geq T \\ 0 & S_N < T \end{cases}.$

The manufacturer's objective is to set a target T to maximize supplier *high effort proportion.* The supplier high effort proportion $\bar{e}$ is a metric defined as expected total high effort exerted by the supplier divided by the number of decision making periods. To derive the optimal target T^* we first in Lemma 3.1 characterize supplier's best response to the manufacturer's announced target and then we derive manufacturer's optimal target that maximizes supplier high effort proportion in Proposition 3.1. For the ease of exposition, we denote the relative reward as $\Delta \triangleq \frac{R}{c}$ and we denote supplier actions set as A_1 when it exerts high effort in the first period when its score is 0, i.e., $e_1(0) = H$ and exerts high in the second period, i.e., $e_2(0) = H$, $e_2(1) = H$, and similarly we denote A_2 as $e_1(0) = L$, $e_2(0) = L$, $e_2(1) = L$, A_3 as $e_1(0) = H$, $e_2(0) = L$, $e_2(1) = H$, A_4 as $e_1(0) = L$, $e_2(0) = L$, $e_2(1) = H$, A_5 as $e_1(0) = H$, $e_2(0) = H$, $e_2(1) = L$, A_6 as $e_1(0) = L$, $e_2(0) = H$, $e_2(1) = L$, A_7 as $e_1(0) = L$, $e_2(0) = H$, $e_2(1) = H$ and A_8 as $e_1(0) = H$, $e_2(0) = L$, $e_2(1) = L$. Note that the high effort proportion under action A_1, A_2, A_3, A_4, A_5, A_6, A_7, and A_8 is $\bar{e}(A_1) = 1$, $\bar{e}(A_2) = 0$, $\bar{e}(A_3) = \frac{1+p}{2}$, $\bar{e}(A_4) = \frac{q}{2}$, $\bar{e}(A_5) = \frac{2-p}{2}$, $\bar{e}(A_6) = \frac{1-q}{2}$, $\bar{e}(A_7) = \frac{1}{2}$ and $\bar{e}(A_8) = \frac{1}{2}$ respectively.

Lemma 3.1 (Supplier's Optimal Effort Decision). *Supplier's best response to the targeted score $T \in \{0,1,2\}$ is as follows:*

- *When target is 0 the supplier best response is to exert A_2.*
- *When target is 1 the supplier best response is to exert A_2 when $\Delta \le \frac{1}{p-q}$, exert A_6 when $\frac{1}{p-q} < \Delta \le \frac{1-p+q}{(p-q)(1-p)}$ and exert A_5 when $\frac{1-p+q}{(p-q)(1-p)} < \Delta$.*
- *When target is 2 the supplier best response is to exert A_2 when $\Delta \le \frac{1}{p-q}$, exert A_4 when $\frac{1}{p-q} < \Delta \le \frac{1+p-q}{(p-q)p}$ and exert A_3 when $\frac{1+p-q}{(p-q)p} < \Delta$.*

Lemma 3.1 characterizes supplier optimal effort decision depending on the relative reward Δ. At each targeted score, it is trivial to observe that the high effort proportion increases in the relative reward Δ. This result indicates that a higher reward or a lower high effort cost induces the supplier to put in more effort in order to achieve a score above the targeted score and in turn gain the reward.

Proposition 3.1 (Optimal Targeted Score). *The manufacturer's optimal targeted score T^* that maximizes supplier high effort proportion $\bar{e}$ is as follows:*

- *When* $\Delta \leq \frac{1}{p-q}$ *supplier never exerts low effort for any targeted score, and the optimal targeted score is* $T^* \in \{0,1,2\}$ *that leads to* $\bar{e}^*(A_2) = 0$.
- *When* $\frac{1}{p-q} < \Delta \leq \min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\}$ *the optimal targeted score is* $T^* = 2$ *that leads to* $\bar{e}^*(A_4) = \frac{q}{2}$ *when* $q \geq \frac{1}{2}$ *and the optimal targeted score is* $T^* = 1$ *that leads to* $\bar{e}^*(A_6) = \frac{1-q}{2}$ *otherwise.*
- *When* $\min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} < \Delta \leq \max\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\}$ *the optimal targeted score is* $T^* = 2$ *that leads to* $\bar{e}^*(A_3) = \frac{1+p}{2}$ *when* $p + q \geq 1$ *and the optimal targeted score is* $T^* = 1$ *that leads to* $\bar{e}(A_5) = \frac{2-p}{2}$ *otherwise.*
- *When* $\max\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} < \Delta$ *the optimal targeted score is* $T^* = 2$ *that leads to* $\bar{e}^*(A_3) = \frac{1+p}{2}$ *when* $p \geq \frac{1}{2}$ *and the optimal targeted score is* $T^* = 1$ *that leads to* $\bar{e}(A_5) = \frac{2-p}{2}$ *otherwise.*

Corollary 3.1. *Under the optimal targeted score (as defined in Proposition 3.1) the high effort proportion,* $\bar{e}^*$*, increases in the relative reward* Δ*.*

Proposition 3.1 characterizes the targeted score that maximizes suppliers' performance. Setting a target below the optimal target makes it easy for the supplier to achieve and in turn leads to a lower high effort proportion compared to the optimal target. On the other hand, setting the target above the optimal target makes it too hard for the supplier to achieve and therefore discourage the supplier from exerting high effort. Fixing the cost, Corollary 3.1. shows that a higher reward motivates the supplier to improve its performance by exerting more effort.

3.1.2. Relative Approach

Under the Relative approach the manufacturer engages two suppliers in a two-period contractual agreement. The manufacturer requires each supplier to deliver a batch of product at each period. The manufacturer evaluates each supplier performance independently and assigns a score to the supplier at the end of each period $n \in \{1,2\}$. If supplier i performance at period n is acceptable then the supplier gains 1 score, i.e., $s_{i,n} = 1$ and otherwise it receives no score, i.e., $s_{i,n} = 0$. We denote supplier i's cumulative scores up to period n as $S_{i,n} = \sum_{t=1}^{n} s_{i,t}$. At each period n suppliers independently decide on their effort $e_{i,n}$ which can be either high effort denoted as H or low effort denoted as L after observing its own score in the previous periods. Supplier incurs cost of $C > 0$ when it exerts high effort and 0 otherwise. Supplier i's period n score $s_{i,n}$, is considered acceptable by the manufacturer with probability p when it exerts high effort and with probability q when low effort. Similar to the Absolute approach, acceptable performance is more likely to be resulted from exerting high effort than from exerting low effort, i.e., $q < p$.

At the end of the contract, the manufacturer rewards suppliers such that the supplier with the highest final cumulative score receives R_1 and the other supplier receives R_2. Without loss of generality we assume that $R_1 \geq R_2$. Note that in case both suppliers obtain the same final score then they equally share the reward, i.e., each supplier receives $\frac{R_1+R_2}{2}$. Here we denote the relative reward as $\widetilde{\Delta} \triangleq \frac{R_1-R_2}{2C}$. We assume that suppliers are risk-neutral and expected payoff maximizer. Given supplier i's cumulative score up to period n, $S_{i,n-1}$, supplier objective is to choose his effort level $e_{i,n}(S_{i,n-1})$ to maximize his expected payoff from period n onward, denoted by $\pi_{i,n}(S_{i,n-1}) = \max_{e_{i,n} \in \{H,L\}} \{\pi_{i,n}(S_{i,n-1}, H), \pi_n(S_{i,n-1}, L)\}$ where $\pi_{i,n}(S_{i,n-1}, H) = p\pi_{i,n+1}(S_{i,n-1} +$

$1) + (1-p)\pi_{i,n+1}(S_{i,n-1}) - C$, $\pi_{i,n}(S_{i,n-1}, L) = q\pi_{i,n+1}(S_{i,n-1}+1) + (1-q)\pi_{i,n+1}(S_{i,n-1})$ and $\pi_{i,N+1}(S_{i,N}) = \begin{cases} R_1 & S_{i,N} > S_{-i,N} \\ \frac{R_1+R_2}{2} & S_{i,N} = S_{-i,N} \\ R_2 & S_{i,N} < S_{-i,N} \end{cases}$.

The manufacturer objective is to set a reward scheme $R = \{R_1, R_2\}$ and exhaust its budget $2R$ (i.e., $R_1 + R_2 \leq 2R$) to maximize suppliers' high effort proportion. To derive the optimal reward scheme $R = \{R_1, R_2\}$, we first characterize the suppliers' best response to the manufacturer's announced reward scheme in Lemma 3.2 and then we will derive the manufacturer's optimal reward scheme that maximizes supplier high effort proportion in Proposition 3.2. Suppliers' equilibrium actions in response to the reward scheme $R = \{R_1, R_2\}$ is described in the following 7 cases, and we denote constraint E_1 as $(1-p)(1-q) \leq p^2$, E_2 as $(1-q)^2 \leq qp$, E_3 as $(1-p)^2 \geq qp$, E_4 as $(1-p)(1-q) \geq q^2$ and to define the mixed strategies, we denote $\mu_{i,n}(S_{i,n-1})$ as the probability that supplier i exert high effort at period n when its cumulative score is $S_{i,n-1}$ such that $\mu_{i,2}(0) = \frac{1-q}{p-q} - \frac{1-\left(\frac{2C}{(R_1-R_2)(p-q)}\right)}{(p-q)\left(\mu_{i,1}(0)(1-p)+\left(1-\mu_{i,1}(0)\right)(1-q)\right)}$ and $\mu_{i,2}(1) = \frac{1-\left(\frac{2C}{(R_1-R_2)(p-q)}\right)}{(p-q)\left(\mu_{i,1}(0)p+\left(1-\mu_{i,1}(0)\right)q\right)} - \frac{q}{p-q}$.

Lemma 3.2 (Supplier's Equilibrium Effort). *Suppliers' equilibrium effort in response to the relative reward $\tilde{\Delta}$ are described in the following 7 cases:*

- *When $q \geq \frac{1}{2}$ and E_2 holds, the equilibrium actions are A_2A_2, A_4A_4, A_3A_3 and A_1A_1 when $\tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-q)^2)}$, $\frac{1}{(p-q)(1-(1-q)^2)} < \tilde{\Delta} \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ and $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ respectively.*

- *When* $q \leq \frac{1}{2}$ *and* E_2 *holds, the equilibrium actions are* A_2A_2, *mixed strategy with* $\mu_{i,n}(S_{n-1})$, A_4A_4, A_3A_3 *and* A_1A_1 *when* $\tilde{\Delta} \leq \frac{1}{(p-q)(1-q^2)}$, $\frac{1}{(p-q)(1-q^2)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-q)^2)}$, $\frac{1}{(p-q)(1-(1-q)^2)} < \tilde{\Delta} \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ *and* $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ *respectively.*
- *When* E_2 *and* E_4 *do not hold, the equilibrium actions are* A_2A_2, *mixed strategy with* $\mu_{i,n}(S_{n-1})$, A_3A_3 *and* A_1A_1 *when* $\tilde{\Delta} \leq \frac{1}{(p-q)(1-q^2)}$, $\frac{1}{(p-q)(1-q^2)} < \tilde{\Delta} \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$, $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ *respectively.*
- *When* E_3 *does not hold and* E_4 *holds, the equilibrium actions are* A_2A_2, A_6A_6, *mixed strategy with* $\mu_{i,n}(S_{n-1})$,A_3A_3 *and* A_1A_1 *when* $\tilde{\Delta} \leq \frac{1}{(p-q)(1-q^2)}$, $\frac{1}{(p-q)(1-q^2)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-q)^2)}$, $\frac{1-p+q}{(p-q)(1-p+qp)} < \tilde{\Delta} \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ *and* $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ *respectively.*
- *When* E_1 *and* E_3 *hold, the equilibrium actions are* A_2A_2, A_6A_6, A_5A_5, *mixed strategy with* $\mu_{i,n}(S_{n-1})$,A_3A_3 *and* A_1A_1 *when* $\tilde{\Delta} \leq \frac{1}{(p-q)(1-q^2)}$, $\frac{1}{(p-q)(1-q^2)} < \tilde{\Delta} \leq \frac{1-p+q}{(p-q)(1-p+qp)}$, $\frac{1-p+q}{(p-q)(1-p+qp)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-p)^2)}$, $\frac{1}{(p-q)(1-(1-p)^2)} < \tilde{\Delta} \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ *and* $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ *respectively.*
- *When* $p \geq \frac{1}{2}$ *and* E_1 *does not hold, the equilibrium actions are* A_2A_2, A_6A_6, A_5A_5, *mixed strategy with* $\mu_{i,n}(S_{n-1})$ *and* A_1A_1 *when* $\tilde{\Delta} \leq \frac{1}{(p-q)(1-q^2)}$, $\frac{1}{(p-q)(1-q^2)} < \tilde{\Delta} \leq \frac{1-p+q}{(p-q)(1-p+qp)}$, $\frac{1-p+q}{(p-q)(1-p+qp)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-p)^2)}$, $\frac{1}{(p-q)(1-(1-p)^2)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ *and* $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ *respectively.*
- *When* $p \leq \frac{1}{2}$ *and* E_1 *does not hold, the equilibrium actions are* A_2A_2, A_6A_6, A_5A_5 *and* A_1A_1 *when* $\tilde{\Delta} \leq \frac{1}{(p-q)(1-q^2)}$, $\frac{1}{(p-q)(1-q^2)} < \tilde{\Delta} \leq \frac{1-p+q}{(p-q)(1-p+qp)}$, $\frac{1-p+q}{(p-q)(1-p+qp)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-p)^2)}$ *and* $\frac{1}{(p-q)(1-(1-p)^2)} < \tilde{\Delta}$ *respectively.*

In Lemma 3.2 we derive suppliers' best response to the announced reward scheme $\{R_1, R_2\}$. It is trivial to observe that the high effort proportion increases in the relative reward $\widetilde{\Delta}$. Using Lemma 3.2 we derive the manufacturer's optimal reward scheme that maximizes suppliers' high effort proportion in Proposition 3.2.

Proposition 3.2 (Optimal Reward Scheme: The Winner Takes All). *Allocating the whole budget to the supplier with the highest score* $R_1^* = 2R$ *and* $R_2^* = 0$ *maximizes suppliers' high effort proportion.*

Through Lemma 3.2, it is trivial to observe that the equilibrium high effort proportion increases in the relative reward $\widetilde{\Delta}$ and in turn in the differences between the smallest and the largest reward, i.e., $R_1 - R_2$. This observation indicates that the manufacturer can induces a higher equilibrium high effort proportion by increasing the gap between the smallest and the largest reward. Using this facts in Proposition 3.2 we derive that allocating the whole reward pie $2R$ to the supplier with the largest final score maximizes suppliers' equilibrium high effort proportion. Plugging the optimal reward scheme in the relative reward $\widetilde{\Delta} = \frac{R_1^* - R_2^*}{2c}$ we have that $\widetilde{\Delta} = \frac{2R-0}{2c} = \frac{R}{c} = \Delta$, and therefore the relative reward under the optimal reward scheme is equal to the relative reward under the Absolute approach.

Corollary 3.2. *Under the optimal reward scheme (as defined in Proposition 3.2) the high effort proportion,* $\bar{e}^*$*, increases in the relative reward* Δ*.*

Fixing the cost, Corollary 3.2 shows that a larger reward pie motivates the suppliers to improve their performance by exerting more effort.

In Section 3.1.1, we derive the optimal effort decision for a supplier under the Absolute approach and we derive the manufacturer's optimal target. In Section 3.1.2, we analyze the Relative approach and derive suppliers' equilibrium effort and then we derive the optimal reward scheme that maximizes suppliers' equilibrium high effort proportion. In the next Section, we compare the high effort proportion under both approaches to derive the manufacturer's optimal decision regarding which of the approaches to choose to maximize the supplier high effort proportion.

3.1.3. Manufacturer's Optimal Approach

Comparing the equilibrium high effort proportion under both Absolute and Relative approach, we derive the manufacturer's optimal approach that maximizes suppliers' high effort proportion in Proposition 3.3.

Proposition 3.3 (Manufacturer's Optimal Approach). *The Absolute approach leads to a weakly higher high effort proportion than the Relative approach when the relative reward Δ is smaller than a threshold τ, and otherwise the Relative approach leads to a weakly higher high effort proportion. When E_2 holds, then when $q \geq \frac{1}{2}$ we have that $\tau = \frac{1}{(p-q)(1-(1-q)^2)}$ and otherwise $\tau = \frac{1+p-q}{(p-q)(1+qp-q)}$. When E_2 does not hold then $\tau = \frac{1}{(p-q)(1-q^2)}$.*

Proposition 3.3 shows that the Relative approach leads to a higher high effort proportion compared to the Absolute approach when the relative reward is larger than the threshold τ. Using Proposition 3.3 the manufacturer can determine which approach to select based on the suppliers' capabilities (i.e., p, q, and C) and the manufacturer's budget R.

3.2. Experimental Design and Result

In Section 3.1, we theoretically analyze suppliers' performance under both Absolute and Relative approach and compared suppliers' performance under both approaches with each other to derive the manufacturer's optimal decision. In this Section, we first set up hypotheses based on the theoretical findings in Section 3.1 and then we design human-subject experiment to test our theoretical findings.

3.2.1. Experimental Hypotheses

The theoretical model in Section 3.1 provides two empirically testable predictions. First, the equilibrium high effort proportion increases in the relative reward Δ (i.e., $\Delta = \frac{R}{C}$) under both approaches. Second, the Absolute approach improves suppliers' performance more than Relative approach when the relative reward is less than the threshold τ, and when the relative reward is higher than the threshold then the Relative approach leads to a higher suppliers' performance.

Hypothesis 3.1 (The Effect of Relative Reward on Suppliers' Performance). *Suppliers' performance weakly increases in the relative reward under both approaches.*

Our theoretical model predicts that suppliers' performance increases in the relative reward under both approaches, Lemma 3.1 and Lemma 3.2. A higher reward makes it more profitable for the suppliers to exert high effort and in turn increase their chances to earn the reward. On the other hand, a higher cost of effort makes it more expensive for the supplier to exert high effort.

Hypothesis 3.2 (Suppliers' Performance Under Relative Vs. Absolute Approach). *When relative reward is smaller than the threshold suppliers' performance is higher under the Absolute approach and otherwise suppliers' performance is higher under the Relative approach.*

The theoretical analysis in Proposition 3.3 predicts that the Relative approach improves suppliers' performance when the relative reward is higher than the threshold τ. This prediction indicates that competition improves suppliers' performance when the relative reward is large enough, and therefore the manufacturer is better off by imposing the Relative approach.

3.2.2. Experimental Design

In our experiments, we vary the incentive approach (Relative and Absolute) and the reward (13 ECU, 26 ECU and 45 ECU) for a 2×3 full factorial between-subjects design. We fixed $q = 0.3$, $p = 0.7$, and $C = 10$ ECU (Experimental Currency Unit) in all treatments. In total we recruited 143 participants for 6 treatments and each human-subject participated in one treatment only. Treatments following the Absolute approach and Relative approach are labeled as A_{reward} and R_{reward} respectively. We varied the subscript reward to be 13 ECU, 26 ECU and 45 ECU. Table 3.1 summarizes the 6 treatments and the number of independent cohorts in each treatment.

Table 3.1. Summary of the Experimental Design

		Approach	
		Absolute	Relative
Reward	13 ECU	A_{13} (24 subjects)	R_{13} (4 cohorts of 6)
	26 ECU	A_{26} (24 subjects)	R_{26} (4 cohorts of 6)
	45 ECU	A_{45} (23 subjects)	R_{45} (4 cohorts of 6)

We recruited subjects through SONA, which is an online recruitment system (https://utdallasjindal.sona-systems.com), offering earning cash as the only incentive to participate. We conducted all sessions at The University of Texas at Dallas. Upon arrival at the laboratory the subjects were seated at computer terminals in isolated cubicles. We handed out written instructions (see Appendix B for samples) to participants. After they read the instructions, to ensure common knowledge about the game's rules we then read the instructions aloud before starting the actual game. In all treatments, participants played 20 rounds of the game (each round included 2 periods, so in total, each participant made 40 decisions) with random matching each round in the Relative approach treatments.

We programmed the experimental interface using the Z-Tree system (Fischbacher 1999). At the end of each session, we computed cash earnings for each participant by multiplying the total earnings from all rounds by a pre-determined exchange rate and adding it to a $5 participation fee. Participants were paid their earnings in private and in cash, at the end of the session. Average earnings, including the show-up fee, were approximately $10, and each session lasted less than one hour.

3.2.3. Experimental Results

Figure 3.1 shows the observed proportional high effort in Absolute (solid line) and Relative (dashed line) treatments. We formally compare suppliers high effort proportion between treatments using a one-sided t-test, and the alternative hypothesis as implied by Hypothesis 3.1 and Hypothesis 3.2 and summarize these results in Table 3.2. The unit of analysis is a cohort.

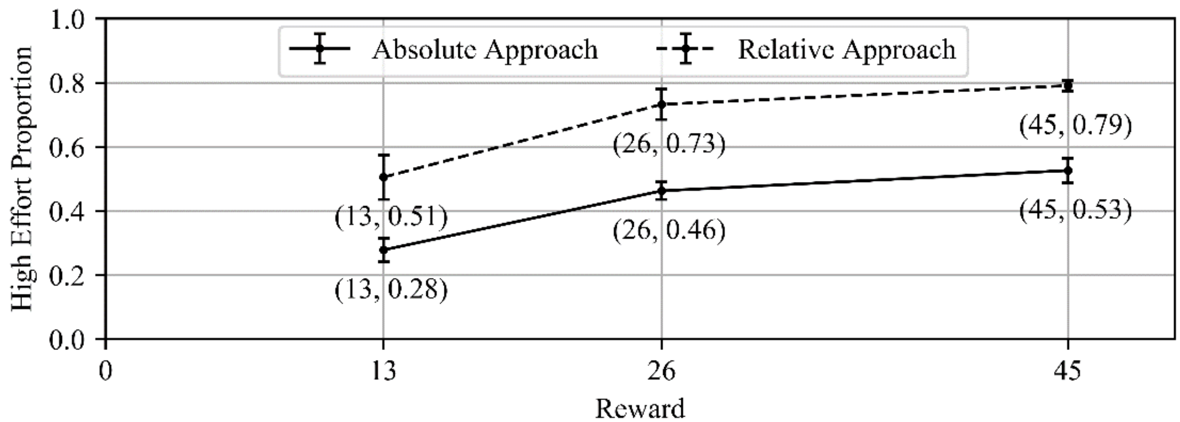

Figure 3.1. High Effort Proportion under Absolute and Relative Treatments

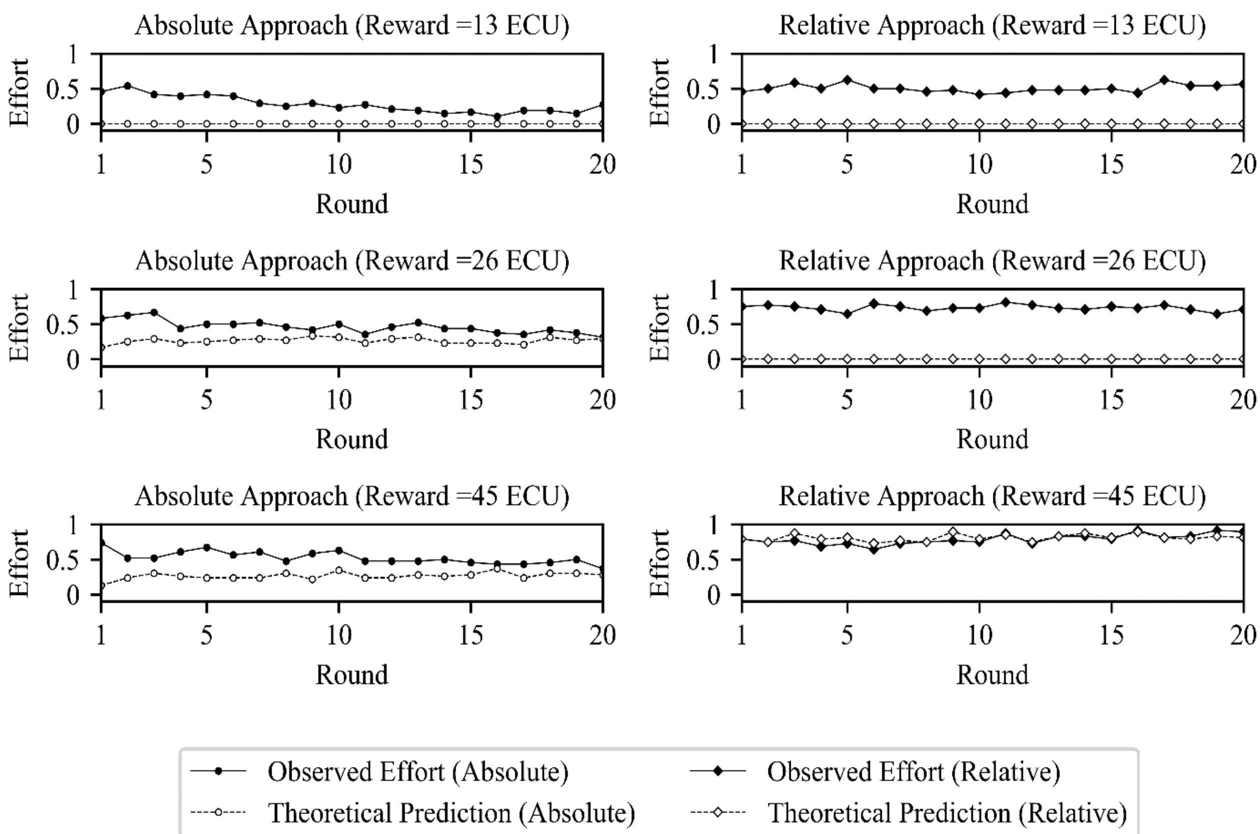

Figure 3.2. Observed Average Effort Vs. Theoretical Prediction under Absolute (Left) and Relative (Right) Treatments

The statistical tests in Table 3.2 reveal two main findings. First, high effort proportion increases in reward. This observation is always valid except under Relative approach for $R_{26} < R_{45}$ and in this case under 5% significant level we cannot reject that suppliers' performance are equal in R_{26} and R_{45}. This is in line with our theoretical predictions and shows that higher reward weakly induces higher suppliers' performance under both approaches. Second, Relative approach motivates subjects to exert more effort compared to the Absolute approach at any reward. When reward is large (i.e., reward is 45 ECU) the experimental observations validate the theoretical predictions that high effort proportion is higher under the Relative approach compared to the Absolute approach. However, when the reward is small (i.e., Reward is either 13 or 26 ECU) the experimental observation is against the theoretical predictions that for small reward Absolute approach leads to higher suppliers' performance.

Figure 3.2 presents observed (solid line) and optimal prediction (dashed line) of high effort proportion under both approaches over 20 rounds when reward is 13, 26, and 45 ECU. Figure 3.2 shows that subjects on average exert more effort than theoretical predictions. We formally test overexertion of effort using a one-sided t-test and summarize these results in Table 3.3.

Except treatment R_{45} in all other treatments under 1% significant level we can conclude that subjects overexert effort compared to the theoretical model prediction. In treatment R_{45} under 1% significant level we cannot reject that the observed high effort proportion and theoretical prediction are equal.

In treatments following the Relative approach, we also derive the *empirical best response*. That is the subject's best response given that the other subject is exerting effort based on the experimental observation. In treatments R_{13} and R_{26} the empirical best response is to exert A_2 and in treatment R_{45} the empirical best response is to exert A_1. This result shows that the average effort based on the empirical best response is less than the experimental observation in treatments R_{13} and R_{26}. In treatment R_{45} the average effort based on the empirical best response is higher than the experimental observation. Therefore, we can conclude that subjects do not follow the rational prediction.

Table 3.2. Summary of the Experimental Results on H 3.1 and H 3.2

		Absolute Approach			Relative Approach			
	Treatments	A_{13}	A_{26}	A_{45}	R_{13}	R_{26}	R_{45}	
	Reward	13	26	45	13	26	45	
	Avg. Effort	0.27	0.46	0.52	0.50	0.73	0.79	
	Std. Error	(0.03)	(0.02)	(0.03)	(0.06)	(0.04)	(0.01)	
	Alternative Hypothesis							*p*-Value
The Effect of Reward on Performance (H 3.1)	$A_{13} < A_{26}$	x	x					0.000
	$A_{26} < A_{45}$		x	x				0.091
	$R_{13} < R_{26}$				x	x		0.020
	$R_{26} < R_{45}$					x	x	0.156
Suppliers' Performance Under Relative Vs. Absolute Approach (H 3.2)	$A_{13} \neq R_{13}$	x			x			0.035
	$A_{26} > R_{26}$		x			x		0.998
	$A_{45} < R_{45}$			x			x	0.000

Figure 3.3 presents the average proportion of observed high effort conditional on the optimal effort being either high (black face marker) or low (white face marker) under Absolute approach (left) and Relative approach (right), over 20 rounds. The figure illustrates that subjects' effort is more consistent with the optimal prediction when the optimal action is to exert high effort compared to the case that the optimal action is to exert low effort.

Table 3.3. Summary of the Experimental Results

		Absolute Approach			Relative Approach			
	Treatments	A_{13}	A_{26}	A_{45}	R_{13}	R_{26}	R_{45}	
	Reward	13	26	45	13	26	45	
	Avg. Effort	0.27	0.46	0.52	0.50	0.73	0.79	
	Std. Error	(0.03)	(0.02)	(0.03)	(0.06)	(0.04)	(0.01)	
	Theoretical Prediction	0.00	0.26	0.26	0.00	0.00	0.81	
	Std. Error	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	
	Alternative Hypothesis							*p*-Value
Overexertion of Effort	$A_{13} > 0.00$	x						0.000
	$A_{26} > 0.26$		x					0.000
	$A_{45} > 0.26$			x				0.000
	$R_{13} > 0.00$				x			0.002
	$R_{26} > 0.00$					x		0.000
	$R_{45} > 0.81$						x	0.851

Figure 3.4 presents observed proportion of high effort conditional on whether the optimal effort is low (X axis) or the optimal effort is high (Y axis) at the individual level. In both figures the theoretical prediction is the point (0,1) where the probability of exerting high is 0 when the optimal effort to exert is low and the probability of exerting high is 1 when the optimal effort to exert is high. These figures show that subjects are prone to make less mistakes when the optimal effort is high, as the dots on the graphs are mostly on the upper triangular and above the 45 degrees line.

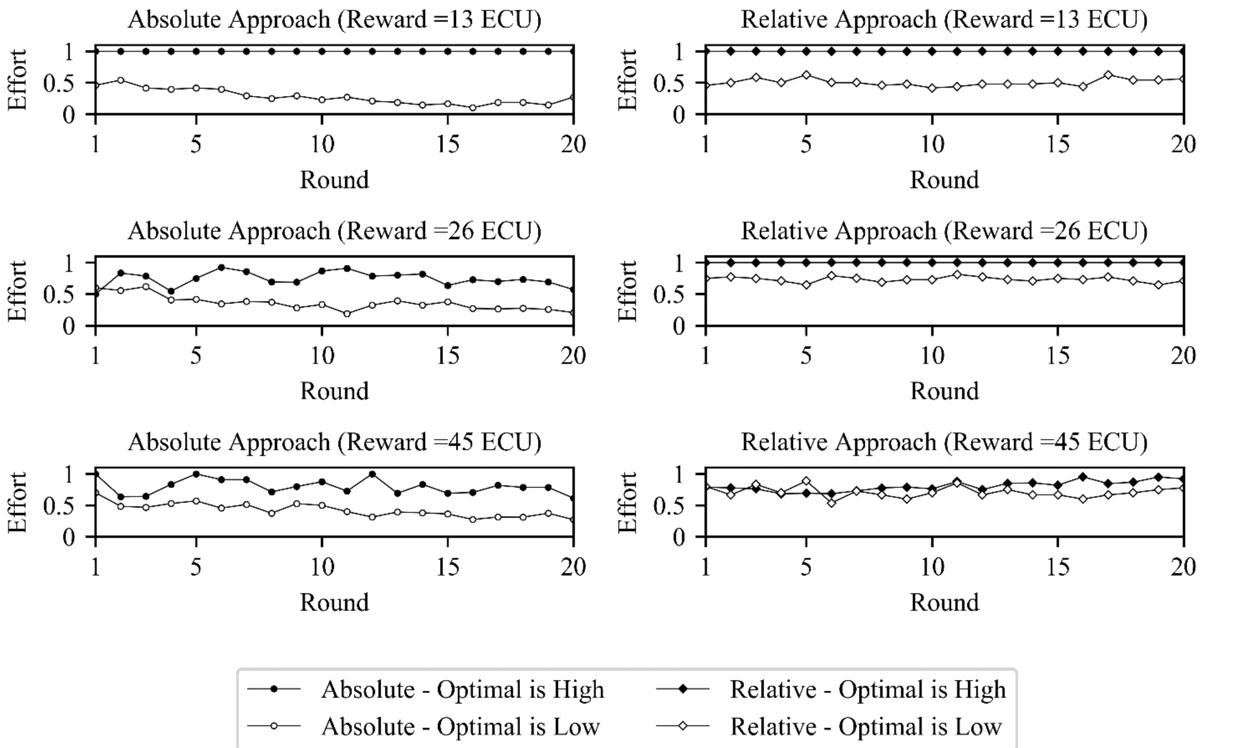

Figure 3.3. Average High Effort Conditional on the Optimal Effort Is High (Black Face Markers) or Low (White Face Markers)

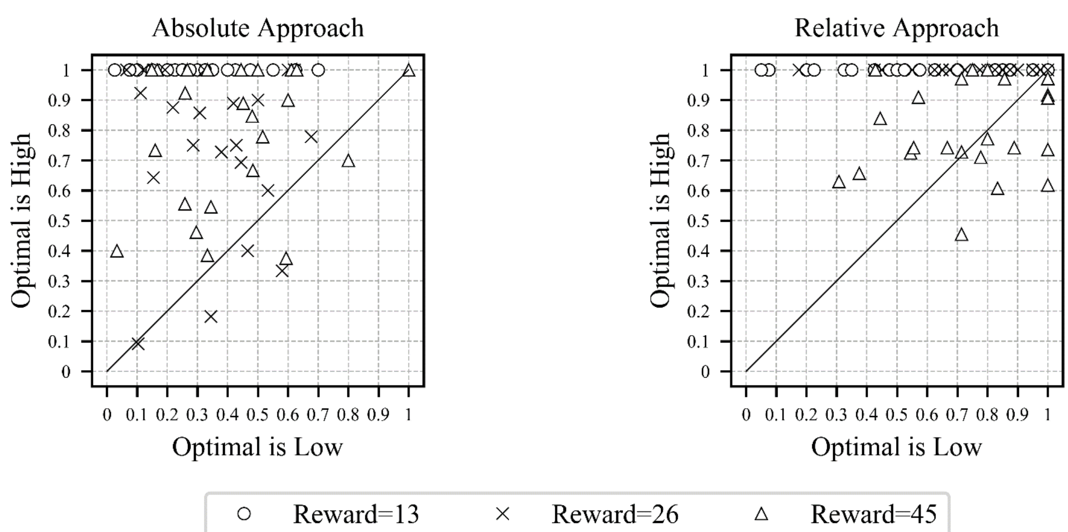

Figure 3.4. Average High Effort Conditional on Whether the Optimal Effort Is Low (X Axis) or the Optimal Effort Is High (Y Axis) under the Absolute Approach (Left) and Relative Approach (Right)

We formally test observation in Figure 3.4 and study subjects' decisions conditional on optimal effort being high through regression analysis. We run a logit regression where the dependent variable is 1 when the subject's decision is consistent with the optimal effort (i.e., $e_{i,n}(S_{i,n-1}) = e_n^*(S_{i,n-1})$) and 0 otherwise. Independent variables are listed in the first column of Table 3.4.

Table 3.4 summarizes the logistic regression results. Note that model (5) leads to the least AIC and BIC and the highest log-likelihood compared to the other models. The result presents three main findings. First, positive coefficient of *Optimal Effort is High* shows that subject's effort is more consistent with the theoretical prediction when the optimal effort is to exert high effort. Second, the positive and significant coefficient of the *Round* indicates that the likelihood of following theoretical prediction increases over rounds. Subjects learn to make better decisions by gaining more experience over rounds. Third, the positive and significant coefficient of *Period × 1 if Absolute Approach* shows that subjects' decision becomes more consistent with the theoretical predication over periods in treatments under absolute approach. When subjects get closer to the end of the contract life-span, they can better evaluate the chance of achieving the target and in turn they can make more rational decision. Note that in each cell, the first, and second row presents the coefficient estimation, and standard error (in parenthesis), respectively. Additionally, *p*-Value <0.01 ***, <0.05 **, and <0.1*.

Table 3.4. Summary of the Regression Analysis

Independent Variables	(1)	(2)	(3)	(4)	(5)
1 if Optimal Effort is High	1.328*** (0.107)	1.369*** (0.107)	1.403*** (0.111)	1.361*** (0.113)	1.159*** (0.122)
1 if Absolute Approach	--	1.104*** (0.201)	1.106*** (0.199)	1.129*** (0.203)	-0.301 (0.461)
Reward $\in \{13,26,45\}$	--	--	-0.010 (0.007)	-0.009 (0.007)	-0.006 (0.007)
Period $\in \{1,2\}$	--	--	--	0.220*** (0.063)	0.099 (0.186)
Round $\in \{1 \cdots 20\}$	--	--	--	0.046*** (0.005)	0.045* (0.024)
Round × Period	--	--	--	--	-0.017 (0.015)
Round × 1 if Absolute Approach	--	--	--	--	0.045 (0.034)
Period × 1 if Absolute Approach	--	--	--	--	0.571** (0.266)
Round × Period × 1 if Absolute Approach	--	--	--	--	0.006 (0.022)
Constant	0.112 (0.112)	-0.447** (0.144)	-0.149 (0.254)	-0.989*** (0.284)	-0.552 (0.393)
N (Observations)	5720	5720	5720	5720	5720
N (Groups)	143	143	143	143	143
Log Likelihood	-3212.278	-3198.469	-3197.484	-3155.778	-3131.465
AIC	6430.557	6404.939	6404.969	6325.557	6284.929
BIC	6450.512	6431.546	6438.227	6372.119	6358.098

Figure 3.5 presents average payoff of cohorts per unit of high effort (i.e., cohorts' payoff divided by total effort) under Absolute approach (gray bars) and under Relative approach (hatched light gray bars). Under 5% significant level we conclude that subjects earn more under Absolute approach for each unit of effort they exert compared to the Relative approach. This observation indicates that the manufacturer is better off by imposing the Relative approach compared to the Absolute approach. The manufacturer incurs less cost for each unit of high effort that it receives from suppliers under the Relative approach than Absolute approach.

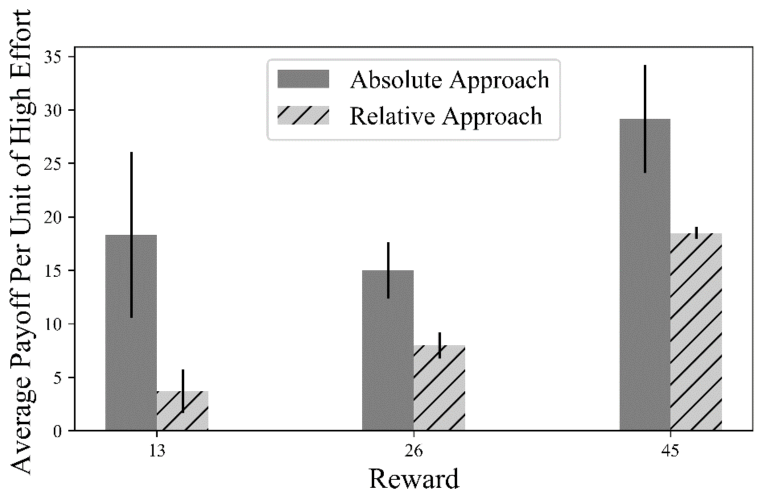

Figure 3.5. Average Subject's Payoff Per Unit of High Effort Under Absolute and Relative Approach

CHAPTER 4

HOW SUPPLIER SCORECARDS AFFECT PROCUREMENT QUALITY: A BEHAVIORAL STUDY

In what follows, we introduce the theoretical model in Section 4.1 We then describe the Behavioral Analysis in Sections 4.2. All experimental instructions are provided in Appendix B, and additional results on the experimental outcomes are provided in Appendix C.

4.1. Analytical Model

The model setting follows Absolute approach as described in Section 3.1.1 of chapter 4 except here the contract lasts for N periods. We identify the normative benchmark in the Proposition 4.1.

Proposition 4.1. (Supplier's optimal effort decision) *For each period* $n \in \{1, 2, \ldots, N\}$, *there exist two thresholds* $\underline{S}_n$ *and* $\overline{S}_n$ *such that it is optimal for the supplier to choose* $e_n = High$ *if and only if* $\underline{S}_n \leq S_{n-1} \leq \overline{S}_n$.

The insight to the proposition is that the supplier "gives up" (i.e., stopping to aggressively pursue contract renewal by high effort cost) if his current score is too low to give him a good chance of meeting the buyer's final target level T, and he "takes a break" (i.e., economically saving effort cost while maintaining high contract renewal probability) if his current score is so high that he can risk losing the score in the current period. The thresholds depend on the targeted score T, success probability of high effort p, success probability of low effort q, and the relative reward $\frac{R}{C}$. They do not have closed-form expressions but can be derived by backward-induction solving the supplier's dynamic decision making.

4.2. Behavioral Analysis

In Section 4.1, we theoretically analyze suppliers' performance. Here, we are interested in how human subjects, in supplier role, make effort decisions throughout the N-period contract life span, compared to the normative benchmark. We use the average per-period high effort as a simple metric to measure the impact of supplier choices to the buyer's prespecified target. In this Section, we first illustrate experimental results and then we design human-subject experiment to test our theoretical findings.

4.2.1. Experimental Design

In this Section we describe the laboratory experiment that we designed to test the analytical results in the previous Section. In all treatments, we set $q = 0.3$, $N = 10$ and $R = 120$, and we vary the reliability level p and the target level T. We used two reliability levels: low reliability of $p = 0.4$ and high reliability of $p = 0.7$. For $p = 0.4$ condition we used $T = 3$, 4, 5 and 7; for $p = 0.7$ condition we used $T = 4$, 7 and 9, for a total of seven treatments. We display optimal strategies for the seven treatments in our study in Figure 4.1.

For each reliability level we included a treatment with the optimal target level, as well as a treatment with a target level that is too high and too low. For the $p = 0.4$ condition we also included an extra treatment with an even higher target level in order to gain further insights into how participants choose effort levels in that setting. Figure 4.2 plots optimal average per-period effort for low and high reliability conditions for a range of target levels and indicates the target levels of the seven treatments in our study.

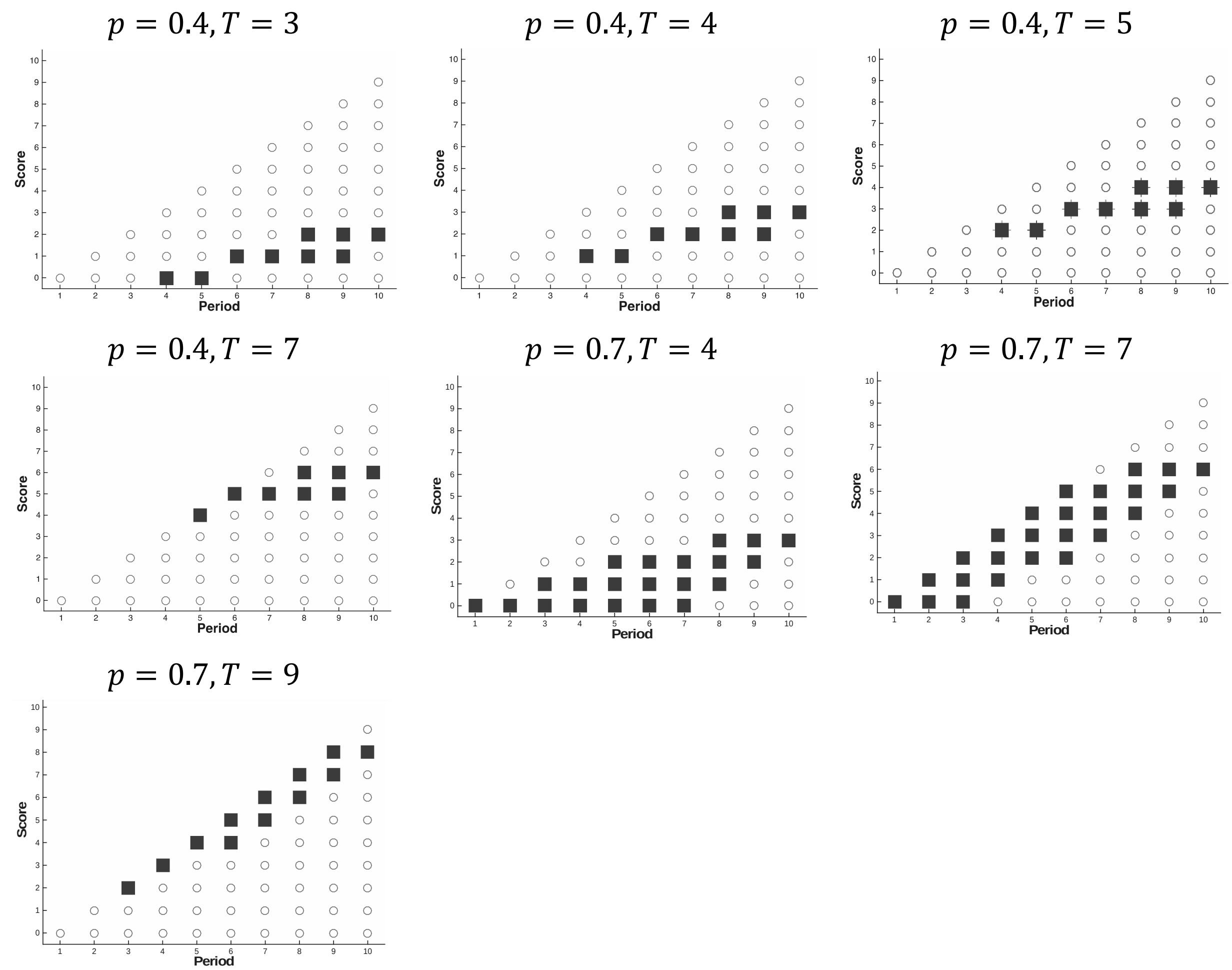

Figure 4.1. Optimal Strategies

In all treatments except treatment with $p = 4$ and $T = 7$, we recruited 20 participants and in treatment with $p = 4$ and $T = 7$ we recruited 10 participants. In total we include 130 participants in all 7 treatments. We conducted all sessions at a public university in the United States, in a computer laboratory dedicated to research. Our participants were students, mostly master level, primarily business and engineering majors. We recruited them through SONA, which is an online recruitment system (http://www.sona-systems.com), offering earning cash as the only incentive to participate.

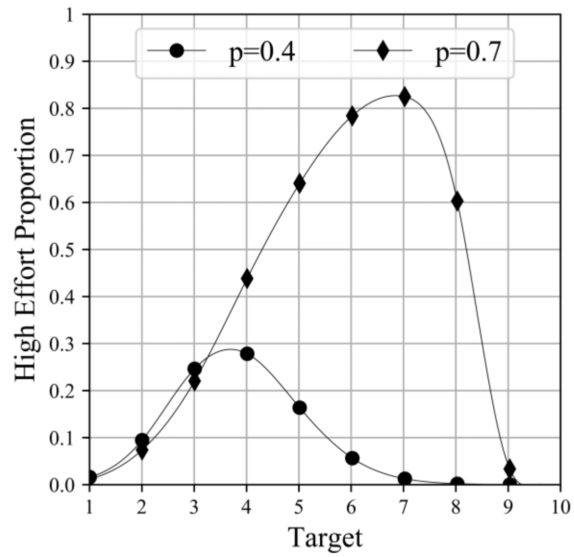

Figure 4.2. Theoretical Predictions and Experimental Treatments

Upon arrival at the laboratory the subjects were seated at computer terminals in isolated cubicles. We handed out written instructions (see Appendix B for samples) to participants. After they read the instructions, to ensure common knowledge about the game's rules we then read the instructions aloud before starting the actual game. In All treatments participants played 20 rounds of the game (each round included 10 periods, so in total, each participant made 200 decisions).

We programmed the experimental interface using the zTree system (Fischbacher 1999). At the end of each session we computed cash earnings for each participant by multiplying the total earnings from all rounds by a pre-determined exchange rate and adding it to a $5 participation fee. Participants were paid their earnings in private and in cash, at the end of the session. Average earnings, including the show-up fee, were approximately $30, and each session lasted less than one hour.

4.2.2. Experimental Result

Figure 4.3 shows observed and theoretical model prediction of average effort over rounds. This figure shows that subjects overexert effort compared to the theoretical model prediction. We formally test overexertion of effort in our study using a one-sided t-test and summarize these results in Table 4.1. In all treatments except treatment with $p = 0.7$ and $T = 4$, we observe that subjects' decision systematically deviates from the theoretical model prediction.

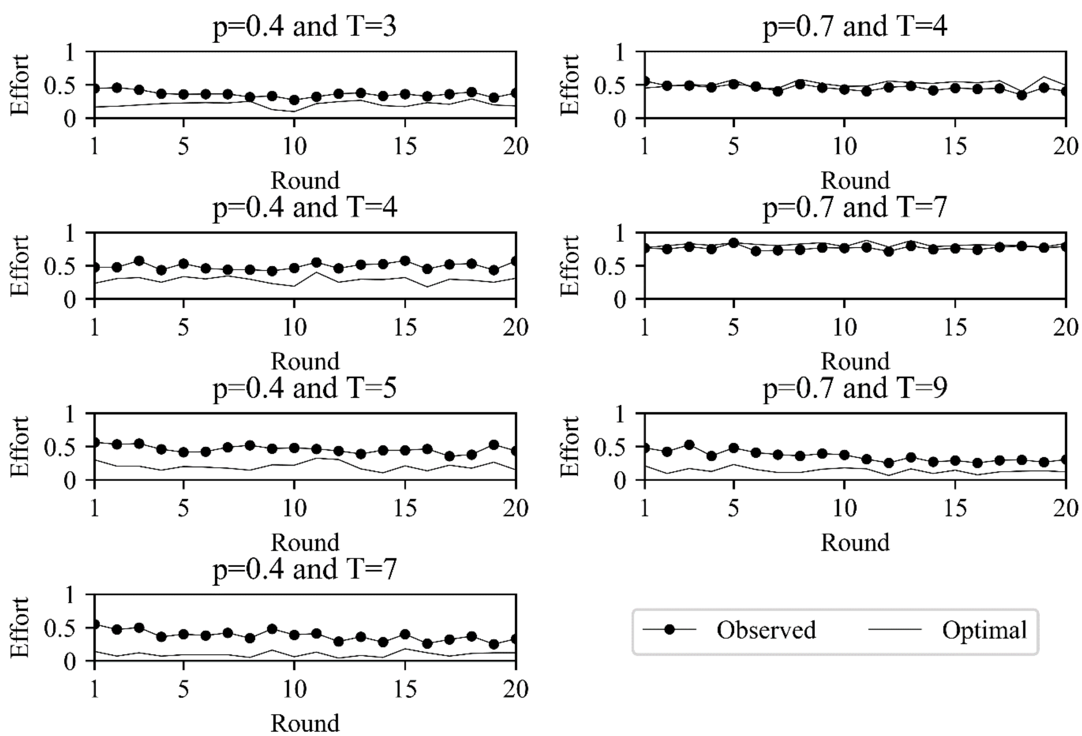

Figure 4.3. Observed High Effort Proportion Vs. Theoretical Model Prediction Over Rounds

4.2.3. Behavioral Model

In this Section we propose a behavioral model to explain subjects' decision-making behavior and bridge the gap between the experimental observation and the theoretical prediction. In the behavioral model we incorporate three factors, *psychological utility*, *perceived probability* and *bounded rationality*.

Table 4.1. Summary of the Experimental Results

Treatments	Low Reliability ($p = 0.4$)				High Reliability ($p = 0.7$)		
Target (T)	3	4	5	7	4	7	9
Avg. Effort	0.3592	0.4922	0.4625	0.378	0.4528	0.764	0.354
Std. Err.	(0.0343)	0.0455)	(0.052)	(0.0562)	(0.0225)	(0.0238)	(0.0481)
Theoretical Prediction	0.2038	0.2838	0.2032	0.098	0.5085	0.814	0.138
Std. Err.	(0.0091)	(0.0103)	(0.009)	(0.0144)	(0.0268)	(0.0121)	(0.0249)
Alternative Hypothesis:	Observed Effort Is Higher Than Theoretical Prediction						
p-Value	0.0025	0.0005	0.0033	0.0000	0.1515	0.0067	0.0001

Psychological utility (Joy of winning): the experimental results highlight that the average proportion of high effort is significantly above optimal. Several studies (Chen et al. 2011, Lim 2010, Price and Sheremeta 2011, Sheremeta 2010) have reported that subjects overexert effort because of extra non-monetary utility that they gain as a winner. In our behavioral model, we consider that in addition to the monetary outcomes from reaching the target, subject also derive extra nonpecuniary utility from winning. We denote αR (recall that R denotes the supplier gain if the contract is renewed) as psychological utility that subjects gain from winning in addition to the monetary utility of winning R. If $\alpha = 0$ then our behavioral model becomes identical to the theoretical model. On the other hand, $\alpha > 0$ confirms the existence of non-monetary utility from winning. Given suppliers' performance score at period n, namely, S_{n-1}, he chooses e_n to maximize his expected net payoff from period n onward, denoted by $U_n(S_{n-1})$. In particular, for $n \in \{1, 2, \dots, N\}$ we have:

$$U_n(S_{n-1}) \\ = \max_{e_n \in \{Low, High\}} \begin{cases} pU_{n+1}(S_{n-1}+1) + (1-p)U_{n+1}(S_{n-1}) - C, & if\ e_n = High; \\ qU_{n+1}(S_{n-1}+1) + (1-q)U_{n+1}(S_{n-1}), & if\ e_n = Low, \end{cases} \tag{10}$$

where

$$U_{N+1}(S_N) = \begin{cases} R + \alpha R & , \quad if\ S_N \geq T; \\ 0 & , \quad if\ S_N < T. \end{cases} \tag{11}$$

Perceived probability: Several studies have shown that people perception of probability does not follow a linear function (Gonzalez and Wu 1999). They empirically show that people overweight small probability and underweight large probability. They consider a probability weighting function that is shaped like an inverted "S": concave for low probabilities, convex for high probabilities. They explain that people become less sensitive to changes in probability as they move away from the two endpoints in probability 0 and 1. In their model this phenomenon is captured by γ and it shows the curvature of the weighting function. The elevation in the model is captured by δ and explains the attractiveness of the gamble to the decision maker. They estimate the probability weighting function $W(.)$ with the following form:

$$W(p) = \frac{\delta p^{\gamma}}{\delta p^{\gamma} + (1-p)^{\gamma}} \tag{12}$$

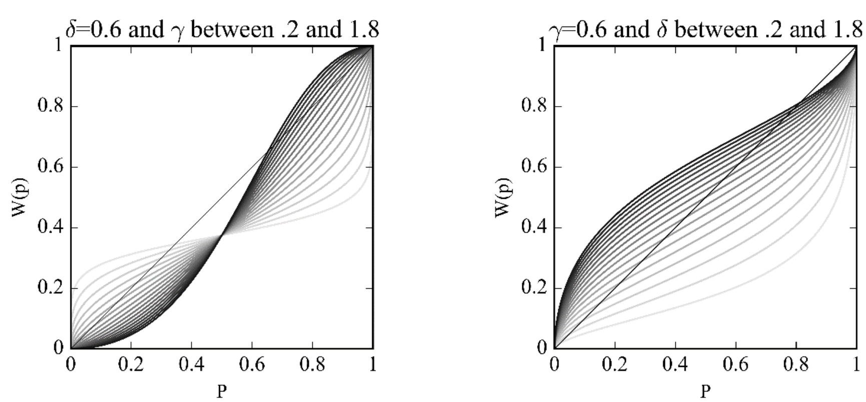

Figure 4.4. Perceived Probability W(p) as a function of γ (left) and as a function of δ (right)

Note. This figure is from Gonzalez and Wu (1999). In the left figure $\delta = 0.6$ and γ is changing from 0.2 to 1.8. In the right figure $\gamma = 0.6$ and δ is changing from 0.2 to 1.8.

Figure 4.4 shows how perceived probability changes with respect to δ and γ. In the behavioral model we incorporate the same probability weighting function to control for subjects perceived probability. Note that when $\delta = \gamma = 1$ then $W(p) = p$ and therefore the behavioral model becomes identical to the theoretical benchmark.

Bounded rationality*:* another phenomenon that might have impacted subjected decision making is that subjects are prone to make mistake in their decision making. This mistake add noise to their desicion. In our model, we capture this noise using quantal choice model introduced by McKelvey and Palfrey (1995). The main parameter in this model is σ which determines the sensitivity of the decisions probabilities with respect to payoffs. When supplier i's score at time n is s_{n-1}, the target is T and the reliability level is p, we denote utility to go of exerting $e_{i,n}(s_{n-1}, p, T) \in \{High, Low\}$ as $U_n^{e_{i,n}(s_{n-1},p,T)}(s_{n-1})$. Applying the Quantal Response Model the probability of exerting $High$ is $Prob\big(e_{i,n}(s_{n-1}, p, T) = High\big) = \frac{\exp[\sigma \cdot U_n^H(s_{n-1})]}{\exp[\sigma \cdot U_n^L(s_{n-1})] + \exp[\sigma \cdot U_n^H(s_{n-1})]}$. We note that the larger the noise σ is, the closer the subjects' decision to the optimal decision is. When $\sigma = 0$ then $Prob\big(e_{i,n}(s_{n-1}, p, T) = High\big) = 0.5$ which means that subjects' decisions consist of all errors. When $\sigma \to \infty$ then we have $Prob\big(e_{i,n}(s_{n-1}, p, T) = High\big) = \begin{cases} 1, & if\ U_n^H(s_{n-1}) > U_n^L(s_{n-1}) \\ 0, & Otherwise \end{cases}$ and therefore the behavioral model becomes identical to the theoretical model benchmark. Given the utility specification, we estimate the proposed behavioral parameter (i.e., δ, γ, α, and σ) using the entire experimental data set via maximum likelihood estimation. The log-likelihood (LL) function is as following:

$$LL = \sum_{i}\sum_{n}\sum_{s_{n-1}}\sum_{p}\sum_{T}\Big(e_{i,n}(s_{n-1},p,T)\, log\, Prob_{i,n}\big(e_{i,n}(s_{n-1},p,T) = High\big) + \Big(1 - e_{i,n}(s_{n-1},p,T)\Big)\, log\, Prob_{i,n}\big(e_{i,n}(s_{n-1},p,T) = Low\big)\Big) \quad (13)$$

Table 4.2. Behavioral Model Estimation

Parameters of Estimation	Only Noise	Without Perceived Probability	Without Elevation ($\delta = 1$)	Full Model
δ	-	-	-	1.1380 (0.0170)
γ	-	-	0.9304 (0.0284)	0.8849 (0.0270)
α	-	0.0230 (0.0134)	0.0928 (0.0337)	0.1083 (0.0357)
σ	0.2772 (0.0044)	0.2739 (0.0048)	0.2729 (0.0048)	0.2840 (0.0051)
$-LL$	14655	14653	14650	14616
p-Value	0.0000	0.0000	0.0000	
BIC	29320.16	29326.33	29330.49	29272.66
AIC	29312.00	29310.00	29306.00	29240.00

The behavioral parameters estimation is presented in Table 4.2. The negative log-likelihood is smaller under the full model and it also leads to a smallest BIC and AIC compared to other models. The estimation reveals three main findings. First, subjects overperceive the utility of winning and in their decision making they behave as the reward is $\alpha = 11\%$ more than the monetary reward (i.e., they perceive utility of wining as 132 ECU). Second, the estimation validates that subjects are prone to make mistake in their decision making and the model estimates $\sigma = 0.2840$. Third, subjects perceive probability higher than what it is, and the marginal increase in the perceived probabilities are higher when the probabilities are smaller, the probability weighting function is concave for small probabilities. Figure 4.5 shows that subject perceived probability of 0.3, 0.4, and 0.7 are 0.35, 0.44, and 0.71 respectively.

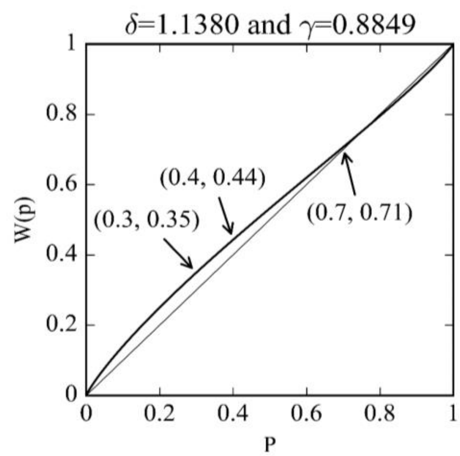

Figure 4.5. Probability Weighting Function Based on the Behavioral Model Estimations

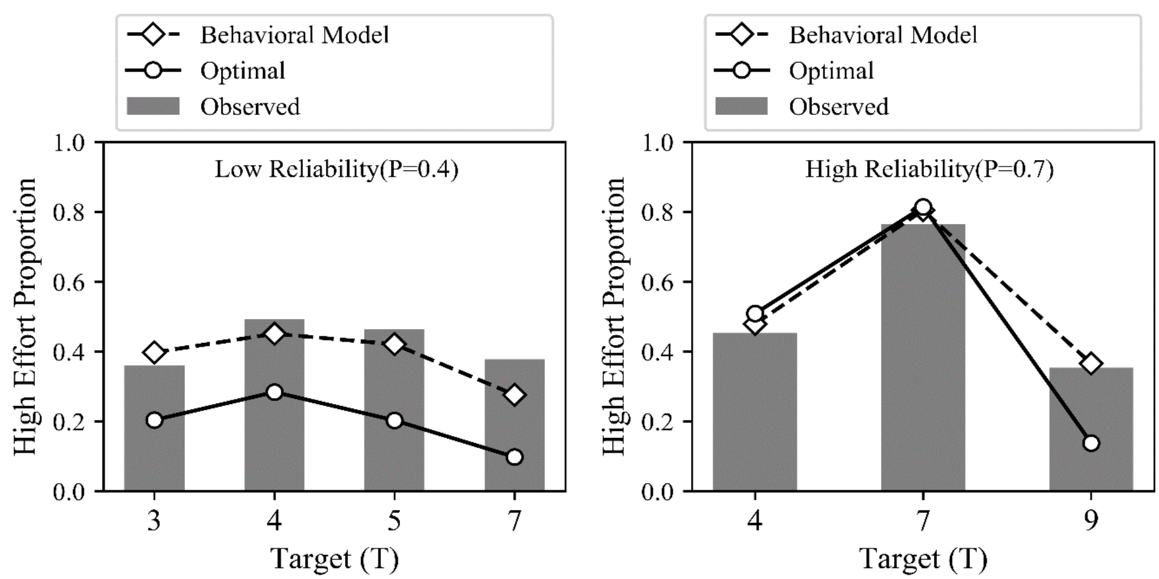

Figure 4.6. Observed, Theoretical Model Prediction and the Behavioral Model Prediction of High Effort Proportion

Figure 4.6 presents the observed high effort proportion (gray bars), the optimal prediction (circle markers), and the behavioral model prediction (diamond markers). We observe that the behavioral model prediction fits the observation quite well. Under 5% significant level we cannot reject that the behavioral model prediction and the observed effort are equal. Manufacturers can utilize the behavioral predictions to better set the target and motivate suppliers to improve their performance by exerting more effort.

Table 4.3. Summary of Experimental Result

Target (T)	3	4	5	7	4	7	9
Observed	0.3592	0.4922	0.4625	0.378	0.4528	0.764	0.354
Std. Err.	(0.0343)	(0.0455)	(0.052)	(0.0562)	(0.0225)	(0.0238)	(0.0481)
Optimal	0.2038	0.2838	0.2032	0.098	0.5085	0.814	0.138
Std. Err.	(0.0091)	(0.0103)	(0.009	(0.0144)	(0.0268)	(0.0121)	(0.0249)
Behavioral Model	0.3916	0.4474	0.4228	0.3242	0.4526	0.7934	0.3854
Std. Err.	(0.0036)	(0.0034)	(0.0038)	(0.0076)	(0.0142)	(0.0081)	(0.0188)
Alternative Hypothesis:	Observed Effort Is Not Equal to Behavioral Model Prediction						
p-Value	0.2336	0.1569	0.2812	0.1512	0.4031	0.0641	0.2050

Figure 4.7 represents the average proportion of behavioral model predicted high effort and observed high effort conditional on the optimal effort being either high or low, over 20 rounds. The figure shows that the behavioral prediction can closely predict the noisy behavior of subjects. Under 1% significant level we cannot reject that the observed and the behavioral prediction are equal in all 7 treatments.

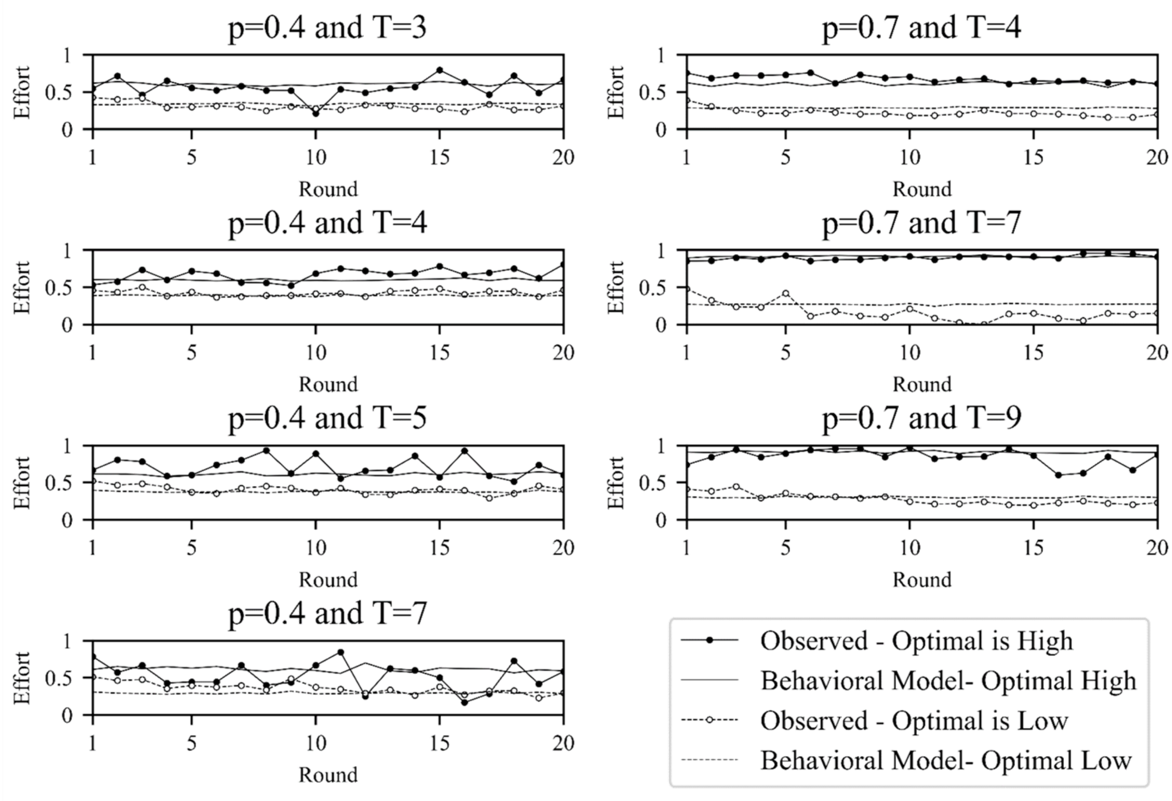

Figure 4.7. Observed and Behavioral Prediction Effort Conditional on Optimal Being High or Low

CHAPTER 5

CONCLUSION

In summary, in this dissertation, we study supplier performance management in situation where the supplier performance is not observable and therefore is not contractible by the OEM. The result typically is a strategy or policy recommendation to OEM to induce desirable performance of its suppliers. We analyzed supplier performance management under two contexts: (1) supplier performance under risk-sharing contracts, and (2) supplier performance with the supplier scorecard system.

(1) Supplier Performance Under Risk-Sharing Contracts:

We analyze the impact of risk-sharing contracts on the project progress using analytical modeling and behavioral experiments in Chapter 2. We show analytically that in the absence of information feedback, there exist multiple equilibria in which contractors exert the same amount of effort and finish the project at the same time. Among the multiple equilibria, we show that contractors exert the lowest effort, and therefore cause a severe project delay, if the secure equilibrium is selected. We then show that providing information feedback regarding other contractors' progress is effective in inducing coordination among contractors even in the conservative benchmark where a secure equilibrium is selected. In addition, we find that coordination becomes more difficult as the project becomes more complex, reflected by the fact that the minimum number of times information feedback must be provided to induce the maximum beneficial effort increases linearly in the number of contractors.

In line with our analytical model, we design behavioral experiments varying the within round information feedback frequency and the number of contractors. We observe that the average effort is significantly lower than the maximum beneficial effort in treatments with no within round information feedback. Additionally, the average effort with four contractors converges to the secure equilibrium effort over time, indicating that the maxmin equilibrium selection strategy is a reasonable description of behavior. We further observe that the coordination increases as more within round information feedback opportunities are provided. Finally, we observe that increasing the number of contractors from two to four reduces coordination. This result confirms that coordination becomes more difficult with more contractors working on the project. We also observe that contractors' payoff weakly increases in the number of within round information feedback and decreases in the number of contractors.

In addition, we explore the robustness of our analytical model findings into three extensions. First, we extend our model by considering uncertainty in execution of tasks. Second, we extend the analytical model to consider an assembly system that faces uncertain demand. finally, we extend our model by considering a quadratic cost function. Through analytical and numerical investigation, we showed that information feedback is effective in improving coordination among contractors under both extensions.

Managerially, our study shows that OEMs should be aware of three facts when using the risk-sharing contract. First, contractors may fail to coordinate. As an example, discussed in the introduction, the risk-sharing contract is one of the factors that led to the severe delay in the Boeing 787 development project. Second, our study shows that the coordination issue raised by the risk-sharing contract can be mitigated by providing information feedback. Therefore, enforcing information feedback among contractors is beneficial for the OEM. Finally, as the coordination becomes more difficult with more contractors, the OEM should enforce more frequent information feedback in order to improve coordination.

(2) Supplier Performance with the Supplier Scorecard System:

We study supplier performance with the supplier scorecard system in Chapter 3 and 4.

In Chapter 3, we investigate the effectiveness of Absolute and Relative approach in improving suppliers' performance using analytical modeling and behavioral experiments. We analytically derive the suppliers' optimal effort decisions in response to the incentivizing approach announced by the manufacturer. We then derive the optimal target under the Absolute approach and the optimal reward scheme under the Relative approach that results in the highest suppliers' effort. We show that under the Relative approach, high effort proportion is the highest when the manufacturer allocates its whole budget to the supplier with the highest final score. Under both approaches, we show that the suppliers high effort proportion increases in the relative reward. Comparing the suppliers' resultant high effort proportion under the two approaches, we characterize conditions on which each approach is preferable. We derive a threshold and we show that when the relative reward is less than the threshold the Absolute approach and otherwise the Relative approach results in a higher supplier's effort and therefore it is preferred by the manufacturer.

To test the theoretical predictions, we then conduct a controlled human-subject experiment varying the reward value and the incentivizing approach. We observe that suppliers over-provide effort compared to the theoretical model prediction under both approaches. We observe that the Relative reward results in a higher supplier performance even when the relative reward is less than the theoretical threshold. Through regression analysis, we show that subjects effort decision is more consistent with the theoretical prediction when the theoretical prediction is to exert high effort as well as under the Absolute approach. We further observe that subjects' payoff on average are less under the Relative approach compared to the Absolute approach.

Our findings assist managers in better using supplier scorecard system to incentivize desirable behavior of suppliers. When using the Absolute approach, managers should be aware that depending on supplier capabilities and reward value there exist an optimal target to maximize suppliers' performance. When using the Relative approach, managers can maximize suppliers' performance by allocating the whole reward pie to the supplier with the highest final score. Our study provides evidence of overexertion of effort in the Relative approach compared Absolute approach. The experimental result confirms that OEM is better off by imposing the Relative approach, as suppliers' performance is higher under this approach compared to the Absolute approach.

In Chapter 4, we investigate the effectiveness of Absolute approach in incentivizing suppliers to improve their performance. We analytically solve the supplier's optimal effort decision (high or low) in all periods during the contract, depending on the updated score. We derive that there exists a threshold strategy such that it is optimal for the supplier to exert high effort when its beginning score at each period is between a lower and upper threshold and low effort otherwise. The solution provides a theoretical benchmark.

We test the theoretical results in the laboratory with human subjects in the role of supplier, paid for performance. We observe that suppliers over-provide effort compared to the theoretical model prediction. We develop a behavioral model to organize our data and explain the regularities.

We observe that subjects' psychological utility of wining is what induces the overexertion of effort compared to the theoretical model prediction.

APPENDIX A

PROOFS

A.1. Proof of Proposition 2.1

We consider contractor i's decision in the proof, as the analysis for all other contractors are symmetric. First, consider the case where the least exerted effort by all other contractors e_{-i} is less than the maximum beneficial effort e^* , contractor i's payoff $\pi_i(\boldsymbol{e}) = R(\min(e_i, e_{-i})) - Ce_i$ increases in its effort e_i if e_i is less than e_{-i}, and decreases in its effort otherwise. Therefore, it does not have any incentive to exert anything except e_{-i}. Second, consider the other case where e_{-i} is greater than e^* it is trivial that contractor i does not have incentive to exert any effort beyond e^* as it is dominated by exerting e^*. To summarize, contractor i's best response to the least exerted effort by all other contractors e_{-i} is $b_i(e_{-i}) = \min\{e_{-i}, e^*\}$. By symmetry, all contractors prefer to exert the same effort between the lowest effort $\underline{e}$, and the maximum beneficial effort e^*, and therefore there exist multiple equilibria in which all contractors exert the same amount of effort between the lowest effort $\underline{e}$, and the maximum beneficial effort e^*. □

A.2. Proof of Corollary 2.1

The maxmin strategy is a strategy which maximizes the worst-case payoff, and results in the secure equilibrium. In this game, the worst case occurs when another contractor exerts the lowest effort $\underline{e}$ and result in the longest delay in its task. In this scenario, since contractor i's payoff $\pi_i(\boldsymbol{e}) = R(\underline{e}) - Ce_i$ decreases in its effort, the contractor maximizes its payoff by exerting the lowest effort $\underline{e}$. By symmetry, all contractors' unique secure equilibrium is to exert the lowest effort $\underline{e}$. □

A.3. Proof of Lemma 2.1

In order to prove Lemma 2.1 we first establish Lemma A.1 and Lemma A.2. In Lemma A.1 we show that contractors' order of cumulative efforts does not change when they follow an action based on a threshold strategy, i.e., when all contractors follow an action based on a threshold strategy, any contractor with lower cumulative effort than another contractor at any period will still have a lower cumulative effort than the other contractor in the next period. Lemma A.1 simplifies our analysis in Lemma 2.1. because we can only focus on the contractor who deviates from an action based on the threshold strategy, and every other contractors' order will not change in the next period as they follow an action based on the threshold strategy. In Lemma A.2 we will show how the threshold changes from any period to the next period when contractors follow an action based on a threshold strategy $\mathrm{T}_{\mathrm{n}}^{1} \triangleq \min_{\mathrm{j}=1,\ldots,\min\{\mathrm{G},\mathrm{N}-\mathrm{n}+2\}} \left(\hat{\mathrm{e}}_{\mathrm{j},\mathrm{n}-1} + (\mathrm{N}-\mathrm{n}+2-\mathrm{j})\left(\bar{\mathrm{e}}_{\mathrm{N}} - \underline{\mathrm{e}}_{\mathrm{N}}\right)\right)$. Using Lemma A.2 we characterize how the least total effort changes from one period to the next period which simplifies our analysis in using backward induction to prove Lemma 2.1. Throughout this analysis, let $\delta \triangleq \bar{e}_N - \underline{e}_N$ to simplify the notation. We use $O_{(i),n}$ to label the contractor with the i^{th} smallest cumulative effort in period n in the following lemma.

Lemma A.1. For any period n, when all contractors, take contractor with the i^{th} smallest cumulative effort at the beginning of period n as an example, follow an action based on a threshold strategy $e^*_{O_{(i),n-1},n} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T - \hat{e}_{O_{(i),n-1},n-1}\right)^+\right\}$ for a given threshold T, in the next period they will have the same order as they have in the current period, i.e., $O_{(i),n} = O_{(i),n-1}$.

Proof of Lemma A.1. In order to prove Lemma A.1, considering contractors with i^{th} and $(i+1)^{st}$ smallest cumulative effort at the beginning of period n, we need to show that by following the threshold strategy $e^*_{O_{(i),n-1},n}$ and $e^*_{O_{(i+1),n-1},n}$ the cumulative effort of contractor i remains below the cumulative effort of contractor $i+1$ at the end of period n, i.e. $\hat{e}_{O_{(i),n-1},n-1} + e^*_{O_{(i),n-1},n} \leq \hat{e}_{O_{(i+1),n-1},n-1} + e^*_{O_{(i+1),n-1},n}$, $\forall i \in G$.

We show the result for the case when the cumulative effort of both contractors at the beginning of period n are less than the threshold T, i.e. $\hat{e}_{O_{(i),n-1},n-1} \leq T$, $\hat{e}_{O_{(i+1),n-1},n-1} \leq T$. For the other cases where at least one contractor's cumulative effort is greater than T, the proof is similar but simpler and therefore is omitted for space. We have $\hat{e}_{O_{(i),n-1},n-1} + e^*_{O_{(i),n-1},n} = \min\left\{\bar{e}_N + \hat{e}_{O_{(i),n-1},n-1}, \underline{e}_N + T\right\} \leq \min\left\{\bar{e}_N + \hat{e}_{O_{(i+1),n-1},n-1}, \underline{e}_N + T\right\} = \hat{e}_{O_{(i+1),n-1},n-1} + \min\left\{\bar{e}_N, \underline{e}_N + T - \hat{e}_{O_{(i+1),n-1},n-1}\right\} = \hat{e}_{O_{(i+1),n-1},n-1} + e^*_{O_{(i+1),n-1},n}$. The first equality follows the fact that $\hat{e}_{O_{(i),n-1},n-1} \leq T$ and the inequality follows the fact that $\hat{e}_{O_{(i),n-1},n-1} \leq \hat{e}_{O_{(i+1),n-1},n-1}$. To summarize, we have established that contractors' order will not change in the next period if they follow an action based on the threshold strategy in the current period, i.e., $O_{(i),n} = O_{(i),n-1}$. □

Lemma A.2. *Relabel the contractor with the i^{th} smallest cumulative effort at the beginning of period n as contractor i, i.e., $O_{(i),n-1} = i$ and define threshold strategy $e^*_{i,n} = min\left\{\bar{e}_N, \underline{e}_N + \left(T^1_n - \hat{e}_{i,n-1}\right)^+\right\}$ where $T^1_n \triangleq \min_{j=1,\ldots,min\{G,N-n+2\}}\left(\hat{e}_{j,n-1} + (N-n+2-j)\left(\bar{e}_N - \underline{e}_N\right)\right)$. When all contractors follow the threshold strategy with the threshold of T^1_{n-1} in period $n-1$, the resulting $T^1_n = T^1_{n-1} + \underline{e}_N$. It follows from this lemma that following the threshold strategy from period n to the last period, the least total effort is $T^1_n + (N-n+1)\underline{e}_N$.*

Proof of Lemma A.2. Throughout this analysis, let $\delta \triangleq \bar{e}_N - \underline{e}_N$ to simplify the notation. Also it follows from Lemma A.2 that when all contractors follow the same threshold strategy, their orders do not change in the next period, i.e., $O_{(i),n-1} = O_{(i),n}$. Let contractor k determine the threshold in period $n-1$, i.e., $T_{n-1}^1 = \hat{e}_{k,n-2} + (N-n+3-k)\delta$. It follows from the definition of T_n^1 that k satisfies the following condition:

$$\hat{e}_{k,n-2} + (N-n+3-k)\delta \leq \hat{e}_{i,n-2} + (N-n+3-i)\delta\,, \quad i = 1, \ldots, \min\{G, N-n+3\} \tag{14}$$

We prove the lemma by first establishing that $\hat{e}_{k,n-2} + e_{k,n-1}^* + (N-n+2-k)\delta \leq \hat{e}_{i,n-2} + e_{i,n-1}^* + (N-n+2-i)\delta$ for any contractor $i \leq \min\{G, N-n+2\}$. Then we derive the expression of T_n^1 and show that $T_n^1 = T_{n-1}^1 + \underline{e}_N$. We show analysis for the case where $N - n + 3 \leq G$. The analysis for the other case is similar but simpler and therefore is omitted for space.

We consider two cases where $k > i$ and $k < i$ to establish that $\hat{e}_{k,n-2} + e_{k,n-1}^* + (N-n+2-k)\delta \leq \hat{e}_{i,n-2} + e_{i,n-1}^* + (N-n+2-i)\delta$. Recall that the contractors are labeled from the smallest cumulative effort (contractor 1) to the largest cumulative effort (contractor G).

When $k > i$, it implies that the cumulative effort of contractor k is greater than the cumulative effort of contractor i, i.e., $\hat{e}_{k,n-2} \geq \hat{e}_{i,n-2}$. As both contractors follow the threshold strategy defined by T_{n-1}^1, we have $e_{k,n-1}^* \leq e_{i,n-1}^*$, and adding it to the both side of (14) yields $\hat{e}_{k,n-2} + e_{k,n-1}^* + (N-n+3-k)\delta \leq \hat{e}_{i,n-2} + e_{i,n-1}^* + (N-n+3-i)\delta$. Subtracting δ on both sides, we have $\hat{e}_{k,n-2} + e_{k,n-1}^* + (N-n+2-k)\delta \leq \hat{e}_{i,n-2} + e_{i,n-1}^* + (N-n+2-i)\delta$.

When $k < i$, it implies that the cumulative effort of contractor k is less than the cumulative effort of contractor i, i.e., $\hat{e}_{k,n-2} \leq \hat{e}_{i,n-2}$. As both contractors follow the threshold strategy defined by T^1_{n-1}, we have $e^*_{k,n-1} \geq e^*_{i,n-1}$. To establish the result, we consider two cases where $k = N - n + 3$ and $k < N - n + 3$.

Case 1: When $k = N - n + 3$, we have $T^1_{n-1} = \hat{e}_{k,n-2}$ and therefore $e^*_{k,n-1} = \underline{e}_N$. It follows that $e^*_{i,n-1} = \underline{e}_N$ as $e^*_{i,n-1} \leq e^*_{k,n-1}$. By adding $e^*_{k,n-1}$ and $e^*_{i,n-1}$ to equation (14) (note that $e^*_{k,n-1} = e^*_{i,n-1} = \underline{e}_N$) and subtracting δ on both sides, we have $\hat{e}_{k,n-2} + e^*_{k,n-1} + (N - n + 2 - k)\delta \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N - n + 2 - i)\delta$.

Case 2: When $k < N - n + 3$, we have $T^1_{n-1} = \hat{e}_{k,n-2} + (N - n + 3 - k)\delta \geq \hat{e}_{k,n-2} + \delta$, and therefore $e^*_{k,n-1} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T^1_{n-1} - \hat{e}_{k,n-2}\right)^+\right\} = \bar{e}_N$, and the action of contractor i is $e^*_{i,n-1} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T^1_{n-1} - \hat{e}_{i,n-2}\right)^+\right\}$ which is $\underline{e}_N$ if $0 \geq T^1_{n-1} - \hat{e}_{i,n-2}$, $\underline{e}_N + T^1_{n-1} - \hat{e}_{i,n-2}$ if $\delta \geq T^1_{n-1} - \hat{e}_{i,n-2} \geq 0$, and $\bar{e}_N$ if $T^1_{n-1} - \hat{e}_{i,n-2} \geq \delta$. We next discuss each of the three cases.

Case 2.1: When $0 \geq T^1_{n-1} - \hat{e}_{i,n-2}$ and $e^*_{i,n-1} = \underline{e}_N$, contractor i's cumulative effort is already above the threshold T^1_{n-1}, i.e., $\hat{e}_{i,n-2} \geq T^1_{n-1} = \hat{e}_{k,n-2} + (N - n + 3 - k)\delta$. Adding $e^*_{i,n-1}$ to the both sides of the inequality (note that $e^*_{i,n-1} = \underline{e}_N$), we have $\hat{e}_{i,n-2} + e^*_{i,n-1} \geq \hat{e}_{k,n-2} + (N - n + 3 - k)\delta + \underline{e}_N = \hat{e}_{k,n-2} + e^*_{k,n-1} + (N - n + 2 - k)\delta$. The equality follows the fact that $\delta = \bar{e}_N - \underline{e}_N$ and $e^*_{k,n-1} = \bar{e}_N$. We note the fact that $(N - n + 2 - i)\delta \geq 0$ for any $i \leq N - n + 2$, so we have shown that $\hat{e}_{k,n-2} + e^*_{k,n-1} + (N - n + 2 - k)\delta \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N - n + 2 - i)\delta$.

Case 2.2: When $\delta \geq T^1_{n-1} - \hat{e}_{i,n-2} \geq 0$ and $e^*_{i,n-1} = \underline{e}_N + T^1_{n-1} - \hat{e}_{i,n-2}$, then we can rearrange $e^*_{i,n-1} = \underline{e}_N + T^1_{n-1} - \hat{e}_{i,n-2}$ as $\hat{e}_{i,n-2} + e^*_{i,n-1} - \underline{e}_N = T^1_{n-1} = \hat{e}_{k,n-2} + (N - n + 3 - k)\delta$. Since $(N - n + 2 - i)\delta \geq 0$ for any $i \leq N - n + 2$ adding it to the left hand side of $\hat{e}_{i,n-2} +$

$e^*_{i,n-1} - \underline{e}_N = \hat{e}_{k,n-2} + (N-n+3-k)\delta$ we have $\hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta - \underline{e}_N \geq \hat{e}_{k,n-2} + (N-n+3-k)\delta$, and following the fact that $\delta = \bar{e}_N - \underline{e}_N$ and $e^*_{k,n-1} = \bar{e}_N$, we have $\hat{e}_{k,n-2} + e^*_{k,n-1} + (N-n+2-k)\delta \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$.

Case 2.3: When $T^1_{n-1} - \hat{e}_{i,n-2} \geq \delta$ and $e^*_{i,n-1} = \bar{e}_N$, by adding $e^*_{k,n-1}$ and $e^*_{i,n-1}$ and subtracting δ from both sides of (14) we have $\hat{e}_{k,n-2} + e^*_{k,n-1} + (N-n+2-k)\delta \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$.

To summarize, we have established that $\hat{e}_{k,n-2} + e^*_{k,n-1} + (N-n+2-k)\delta \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$ for any contractor $i \leq \min\{G, N-n+2\}$. We next derive the expression of T^1_n.

We note that for $k < N-n+3$, we have $T^1_{n-1} = \hat{e}_{k,n-2} + (N-n+3-k)\delta \geq \hat{e}_{k,n-2} + \delta$ and therefore $e^*_{k,n-1} = \bar{e}_N$. Following the inequality established in the previous step, we have $T^1_n = \hat{e}_{k,n-2} + e^*_{k,n-1} + (N-n+2-k)\delta = \hat{e}_{k,n-2} + \bar{e}_N + (N-n+2-k)\delta = \hat{e}_{k,n-2} + \bar{e}_N + (N-n+3-k)\delta - \delta = \hat{e}_{k,n-2} + (N-n+3-k) + \underline{e}_N = T^1_{n-1} + \underline{e}_N$.

For $k = N-n+3$, we next establish that the threshold T^1_n is determined by contractor $N-n+2$, i.e., $\hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$ for any contractor $i \leq N-n+2$. Following the fact that $T^1_{n-1} = \hat{e}_{(N-n+3),n-2}$, we have $\hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} - \underline{e}_N = \hat{e}_{N-n+2,n-2} + \min\left\{\bar{e}_N, \underline{e}_N + \left(T^1_{n-1} - \hat{e}_{N-n+2,n-2}\right)^+\right\} - \underline{e}_N = \hat{e}_{N-n+3,n-2} = T^1_{n-1}$.

Therefore, we have that $e^*_{i,n-1} = \min\{\bar{e}_N, \hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} - \hat{e}_{i,n-2}\}$. When $e^*_{i,n-1} = \hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} - \hat{e}_{i,n-2}$, the inequality, $\hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$, trivially holds (as equality). When $e^*_{i,n-1} = \bar{e}_N$, we have $T^1_{n-1} = \hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} - \underline{e}_N \leq \hat{e}_{i,n-2} + (N-n+3-i)\delta$. Rearranging the inequality following the fact that

$\delta = \bar{e}_N - \underline{e}_N$, we have $\hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} \leq \hat{e}_{i,n-2} + (N-n+2-i)\delta + \bar{e}_N = \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$. To summarize these two cases, we have established that $\hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} \leq \hat{e}_{i,n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$. Therefore, by definition of T^1_n, we have $T^1_n = \hat{e}_{N-n+2,n-2} + e^*_{N-n+2,n-1} = T^1_{n-1} + \underline{e}_N$.□

Proof of Lemma 2.1. To simplify our analysis, relabel the contractor with the i^{th} smallest cumulative effort at the beginning of period n as contractor i, i.e., $O_{(i),n-1} = i$. Using backward induction, we show that T^*_n is the subgame perfect secure equilibrium threshold in period n and T^*_n defines contractors' equilibrium actions satisfying the maxmin criteria. Throughout the proof we focus on the case that the total effort is not limited by the maximum beneficial effort e^*, i.e., $T^*_n = \min\{T^1_n, T^2_n\} = T^1_n \triangleq \min_{j=1,\dots,\min\{G,N-n+2\}} \left\{\hat{e}_{O_{(j),n-1},n-1} + (N-n+2-j)\left(\bar{e}_N - \underline{e}_N\right)\right\}$. Otherwise it is trivial to show that reaching any total effort above e^* is dominated by e^*.

In period N, given contractors' cumulative effort vector at the beginning of period N, $\hat{\boldsymbol{e}}_{N-1}$, we show that the equilibrium least total effort $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N)$ is in the range of $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) \in \left[\min\left\{\hat{e}_{1,N-1} + \bar{e}_N, \hat{e}_{2,N-1} + \underline{e}_N\right\},\ \hat{e}_{1,N-1} + \bar{e}_N\right]$, and contractor i's equilibrium in period N is $e^*_{i,N} = \underline{e}_N + \left(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N - \hat{e}_{i,N-1}\right)^+$, recall that contractor 1 and 2 refer to the contractor with the smallest and second smallest cumulative effort at the beginning of period N. We show that when any contractor $j \neq i$ exerts $e^*_{j,N} = \underline{e}_N + \left(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N - \hat{e}_{j,N-1}\right)^+$ then contractor i does not have incentive to deviate from $e^*_{i,N}$. We consider three cases where $(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N \leq \hat{e}_{i,N-1}$, $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N > \hat{e}_{i,N-1} > P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N - \delta$ and $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N - \delta = \hat{e}_{i,N-1}$. Case 1: when $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}^*_N) - \underline{e}_N \leq \hat{e}_{i,N-1}$ we show that

$e_{i,N}^{*} = \underline{e}_N$. Consider contractor i deviates from $e_{i,N}^{*} = \underline{e}_N$ by exerting $\underline{e}_N + \epsilon$. In this case contractor i's payoff $R\left(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*})\right) - C\left(\hat{e}_{i,N-1} + \underline{e}_N + \epsilon\right)$ decreases in ϵ. Case 2: when $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \underline{e}_N > \hat{e}_{i,N-1} > P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \underline{e}_N - \delta$ we show that $e_{i,N}^{*} = P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1}$. Consider contractor i deviates from $e_{i,N}^{*} = P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1}$ by exerting $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1} + \epsilon$ or $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1} - \epsilon$. In this case when it deviates from $e_{i,N}^{*} = P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1}$ by $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1} - \epsilon$ its payoff $R(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \epsilon) - C(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \epsilon)$ decreases in ϵ, and when it deviates from $e_{i,N}^{*} = P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1}$ by $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \hat{e}_{i,N-1} + \epsilon$ its payoff $R\left(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*})\right) - C(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) + \epsilon)$ decreases in ϵ. Case 3: when $P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \underline{e}_N - \delta = \hat{e}_{i,N-1}$ we show that $e_{i,N}^{*} = \bar{e}_N$. Consider contractor i deviates from $e_{i,N}^{*} = \bar{e}_N$ by exerting $\bar{e}_N - \epsilon$. In this case contractor i's payoff $R\left(\hat{e}_{i,N-1} + \bar{e}_N - \epsilon\right) - C\left(\hat{e}_{i,N-1} + \bar{e}_N - \epsilon\right)$ decreases in ϵ. We showed that in all the three cases contractor i's payoff decreases in ϵ and therefore contractor i does not have incentive to deviate from $e_{i,N}^{*} = \underline{e}_N + \left(P(\hat{\boldsymbol{e}}_{N-1} + \boldsymbol{e}_N^{*}) - \underline{e}_N - \hat{e}_{i,N-1}\right)^{+}$.

Next, we show that $\min\left\{\hat{e}_{1,N-1} + \bar{e}_N, \hat{e}_{2,N-1} + \underline{e}_N\right\}$ survives the maxmin criteria. The maxmin strategy is a strategy which maximizes the worst-case payoff, and results in the secure equilibrium. For contractor 1, the worst case occurs when contractor 2 exerts the lowest effort $\underline{e}_N$. In this case, the least total effort among contractors other than contractor 1 is determined by contractor 2's total effort, i.e., $\min_{\forall j \in \{1,\dots,G\} \setminus \{i\}} \left\{\hat{e}_{j,N-1} + e_{j,N}\right\} = \hat{e}_{2,N-1} + e_{2,N} = \hat{e}_{2,N-1} + \underline{e}_N$. In this scenario, contractor 1's payoff increases in its effort if $e_{1,N} \leq \hat{e}_{2,N-1} + \underline{e}_N - \hat{e}_{1,N-1}$, and decreases in its effort otherwise, so contractor 1 can maximize its payoff by exerting $e_{1,N}^{*} = \bar{e}_N$ if $\hat{e}_{1,N-1} + \bar{e}_N \leq$

$\hat{e}_{2,N-1} + \underline{e}_N$, and $e_{1,N}^* = \underline{e}_N + \hat{e}_{2,N-1} - \hat{e}_{1,N-1}$ otherwise, therefore alternatively $e_{1,N}^* = \min\{\bar{e}_N, \underline{e}_N + \hat{e}_{2,N-1} - \hat{e}_{1,N-1}\}$. We note that this is the worst case for any contractor $i \neq 1$ since contractor 1's total effort is less than the total effort of contractors $i \neq 1$, i.e., $\hat{e}_{1,N-1} + e_{1,N}^* \leq \hat{e}_{i,N-1} + \underline{e}_N$. In this case, contractor i's payoff $\pi_{i,N}(\hat{\boldsymbol{e}}_{N-1} + (e_{1,N}^*, e_{2,N}, \dots, e_{G,N})) = R(\hat{e}_{1,N-1} + e_{1,N}^*) - C(\hat{e}_{i,N-1} + e_{i,N})$ decreases in its effort and therefore it does not have incentive to exert anything above the lowest effort $\underline{e}_N$. Therefore $e_{i,N}^* = \underline{e}_N$ is an equilibrium action surviving the maxmin strategy. To summarize, we have shown that $(e_{1,N}^*, \dots, e_{G,N}^*) = (\min\{\bar{e}_N, \underline{e}_N + \hat{e}_{2,N-1} - \hat{e}_{1,N-1}\}, \underline{e}_N, \dots, \underline{e}_N)$ is the equilibrium surviving the maxmin criteria. Alternatively, the equilibrium can be written as a threshold strategy $e_{i,N}^* = \min\left\{\bar{e}_N, \underline{e}_N + \left(T_N^1 - \hat{e}_{\mathrm{i},N-1}\right)^+\right\}$ where $T_N^1 = \min\{\hat{e}_{1,N-1} + \delta, \hat{e}_{2,N-1}\}$. Consequently, the least total effort is $P(\hat{\boldsymbol{e}}_N^*) = \hat{e}_{1,N-1} + e_{1,N}^* = \hat{e}_{1,N-1} + \min\{\bar{e}_N, \underline{e}_N + \left(T_N^1 - \hat{e}_{1,N-1}\right)^+\} = \underline{e}_N + T_N^1$ following that $\hat{e}_{1,N-1} \leq T_N^1 \leq \hat{e}_{1,N-1} + \delta$.

We then establish the induction hypothesis considering contractors follow the equilibrium threshold strategy starting from period n to the last period N, i.e., for any $n \leq t \leq N$. In period t, given cumulative efforts $\hat{\boldsymbol{e}}_{t-1}$, the subgame perfect secure equilibrium action of contractor i is $e_{i,t}^* = \min\left\{\bar{e}_N, \underline{e}_N + \left(T_t^* - \hat{e}_{i,t-1}\right)^+\right\}$ where $T_t^* = T_t^1 = \min_{j=1,\dots,\min\{G,N-t+2\}} \left(\hat{e}_{\mathrm{j},t-1} + (N - t + 2 - j)\delta\right)$ is the subgame perfect secure equilibrium threshold. Moreover, the resulting least total effort $P(\hat{\boldsymbol{e}}_N^*) = (N - t + 1)\underline{e}_N + T_t^*$.

In period $n - 1$, we will show that given cumulative efforts $\hat{\boldsymbol{e}}_{n-2}$, the subgame perfect secure equilibrium action of contractor i is $e_{i,n-1}^* = \min\left\{\bar{e}_N, \underline{e}_N + \left(T_{n-1}^1 - \hat{e}_{i,n-2}\right)^+\right\}$ where $T_{n-1}^1 \triangleq \min_{j=1,\dots,\min\{G,N-n+3\}}\left\{\hat{e}_{\mathrm{j},n-2} + (N - n + 3 - j)\delta\right\}$. Moreover, the resulting least total effort $P(\hat{\boldsymbol{e}}_N^*) =$

$(N-n+2)\underline{e}_N + T_{n-1}^1$. There are three steps to complete the induction. In the first step, we show the threshold strategy $e_{i,n-1}^*$ defined by T_{n-1}^1 is an equilibrium action. In the second step, we show that no thresholds below T_{n-1}^1 define an equilibrium strategy. In the third step, we show that no equilibrium thresholds above T_{n-1}^1 satisfy the maxmin criteria. These three steps in period $n-1$ show that the predicted equilibrium threshold T_{n-1}^1 defines the unique threshold strategy which satisfies the maxmin criteria. In what follows we focus on the case that $N-n+3 \le G$ and $T_{n-1}^1 = \min_{j=1,\dots,N-n+3}\left(\hat{e}_{j,n-2} + (N-n+3-j)\delta\right)$. The other case is similar but simpler and is omitted for space.

<u>Step 1</u>. We show that when any contractor $j \neq i$ follows $e_{j,n-1}^* = \min\left\{\bar{e}_N, \underline{e}_N + \left(T_{n-1}^1 - \hat{e}_{j,n-2}\right)^+\right\}$, then contractor i does not have incentive to deviate from exerting $e_{i,n-1}^*$. Recall that the threshold $T_{n-1}^1 = \min_{j=1,\dots,N-n+3}\left(\hat{e}_{\mathrm{j},n-2} + (N-n+3-j)\delta\right)$. Let contractor k determine T_{n-1}^1, i.e., $T_{n-1}^1 = \hat{e}_{k,n-2} + (N-n+3-k)\delta$. To proceed, we consider two cases: $\hat{e}_{i,n-2} \ge T_{n-1}^1$ and $\hat{e}_{i,n-2} \le T_{n-1}^1$.

Case 1: when $\hat{e}_{i,n-2} \ge T_{n-1}^1$ we have that $\mathrm{e}_{i,n-1}^* = \underline{e}_N$. Consider that contractor i deviates from $\mathrm{e}_{i,n-1}^* = \underline{e}_N$ by exerting $\underline{e}_N + \epsilon$. We have that $P(\hat{\boldsymbol{e}}_N^*) = T_n^1 + (N-n+1)\underline{e}_N = T_{n-1}^1 + \underline{e}_N + (N-n+1)\underline{e}_N \le \hat{e}_{i,n-2} + \underline{e}_N + \varepsilon + (N-n+1)\underline{e}_N$. The first equality follows the induction hypothesis of the least total effort, the second equality follows from Lemma A.2 and the inequality follows that $T_{n-1}^1 \le \hat{e}_{i,n-2}$. It follows that contractor i's payoff $\pi_{i,n-1}\left(\hat{\boldsymbol{e}}_{n-2} + \left(e_{1,n-1}^*, \dots, e_{i,n-1}^* + \varepsilon, \dots, e_{G,n-1}^*\right)\right) = R\left(\hat{e}_{k,n-2} + (N-n+3-k)\delta + (N-n+2)\underline{e}_N\right) - C\left(\hat{e}_{\mathrm{i},n-2} + \underline{e}_N + \varepsilon +\right.$

$(N-n+1)\underline{e}_N\big)$ decreases in ϵ. Therefore, contractor i does not have incentive to deviate from $\mathrm{e}^*_{i,n-1} = \underline{e}_N$.

Case 2: when $\hat{e}_{i,n-2} \le T^1_{n-1}$ we have that $e^*_{i,n-1} = \min\{\bar{e}_N, \underline{e}_N + T^1_{n-1} - \hat{e}_{\mathrm{i},n-2}\}$. To proceed we consider two cases where contractor i deviates from $e^*_{i,n-1}$ by ϵ, and the case where contractor i deviates from $e^*_{i,n-1}$ by $-\epsilon$.

Case 2.1: We first consider the case when contractor i deviates from $e^*_{i,n-1}$ by ϵ. We note that contractor i can only deviate from $e^*_{i,n-1}$ by ϵ when $e^*_{i,n-1} = \underline{e}_N + T^1_{n-1} - \hat{e}_{i,n-2}$, and this case happens when $T^1_{n-1} - \delta < \hat{e}_{i,n-2} \le T^1_{n-1}$. We have that $P(\hat{\boldsymbol{e}}^*_N) = T^1_n + (N-n+1)\underline{e}_N = T^1_{n-1} + \underline{e}_N + (N-n+1)\underline{e}_N \le \hat{e}_{i,n-2} + e^*_{i,n-1} + \varepsilon + (N-n+1)\underline{e}_N$. The first equality follows the induction hypothesis of the least total effort, the second equality follows from Lemma A.2 and the inequality follows that $e^*_{i,n-1} = T^1_{n-1} + \underline{e}_N - \hat{e}_{i,n-2} < e^*_{i,n-1} + \varepsilon$ for any $\epsilon > 0$. It follows that contractor i's payoff $\pi_{i,n-1}\Big(\hat{\boldsymbol{e}}_{n-2} + \big(e^*_{1,n-1}, \dots, e^*_{i,n-1} + \varepsilon, \dots, e^*_{G,n-1}\big)\Big) = R\big(T^1_{n-1} + (N-n+2)\underline{e}_N\big) - C\big(\hat{e}_{\mathrm{i},n-2} + e^*_{i,n-1} + \varepsilon + (N-n+1)\underline{e}_N\big)$ decreases in ϵ. Therefore, contractor i does not have incentive to deviate from $e^*_{i,n-1} = \underline{e}_N + T^1_{n-1} - \hat{e}_{\mathrm{i},n-2}$ by ϵ.

Case 2.2: We then consider contractor i deviates from $e^*_{i,n-1}$ by $-\epsilon$. First, we discuss how the threshold T^1_n changes respective to ϵ and next we show how the least total effort $P(\hat{\boldsymbol{e}}^*_N)$ is affected by ϵ. We denote the gap between contractors i's and $i-1$'s cumulative efforts after period $n-1$ assuming they follow the equilibrium threshold strategy by $u \triangleq \big(\hat{e}_{\mathrm{i},n-2} + e^*_{i,n-1}\big) - \big(\hat{e}_{\mathrm{i}-1,n-2} + e^*_{i-1,n-1}\big)$. For exposition purpose, we note that if the threshold were determined by contractor i in the current period, then the hypothetical threshold should be $T^1_n(i) = \hat{e}_{\mathrm{i},n-2} + e^*_{i,n-1} + (N-n+2-i)\delta$. We denote the gap between the hypothetical threshold $T^1_n(i)$ and the threshold

T_n^1 (defined by contractor k) by $w \triangleq \mathrm{T_n^1(i)} - \mathrm{T_n^1} = \left(\hat{e}_{i,n-2} + e_{i,n-1}^*\right) - \left(\hat{e}_{k,n-2} + e_{k,n-1}^*\right) + (k - i)\delta$. Below we consider three cases when $w \leq u$: $\varepsilon \leq w \leq u$, $w \leq \varepsilon \leq u$ and $w \leq u \leq \varepsilon$. For the other case when $u \leq w$, the analysis is similar to the case of $\varepsilon \leq w \leq u$ and is therefore omitted.

When $\varepsilon \leq w \leq u$, the order of cumulative efforts among the contractors does not change (because of $\epsilon \leq u$) and contractor k still determines the threshold in period n (because of $\epsilon \leq w$). It follows that $T_n^1 = \hat{e}_{k,n-2} + e_{k,n-1}^* + (N - n + 2 - k)\delta$. When $w \leq \varepsilon \leq u$, the order of cumulative efforts among the contractors does not change (because of $\epsilon \leq u$), but now contractor i determines the threshold in the next period (because of $w \leq \varepsilon$). It follows that $T_n^1 = \hat{e}_{\mathrm{i},n-2} + e_{i,n-1}^* - \varepsilon + (N - n + 2 - i)\delta$. When $w \leq u \leq \varepsilon$, the order of cumulative efforts among the contractors i and $i-1$ changes (because of $\epsilon > u$) and contractor $i-1$ will be the contractor with i^{th} smallest cumulative effort in period n. We note that in this case, contractor $i-1$ determines the threshold in the next period, i.e., $T_n^1 = \hat{e}_{i-1,n-2} + e_{i-1,n-1}^* + (N - n + 2 - i)\delta \leq \hat{e}_{k,n-2} + e_{k,n-1}^* + (N - n + 2 - k)\delta$ and the inequality follows from the fact that $w \leq u$, which implies that $u - w = \left(\hat{e}_{k,n-2} + e_{k,n-1}^*\right) - \left(\hat{e}_{\mathrm{i}-1,n-2} + e_{i-1,n-1}^*\right) - (k - i)\delta \geq 0$.

Based on the induction hypothesis $P(\hat{\boldsymbol{e}}_N^*) = T_n^1 + (N - n + 1)\underline{e}_N$ and contractors follow the equilibrium threshold strategy starting from period n to the last period N, contractor i's payoff is as follows:

$$\pi_{i,n-1}\left(\hat{\boldsymbol{e}}_{n-2}+\left(e_{1,n-1}^{*},\dots,e_{i,n-1}^{*}-\varepsilon,\dots,e_{G,n-1}^{*}\right)\right)$$

$$=\begin{cases} R\left(\hat{e}_{\mathrm{k},n-2}+e_{k,n-1}^{*}+(N-n+2-k)\delta+(N-n+1)\underline{e}_{N}\right) \\ \qquad -C\left(\hat{e}_{\mathrm{k},n-2}+e_{k,n-1}^{*}+(N-n+2-k)\delta+(N-n+1)\underline{e}_{N}\right), & \varepsilon\le w\le u \\ R\left(\hat{e}_{\mathrm{i},n-2}+e_{i,n-1}^{*}-\varepsilon+(N-n+2-i)\delta+(N-n+1)\underline{e}_{N}\right) \\ \qquad -C\left(\hat{e}_{\mathrm{i},n-2}+e_{i,n-1}^{*}-\varepsilon+(N-n+2-i)\delta+(N-n+1)\underline{e}_{N}\right) & w\le\varepsilon\le u \\ R\left(\hat{e}_{\mathrm{i}-1,n-2}+e_{i-1,n-1}^{*}+(N-n+2-i)\delta+(N-n+1)\underline{e}_{N}\right) \\ \qquad -C\left(\hat{e}_{\mathrm{i}-1,n-2}+e_{i-1,n-1}^{*}+(N-n+2-i)\delta+(N-n+1)\underline{e}_{N}\right) & w\le u\le\varepsilon \end{cases} \tag{15}$$

It is immediate that the payoff function weakly decreases in ϵ, and therefore contractor i does not have incentive to deviate from $e_{i,n-1}^{*}$ by $-\epsilon$.

Step 2. In this step, we will show that no thresholds below T_{n-1}^{1} define an equilibrium threshold strategy. For contractor i, we consider a threshold strategy defined by a different threshold $\mathrm{T}_{n-1}^{'}$, i.e., $\mathrm{e}_{i,n-1}^{\prime}=\min\left\{\bar{e}_{N},\underline{e}_{N}+\left(\mathrm{T}_{n-1}^{'}-\hat{e}_{i,n-2}\right)^{+}\right\}$ where $T_{n-1}^{\prime}<T_{n-1}^{1}$, and we will show that the threshold strategy defined by $\mathrm{T}_{n-1}^{'}$ is not an equilibrium strategy. In this case, there exists at least one contractor i such that $e_{i,n-1}^{\prime}\neq e_{i,n-1}^{*}$. Then we show that either all contractors are indifferent between $e_{i,n-1}^{\prime}$ and $e_{i,n-1}^{*}$ or there is at least one contractor that has incentive to deviate from $e_{i,n-1}^{\prime}$.

From the definition of T_{n}^{1} let contractor k determine the threshold in period n when all contractors follow the threshold strategy based on the threshold T_{n-1}^{1} in period $n-1$, i.e., $\exists\, k\in\{1,\dots,N-n+2\}$ such that $T_{n}^{1}(\hat{\boldsymbol{e}}_{n-2}+\boldsymbol{e}_{n-1}^{*})=\hat{e}_{\mathrm{k},n-2}+e_{k,n-1}^{*}+(N-n+2-k)\delta$. Let contractor k' determine the threshold in period n when all contractors follow the threshold strategy based on the threshold $T_{n-1}^{\prime}$ in period $n-1$, i.e., $\exists\, k'\in\{1,\dots,N-n+2\}$ such that $T_{n}^{1}(\hat{\boldsymbol{e}}_{n-2}+\boldsymbol{e}_{n-1}^{\prime})=\hat{e}_{k',n-2}+e_{k',n-1}^{\prime}+(N-n+2-k')\delta$. We note that if $T_{n}^{1}(\hat{\boldsymbol{e}}_{n-2}+$

$\boldsymbol{e}'_{n-1}) = T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}^*_{n-1})$, all contractors are indifferent between taking an action based on the threshold T_{n-1}^1 and taking and action based on the threshold T'_{n-1}. Therefore, we focus on the case where $T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1}) < T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}^*_{n-1})$ and will show that at least one contractor has incentive to deviate from taking an action based on the T'_{n-1}.

When $T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1}) < T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}^*_{n-1})$, we consider contractor k' deviates from $\mathrm{e}'_{k',n-1}$ by ϵ. First we show how the threshold $T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1})$ changes when contractor k' deviates from $\mathrm{e}'_{k',n-1}$ by ϵ, and then based on the result we show how the least total effort $P(\hat{\boldsymbol{e}}'_N)$ changes respective to ϵ. For exposition purpose, we denote $k^{"}$ as the contractor that defines the threshold when we exclude contractor k', i.e., $\exists k^{"} \in \{1, \dots, N-n+2\} \setminus \{k'\}$, such that $\forall\, j \in \{1, \dots, N-n+2\} \setminus \{k'\}$, $T_n^{1^{"}} = \hat{e}_{k^{"},n-2} + e'_{k^{"},n-1} + \left(N-n+2-k^{"}\right)\delta \leq \hat{e}_{j,n-2} + e'_{j,n-1} + (N-n+2-j)\delta$. When $\epsilon \leq T_n^{1^{"}} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1})$ the threshold in the next period is $T_n^1\left(\hat{\boldsymbol{e}}_{n-2} + \left(e'_{1,n-1}, \dots, e'_{k',n-1} + \epsilon, \dots, e'_{G,n-1}\right)\right) = \hat{e}_{k',n-2} + e'_{k',n-1} + \epsilon + (N-n+2-k')\delta$; When $\epsilon > T_n^{1^{"}} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1})$ the threshold in the next period is $T_n^1\left(\hat{\boldsymbol{e}}_{n-2} + \left(e'_{1,n-1}, \dots, e'_{k',n-1} + \epsilon, \dots, e'_{G,n-1}\right)\right) = T_n^{1^{"}}$. It follows from the induction hypothesis of the least total effort that:

$$P(\hat{\boldsymbol{e}}'_N) = \begin{cases} \hat{e}_{k',n-2} + e'_{k',n-1} + \epsilon + (N-n+2-k')\delta + (N-n+1)\underline{e}_N & \epsilon \leq T_n^{1^{"}} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e} \\ T_n^{1^{"}} + (N-n+1)\underline{e}_N & \epsilon > T_n^{1^{"}} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e} \end{cases} \tag{16}$$

Therefore, contractor k''s payoff is as follows:

$$\pi_{k',n-1}\left(\hat{\boldsymbol{e}}_{n-2} + \left(e'_{1,n-1}, \dots, e'_{k',n-1} + \epsilon, \dots, e'_{G,n-1}\right)\right) =$$

$$\begin{cases} R\left(\hat{e}_{k',n-2} + e'_{k',n-1} + \epsilon + (N-n+2-k')\delta + (N-n+1)\underline{e}_N\right) \\ \qquad -C\left(\hat{e}_{k',n-2} + e'_{k',n-1} + \epsilon + (N-n+2-k')\delta + (N-n+1)\underline{e}_N\right) \\ \qquad\qquad \epsilon \le T_n^{1''} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1}) \\ R\left(T_n^{1''} + (N-n+1)\underline{e}_N\right) \\ \qquad -C\left(\hat{e}_{k',n-2} + e'_{k',n-1} + \epsilon + (N-n+2-k')\delta + (N-n+1)\underline{e}_N\right) \\ \qquad\qquad \epsilon \le T_n^{1''} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1}) \end{cases} \tag{17}$$

It follows from equation (17) that contractor k''s payoff increases in ϵ when $\epsilon \le T_n^{1''} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1})$ and its payoff decreases in ϵ when hen $\epsilon > T_n^{1''} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1})$. Therefore, contractor k' has incentive to deviate from $e'_{k',n-1}$ by $T_n^{1''} - T_n^1(\hat{\boldsymbol{e}}_{n-2} + \boldsymbol{e}'_{n-1})$, and we have shown that no thresholds below T_{n-1}^1 define an equilibrium threshold strategy.

Step 3. In this step, we show that there does not exist an equilibrium threshold strategy defined by $T'_{n-1} > T_{n-1}^1$, i.e., $e'_{i,n-1} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T'_{n-1} - \hat{e}_{i,n-2}\right)^+\right\}$, satisfying the maxmin criteria. Consider the worst case scenario when all other contractors ($j \ne i$) follow the threshold strategy $\mathrm{e}^*_{j,n-1} = \min\left\{\bar{e}_N, \underline{e}_N + \left(\mathrm{T}_{n-1}^1 - \hat{e}_{j,n-2}\right)^+\right\}$ and contractor i exerts $e'_{i,n-1} = \min\left\{\bar{e}_N, \underline{e}_N + \left(T'_{n-1} - \hat{e}_{i,n-2}\right)^+\right\}$. We note that this is the worst case for contractor i because it exerts $e'_{i,n-1} > e^*_{i,n-1}$ while everybody else $\mathrm{e}^*_{j,n-1}$ which leads to the least total effort of $P(\hat{\boldsymbol{e}}^*_N)$ which is weakly less than the total effort of contractor i. This follows a similar proof of Step 1 above, where we have showed that no contractor has incentive to deviate from the threshold strategy $\mathrm{e}^*_{i,n-1}$ defined by T_{n-1}^1 when all other contractors follow $\mathrm{e}^*_{j,n-1}$. Therefore, in the worst-case scenario contractor

i has incentive to deviate from $e'_{i,n-1}$ to $e^*_{i,n-1}$. Consequently, we have shown that there does not exist an equilibrium threshold strategy defined by $T'_{n-1} > T^1_{n-1}$ satisfying the maxmin criteria. □

A.4. Proof of Proposition 2.2

It follows from the subgame perfect secure equilibrium threshold $T^*_n = \min\{T^1_n, T^2_n\}$ in Lemma 2.1 that all contractors exert the highest effort $\bar{e}_N$ until they reach the threshold $T^1_n \triangleq \min_{j=1,\dots,\min\{G,N-n+2\}} \left(\hat{e}_{j,n-1} + (N-n+2-j)\left(\bar{e}_N - \underline{e}_N\right)\right)$ or $T^2_n \triangleq e^* - (N-n+1)\underline{e}_N$, and after that they will exert the lowest effort $\underline{e}_N$. We denote n* as the number of periods with an effort above $\underline{e}_N$. It follows from T^1_n that all contractors exert the highest effort in the first $N-G+1$ periods if the total effort is not limited by the maximum beneficial effort e^*, and therefore $n^* \leq N-G+1$ if $N \geq G$ and otherwise $n^* = 0$. It follows from T^2_n that contractors exert an effort above $\underline{e}_N$ until they reach the maximum beneficial effort e^*, i.e., $n^*\bar{e}_N + (N-n^*)\underline{e}_N \geq e^*$ and therefore $n^* = \left\lceil \frac{e^*-N\underline{e}_N}{\bar{e}_N-\underline{e}_N} \right\rceil$, where $\lceil x \rceil$ denotes the smallest integer that is above x. We then have $n^* = \min\left\{\left\lceil \frac{e^*-N\underline{e}_N}{\bar{e}_N-\underline{e}_N} \right\rceil, (N-G+1)^+\right\}$, and it follows that the secure equilibrium action of contractor i is

$$e^*_{i,n} = \begin{cases} \min\{\bar{e}_N, e^* - (n-1)\bar{e}_N - (N-n)\underline{e}_N\} & n = 1, \dots, n^* \\ \underline{e}_N & n = n^*+1, \dots, N \end{cases}. \ \square$$

A.5. Proof of Proposition 2.3

It follows from Proposition 2.2 that if $N - G + 1 \leq \left\lceil \frac{e^*-N\underline{e}_N}{\bar{e}_N-\underline{e}_N} \right\rceil$ then the equilibrium secure total effort is $(N-G+1)\bar{e}_N + (G-1)\underline{e}_N$ which is less than the maximum beneficial effort e* and otherwise the secure total effort is e^* when $N - G + 1 \geq \frac{e^*-N\underline{e}_N}{\bar{e}_N-\underline{e}_N}$. It follows that $N^* =$

$\left\lceil (G-1)\frac{\bar{e}-\underline{e}}{\bar{e}-e^*} \right\rceil$ is the minimum required number of information feedback to reach the maximum beneficial effort. □

A.6. Proof of Lemma 2.2

We start from the second period and we derive contractors 1's best response to a given contractor 2's effort in the second period $e_{2,2}$ and a given public information $y_{1,1}$ and $y_{2,1}$. Contractor 1's expected payoff in the second period follows $E_{\epsilon_{1,2},\epsilon_{2,2}}[\pi_{1,2}(e_{1,2}|e_{2,2})] = E_{\epsilon_{1,2},\epsilon_{2,2}}[\min\{y_{1,1}+e_{1,2}+\epsilon_{1,2}, y_{2,1}+e_{2,2}+\epsilon_{2,2}\} - Ce_{1,2}]$.

Taking the derivative from $E_{\epsilon_{1,2},\epsilon_{2,2}}[\pi_{1,2}(e_{1,2}|e_{2,2})]$ with respect to $e_{1,1}$ we have $\frac{\partial}{\partial e_{1,2}} E_{\epsilon_{1,2},\epsilon_{2,2}}[\pi_{1,2}(e_{1,2}|e_{2,2})] = E_{\epsilon_{1,2},\epsilon_{2,2}}\left[\frac{\partial}{\partial e_{1,1}}(\min\{y_{1,1}+e_{1,2}+\epsilon_{1,2}, y_{2,1}+e_{2,2}+\epsilon_{2,2}\} - Ce_{1,2})\right] = E_{\epsilon_{1,2},\epsilon_{2,2}}[1_{y_{1,1}+e_{1,2}+\epsilon_{1,2}\le y_{2,1}+e_{2,2}+\epsilon_{2,2}}] - C = G_{\epsilon_2}(y_{2,1}+e_{2,2}-y_{1,1}-e_{1,2}) - C$.

Therefore, contractor 1's best response to contractor 2's effort $e_{2,2}$ is $b_{1,2}(e_{2,2}) = e_{2,2} + y_{2,1} - y_{1,1} - G_{\epsilon_2}^{-1}(C)$. Similarly, contractor 2's best response to contractor 1's effort $e_{1,2}$ is $b_{2,2}(e_{1,2}) = e_{1,2} + y_{1,1} - y_{2,1} + G_{\epsilon_2}^{-1}(1-C) = e_{1,2} + y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C)$. The last equality follows the fact that ϵ_2 is symmetric and therefore $G_{\epsilon_2}^{-1}(1-C) = -G_{\epsilon_2}^{-1}(C)$.

Next, we consider the case that $\frac{1}{2} < C$ as when $C \le \frac{1}{2}$ even in the setting with no within round information feedback contractors exert the highest possible effort.

When $C \ge \frac{1}{2}$, we consider two cases: $y_{1,1} \le y_{2,1}$ and $y_{1,1} \ge y_{2,1}$. When $y_{1,1} \le y_{2,1}$, contractor 2's best response is to always exert $y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C)$ less than any effort contractor 1 exerts, i.e., $b_{2,2}(e_{1,2}) = e_{1,2} + y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C)$ (note that $G_{\epsilon_2}^{-1}(C) \le 0$ as $C \ge \frac{1}{2}$ and $y_{1,1} - y_{2,1} \le 0$

as $y_{1,1} \leq y_{2,1}$). On the other hand contractor 1's best response to contractor 2's effort is to match whatever it is behind $y_{2,1} - y_{1,1}$ and subtract $G_{\epsilon_2}^{-1}(C)$ from it, i.e., $b_{1,2}(e_{2,2}) = e_{2,2} + y_{2,1} - y_{1,1} - G_{\epsilon_2}^{-1}(C)$. Therefore, in equilibrium contractor 1 exerts $e_{1,2}^* = \underline{e}_2$ if $y_{2,1} - y_{1,1} - G_{\epsilon_2}^{-1}(C) \leq 0$, exerts $e_{1,2}^* = \underline{e}_2 + y_{2,1} - y_{1,1} - G_{\epsilon_2}^{-1}(C)$ if $0 \leq y_{2,1} - y_{1,1} - G_{\epsilon_2}^{-1}(C) \leq \delta$ and exerts $e_{1,2}^* = \bar{e}_2$ if $\delta \leq y_{2,1} - y_{1,1} - G_{\epsilon_2}^{-1}(C)$. Contractor 2 exerts $e_{2,2}^* = \underline{e}_2$.

When $y_{1,1} \geq y_{2,1}$ by applying a same logic, we have that contractor 1 exerts $e_{1,2}^* = \underline{e}_2$ and contractor 2 exerts $e_{2,1}^* = \underline{e}_2$ if $y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C) \leq 0$, exerts $e_{2,1}^* = \underline{e}_2 + y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C)$ if $0 \leq y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C) \leq \delta$ and exerts $e_{2,1}^* = \bar{e}_2$ if $\delta \leq y_{1,1} - y_{2,1} - G_{\epsilon_2}^{-1}(C)$.

To summarize, we derive the following subgame perfect equilibrium in the second period $e_{i,2}^* = \underline{e}_2 + \min\left\{\delta, \left(y_{-i,1} - y_{i,1} - G_{\epsilon_2}^{-1}(C)\right)^+\right\}$.□

A.7. Proof of Proposition 2.5

Contractor 1's expected payoff in the first period from exerting $e_{1,1}$ is $\pi_{1,1}(e_{1,1}|e_{2,1}) = E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\min\{y_{1,1} + e_{1,2}^* + \epsilon_{1,2}, y_{2,1} + e_{2,2}^* + \epsilon_{2,2}\} - C(e_{1,1} + e_{1,2}^*)\right]$. We first take the derivative of $\pi_{1,1}(e_{1,1}|e_{2,1})$ with respect to $e_{1,1}$ to characterize the best response of contractor 1 to a given contractor 2's effort in the first period $e_{2,1}$. Note that $e_{i,2}^*$ follows the subgame perfect equilibrium that is derived in Lemma 2.2.

$$\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1}\middle|e_{2,1}\right)\right]$$

$$= E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\frac{\partial}{\partial e_{1,1}}\left(\min\{y_{1,1}+e^*_{1,2}+\epsilon_{1,2}, y_{2,1}+e^*_{2,2}+\epsilon_{2,2}\}\right.\right.$$

$$\left.\left.- C\left(e_{1,1}+e^*_{1,2}\right)\right)\right] =$$

$$\begin{aligned}
&E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\Big[1_{\left[\left(y_{1,1}-y_{2,1}\leq-\delta-G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\bar{e}_2+\epsilon_{1,2}\leq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right]}\times(1-C)\\
&+1_{\left[\left(y_{1,1}-y_{2,1}\leq-\delta-G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\bar{e}_2+\epsilon_{1,2}\geq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right]}\times(0-C)\\
&+1_{\left[\left(-\delta-G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq-G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\underline{e}_2+\left(y_{2,1}-y_{1,1}\right)-G_{\epsilon_2}^{-1}(C)+\epsilon_{1,2}\leq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right]}\times(0-0)\\
&+1_{\left[\left(-\delta-G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq-G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\underline{e}_2+\left(y_{2,1}-y_{1,1}\right)-G_{\epsilon_2}^{-1}(C)+\epsilon_{1,2}\geq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right]}\times(0-0)\\
&+1_{\left[\left(-G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\leq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right]}\times(1-C)\\
&+1_{\left[\left(-G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\geq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right]}\times(0-C)\\
&+1_{\left[\left(G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq\delta+G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\leq y_{2,1}+\underline{e}_2+\left(y_{1,1}-y_{2,1}\right)-G_{\epsilon_2}^{-1}(C)+\epsilon_{2,2}\right)\right]}\times(1-C)\\
&+1_{\left[\left(G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq\delta+G_{\epsilon_2}^{-1}(C)\right)\,and\,\left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\geq y_{2,1}+\underline{e}_2+\left(y_{1,1}-y_{2,1}\right)-G_{\epsilon_2}^{-1}(C)+\epsilon_{2,2}\right)\right]}\times(1-C)\\
&+1_{\left[\left(\delta+G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\right)\,and\,\left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\leq y_{2,1}+\bar{e}_2+\epsilon_{2,2}\right)\right]}\times(1-C)\\
&+1_{\left[\left(\delta+G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\right)\,and\,\left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\geq y_{2,1}+\bar{e}_2+\epsilon_{2,2}\right)\right]}\times(0-C)\Big]
\end{aligned}\tag{18}$$

By taking expectation, we can further simplify (18) as (19):

$$
\begin{aligned}
&P\left[\left(y_{1,1}-y_{2,1}\leq -\delta - G_{\epsilon_2}^{-1}(C)\right) \; and \; \left(y_{1,1}+\bar{e}_2+\epsilon_{1,2}\leq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right] \\
&\qquad + P\left[\left(-G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq G_{\epsilon_2}^{-1}(C)\right) \; and \; \left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\right.\right. \\
&\qquad \left.\left.\leq y_{2,1}+\underline{e}_2+\epsilon_{2,2}\right)\right] + P\left(G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq \delta + G_{\epsilon_2}^{-1}(C)\right) \\
&\qquad + P\left[\left(\delta+G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\right) \; and \; \left(y_{1,1}+\underline{e}_2+\epsilon_{1,2}\right.\right. \\
&\qquad \left.\left.\leq y_{2,1}+\bar{e}_2+\epsilon_{2,2}\right)\right] \\
&\qquad - C\left[P\left(y_{1,1}-y_{2,1}\leq -\delta - G_{\epsilon_{1,2}-\epsilon_{2,2}}^{-1}(C)\right)\right. \\
&\qquad + P\left(-G_{\epsilon_{1,2}-\epsilon_{2,2}}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq G_{\epsilon_{1,2}-\epsilon_{2,2}}^{-1}(C)\right) \\
&\qquad + P\left(G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\leq \delta+G_{\epsilon_2}^{-1}(C)\right) \\
&\qquad \left. + P\left(\delta+G_{\epsilon_2}^{-1}(C)\leq y_{1,1}-y_{2,1}\right)\right]
\end{aligned}
\tag{19}
$$

We can compute (19) as (20):

$$
\begin{aligned}
&\int_{-\infty}^{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)} \int_{-\infty}^{-\delta-x} g_{\epsilon_1}(x)g_{\epsilon_2}(y)\partial y\partial x \\
&\qquad + \int_{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)} \int_{-\infty}^{-x} g_{\epsilon_1}(x)g_{\epsilon_2}(y)\partial y\partial x \\
&\qquad + \int_{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x \\
&\qquad + \int_{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}^{\infty} \int_{-\infty}^{\delta-x} g_{\epsilon_1}(x)g_{\epsilon_2}(y)\partial y\partial x \\
&\qquad - C\left(1-\int_{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x\right) =
\end{aligned}
\tag{20}
$$

$$\int_{-\infty}^{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)G_{\epsilon_2}(-\delta-x)\partial x+\int_{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)G_{\epsilon_2}(-x)\partial x$$

$$+\int_{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x$$

$$+\int_{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}^{\infty} g_{\epsilon_1}(x)G_{\epsilon_2}(\delta-x)\partial x \tag{21}$$

$$-C\left(1-\int_{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x\right)$$

Next, we compute each part of (21) separately as following:

Part 1. $\int_{-\infty}^{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}\int_{-\infty}^{-\delta-x} g_{\epsilon_1}(x)g_{\epsilon_2}(y)\partial y\partial x=\int_{-\infty}^{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)G_{\epsilon_1}(-\delta-x)\partial x=\int_{-\infty}^{\frac{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}{\sigma}}\sigma g_{\epsilon_1}(\sigma u)G_{\epsilon_1}(-\delta-\sigma u)\partial u$. The last equality follows from change of variable as $u=\frac{x}{\sigma}$. Next, we standardize the normal distribution. We denote $z\sim N(0,1)$ with probability density function of $g_{z(.)}$ and cumulative density function of $G_z(.)$. $\int_{-\infty}^{\frac{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}{\sigma}}\sigma g_{\epsilon_1}(\sigma u)G_{\epsilon_1}(-\delta-\sigma u)\partial u=\int_{-\infty}^{\frac{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}{\sigma}} g_z(u)G_z\left(-\frac{\delta}{\sigma}-u\right)\partial u=$ $BvN\left[-\frac{\delta}{\sigma\sqrt{2}},\frac{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}{\sigma},\rho=\frac{1}{\sqrt{2}}\right]$. The last equality follows from 10,010.1 of (Owen 1980). Note that BvN is denoted as the bivariate normal cumulative distribution of $BvN[h,k;\rho]=\frac{1}{2\pi\sqrt{1-\rho^2}}\int_{-\infty}^{k}\int_{-\infty}^{h} e^{-\frac{(x^2-2\rho xy+y^2)}{2(1-\rho^2)}}\partial x\partial y$.

Part 2. $\int_{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)G_{\epsilon_2}(-x)\partial x = \int_{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(-x)G_{\epsilon_1}(-x)\partial x$. The equality follows from $g_{\epsilon_1}(-x) = g_{\epsilon_1}(x)$ as normal distribution is symmetric. $\int_{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(-x)G_{\epsilon_1}(-x)\partial x = -\frac{\left[G_{\epsilon_1}^2\left(-\left(e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)\right)\right)-G_{\epsilon_1}^2\left(-\left(e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)\right)\right)\right]}{2}$.

Part 3. $\int_{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x = G_{\epsilon_1}\left(e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)\right) - G_{\epsilon_1}\left(e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)\right)$.

Part 4. $\int_{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}^{\infty} g_{\epsilon_1}(x)G_{\epsilon_2}(\delta-x)\partial x = \int_{\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}}^{\infty} \sigma g_{\epsilon_1}(\sigma u)G_{\epsilon_1}(\delta-\sigma u)\partial u$. The equality follows from change of variable as $u = \frac{x}{\sigma}$. Next, we standardize the normal distribution. $\int_{\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}}^{\infty} \sigma g_{\epsilon_1}(\sigma u)G_{\epsilon_1}(\delta-\sigma u)\partial u = \int_{\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}}^{\infty} g_z(u)G_z\left(-\frac{\delta}{\sigma}-u\right)\partial u$. Applying change of variable as $v=-u$ and the fact that $g_z(-v)=g_z(v)$ as normal distribution is symmetric, we get $\int_{\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}}^{\infty} g_z(u)G_z\left(-\frac{\delta}{\sigma}-u\right)\partial u = -\int_{-\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}}^{-\infty} g_z(v)G_z\left(-\frac{\delta}{\sigma}+v\right)\partial v = BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho=-\frac{1}{\sqrt{2}}\right]$. The last equality follows from 10,010.1 of (Owen 1980).

Part 5. $-C\left(1-\int_{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x\right) = -C\left(1-G_{\epsilon_1}\left(e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)\right)+G_{\epsilon_1}\left(e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)\right)\right)$.

Therefore, by substituting part 1 to 5 in $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1}\middle|e_{2,1}\right)\right] =$ $\int_{-\infty}^{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)G_{\epsilon_2}(-\delta-x)\partial x + \int_{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)G_{\epsilon_2}(-x)\partial x +$

$\int_{e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x + \int_{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}^{\infty} g_{\epsilon_1}(x)G_{\epsilon_2}(\delta - x)\partial x - C\Big(1 -$

$\int_{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}^{e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)} g_{\epsilon_1}(x)\partial x\Big)$ we have that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1}\middle|e_{2,1}\right)\right] =$

$BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, \frac{e_{2,1}-e_{1,1}-\delta-G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] - \frac{\left[G_{\epsilon_1}^2\left(-\left(e_{2,1}-e_{1,1}+G_{\epsilon_2}^{-1}(C)\right)\right) - G_{\epsilon_1}^2\left(-\left(e_{2,1}-e_{1,1}-G_{\epsilon_2}^{-1}(C)\right)\right)\right]}{2} +$

$G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\right) - G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right) +$

$BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = -\frac{1}{\sqrt{2}}\right] - C\left(1 - G_{\epsilon_1}\left(e_{2,1} - e_{1,1} - G_{\epsilon_2}^{-1}(C)\right) + G_{\epsilon_1}\left(e_{2,1} -\right.\right.$

$\left.\left.e_{1,1} - \delta - G_{\epsilon_2}^{-1}(C)\right)\right).$

Next, we want to show that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1}\middle|e_{2,1}\right)\right] \geq 0$ for any $e_{2,1} \leq e_{1,1}$ and we consider three cases: $e_{1,1} = e_{2,1}$, $e_{2,1} < e_{1,1} \leq e_{2,1} + G_{\epsilon_2}^{-1}(C)$ and $e_{2,1} + G_{\epsilon_2}^{-1}(C) \leq e_{1,1}$.

Case 1. When $e_{1,1} = e_{2,1}$ then we want to show that when $C < \frac{1}{\sqrt{2}}$ and $\sigma < \sigma_1$ then $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1} = e_{2,1}\middle|e_{2,1}\right)\right] \geq 0.$

It follows from $G_{\epsilon_1}\left(G_{\epsilon_2}^{-1}(C)\right) = C$ and $G_{\epsilon_1}\left(-G_{\epsilon_2}^{-1}(C)\right) = 1 - C$ that

$\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1} = e_{2,1}\middle|e_{2,1}\right)\right] = BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] -$

$\frac{\left[G_{\epsilon_1}^2\left(-G_{\epsilon_2}^{-1}(C)\right) - G_{\epsilon_1}^2\left(G_{\epsilon_2}^{-1}(C)\right)\right]}{2} + G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right) - G_{\epsilon_1}\left(G_{\epsilon_2}^{-1}(C)\right) + BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho =\right.$

$\left.-\frac{1}{\sqrt{2}}\right] - C\left(1 - G_{\epsilon_1}\left(-G_{\epsilon_2}^{-1}(C)\right) + G_{\epsilon_1}\left(-\delta - G_{\epsilon_2}^{-1}(C)\right)\right) = BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] +$

$C - \frac{1}{2} + G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right) - C + BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = -\frac{1}{\sqrt{2}}\right] - C\left(1 - 1 + C + 1 -\right.$

$\left.G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right)\right) = BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] + BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = -\frac{1}{\sqrt{2}}\right] -$

$\frac{1}{2} + G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right)(1 + C) - C^2 - C$. The last equality follows from simplification. To show $BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta + G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] + BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{\delta + G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = -\frac{1}{\sqrt{2}}\right] - \frac{1}{2} + G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right)(1 + C) - C^2 - C \geq 0$ we want to show that $G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right) \geq \frac{\frac{1}{2} + C^2 + C}{(1+C)}$. When $C < \frac{1}{\sqrt{2}}$ then $\frac{\frac{1}{2} + C^2 + C}{(1+C)} < 1$ and therefore as $\lim_{\sigma \to 0} G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right) = 1$ there exists σ_1 such that for any $\sigma < \sigma_1$ then $G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right) \geq \frac{\frac{1}{2} + C^2 + C}{(1+C)}$. Therefore when $C < \frac{1}{\sqrt{2}}$ and $\sigma < \sigma_1$ then $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1} = e_{2,1} \middle| e_{2,1}\right)\right] \geq 0$.

Case 2. When $e_{2,1} < e_{1,1} \leq e_{2,1} + G_{\epsilon_2}^{-1}(C)$ we want to show that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1} \middle| e_{2,1}\right)\right] \geq 0$. It follows from $\lim_{\sigma \to 0} -\frac{\left[G_{\epsilon_1}^2\left(-\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right)\right) - G_{\epsilon_1}^2\left(-\left(e_{2,1} - e_{1,1} - G_{\epsilon_2}^{-1}(C)\right)\right)\right]}{2} = \frac{1}{2}$ and $\lim_{\sigma \to 0} G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\right) = 1$ that there exists σ_2 such that for any $\sigma < \sigma_2$ we have $-\frac{\left[G_{\epsilon_1}^2\left(-\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right)\right) - G_{\epsilon_1}^2\left(-\left(e_{2,1} - e_{1,1} - G_{\epsilon_2}^{-1}(C)\right)\right)\right]}{2} \geq \frac{1}{2} - \theta$ and $G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\right) \geq 1 - \theta$. Therefore we have that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1} = \frac{e}{2} \middle| e_{2,1} = \frac{e}{2}\right)\right] =$
$BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, \frac{e_{2,1} - e_{1,1} - \delta - G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] - \frac{\left[G_{\epsilon_1}^2\left(-\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right)\right) - G_{\epsilon_1}^2\left(-\left(e_{2,1} - e_{1,1} - G_{\epsilon_2}^{-1}(C)\right)\right)\right]}{2} +$
$G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\right) - G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right) +$
$BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = -\frac{1}{\sqrt{2}}\right] - C\left(1 - G_{\epsilon_1}\left(e_{2,1} - e_{1,1} - G_{\epsilon_2}^{-1}(C)\right) + G_{\epsilon_1}\left(e_{2,1} - e_{1,1} - \delta - G_{\epsilon_2}^{-1}(C)\right)\right) \geq BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, \frac{e_{2,1} - e_{1,1} - \delta - G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = \frac{1}{\sqrt{2}}\right] + \frac{1}{2} - \theta + 1 - \theta - G_{\epsilon_1}\left(e_{2,1} -\right.$

$e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) + BvN\left[-\frac{\delta}{\sigma\sqrt{2}}, -\frac{e_{2,1}-e_{1,1}+\delta+G_{\epsilon_2}^{-1}(C)}{\sigma}, \rho = -\frac{1}{\sqrt{2}}\right] - C\Big(1 - G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} -$ $G_{\epsilon_2}^{-1}(C)\Big) + G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} - \delta - G_{\epsilon_2}^{-1}(C)\Big)\Big) \geq \frac{1}{2} - \theta + 1 - \theta - C - C$. The last inequality follows from $G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) \leq C$ as $e_{2,1} - e_{1,1} < 0$ and the fact that $1 - G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} - G_{\epsilon_2}^{-1}(C)\Big) + G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} - \delta - G_{\epsilon_2}^{-1}(C)\Big) \leq 1$. Therefore, we showed that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1} = \frac{e}{2}\middle| e_{2,1} = \frac{e}{2}\right)\right] \geq \frac{3}{2} - 2\theta - 2C$. Note that for $\theta = \frac{3}{4} - C$ and $C < \frac{3}{4}$ we have that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}[\pi_{1,1}(e_{1,1}|e_{2,1})] \geq 0$.

Case 3. When $e_{2,1} + G_{\epsilon_2}^{-1}(C) \leq e_{1,1}$ we have that for any $e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C) \leq 0$, there exists $0 < \sigma_3$ and $0 < \theta$ such that for any $\sigma < \sigma_3$, we have $G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) \leq \theta$. This follows from the definition of limit that $\lim_{\sigma\to 0} G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) = 0$. Next, we show that the third term in $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}[\pi_{1,1}(e_{1,1}|e_{2,1})]$ is greater than C, i.e., $G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\Big) - G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) \geq C$ and therefore $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}[\pi_{1,1}(e_{1,1}|e_{2,1})] \geq 0$.

$G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\Big) - G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) = 1 - G_{\epsilon_1}\Big(-\Big(e_{2,1} - e_{1,1} +$ $\delta + G_{\epsilon_2}^{-1}(C)\Big)\Big) - G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) \geq 1 - 2\theta$. The last inequality follows from $-G_{\epsilon_1}\Big(-\Big(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\Big)\Big) \geq -G_{\epsilon_1}\Big(-\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big)\Big) \geq -\theta$ and $-G_{\epsilon_1}\Big(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\Big) \geq -\theta$ and therefore $1 - G_{\epsilon_1}\Big(-\Big(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\Big)\Big) -$

$G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right) \geq 1 - 2\theta$. Therefore for $\theta = \frac{1-C}{2}$ we have that $1 - G_{\epsilon_1}\Big(-\big(e_{2,1} - e_{1,1} + \delta + G_{\epsilon_2}^{-1}(C)\big)\Big) - G_{\epsilon_1}\left(e_{2,1} - e_{1,1} + G_{\epsilon_2}^{-1}(C)\right) \geq C$. Therefore, for $\theta = \frac{1-C}{2}$ we have that $\frac{\partial}{\partial e_{1,1}} E_{\epsilon_{1,1},\epsilon_{1,2},\epsilon_{2,1},\epsilon_{2,2}}\left[\pi_{1,1}\left(e_{1,1}\middle|e_{2,1}\right)\right] \geq 0.$

To summarize, we show that when $C < \frac{\sqrt{2}}{2}$ there exists $\bar{\sigma}(C,\delta)$ such that when $\sigma \leq \bar{\sigma}(C,\delta)$ at least one contractor exerts the highest possible effort of $\bar{e}_2$, where $\bar{\sigma}(C,\delta) \triangleq \sup\Big\{\sigma \big| \Big(0 \leq G_{\epsilon_1}\left(\delta + G_{\epsilon_2}^{-1}(C)\right) - \frac{1+2C^2+2C}{2+2C}\Big)$ *and* $\Big(0 \leq G_{\epsilon_1}^2\left(x + G_{\epsilon_2}^{-1}(C)\right) - G_{\epsilon_1}^2\left(x - G_{\epsilon_2}^{-1}(C)\right) + 2G_{\epsilon_1}\left(-x + \delta + G_{\epsilon_2}^{-1}(C)\right) - 4C, \forall x \in \left(0, \min\{\delta, G_{\epsilon_2}^{-1}(C)\}\right]\Big)$ *and* $\Big(0 \leq \frac{1-C}{2} - G_{\epsilon_1}\left(-x + G_{\epsilon_2}^{-1}(C)\right), \forall x \in \left(\min\{\delta, G_{\epsilon_2}^{-1}(C)\}, \delta\right]\Big)\Big\}$.□

A.8. Proof of Proposition 2.6

We consider contractors' decision as a one-shot decision regarding the total production quantity as in this setting the production quantity in each period is not observable by other contractors. We consider contractor i's decision in the proof, as the analysis for all other contractors are symmetric. We also denote $\hat{e}_{-i,N}$ as the least total production quantity by all other contractors. We consider two cases: $\hat{e}_{i,N} \leq \hat{e}_{-i,N}$ and $\hat{e}_{-i,N} \leq \hat{e}_{i,N}$. When $\hat{e}_{i,N} \leq \hat{e}_{-i,N}$ it follows from $\frac{\partial E_D[\pi_i(\hat{\boldsymbol{e}}_N)]}{\partial \hat{e}_{i,N}} = \frac{\partial}{\partial \hat{e}_{i,N}} E_D\left[p\min\{P(\hat{\boldsymbol{e}}_{\boldsymbol{N}}), D\} - C\hat{e}_{i,N}\right] = \frac{\partial}{\partial \hat{e}_{i,N}} E_D\left[p\min\{\hat{e}_{i,N}, D\} - C\hat{e}_{i,N}\right] = E_D\left[p1_{\{\hat{e}_{i,N} \leq D\}} - C\right] = p\bar{F}\left(\hat{e}_{i,N}\right) - C$ that contractor i's expected payoff increases in $\hat{e}_{i,N}$ if $\hat{e}_{i,N}$ is less than e^*, and decreases otherwise, where $e^* = \inf\left\{e: \frac{\partial \bar{F}}{\partial P(\hat{\boldsymbol{e}}_N)}\Big|_{P(\boldsymbol{e}) = e} \leq \frac{C}{p}, e \in \left[\underline{e}, \bar{e}\right]\right\}$. When $\hat{e}_{-i,N} \leq \hat{e}_{i,N}$ it follows from $\frac{\partial E_D[\pi_i(\hat{\boldsymbol{e}}_N)]}{\partial \hat{e}_{i,N}} = \frac{\partial}{\partial \hat{e}_{i,N}} E_D\left[p \min\{P(\hat{\boldsymbol{e}}_N), D\} - C\hat{e}_{i,N}\right] = \frac{\partial}{\partial \hat{e}_{i,N}} E_D\left[p \min\{\hat{e}_{-i,N}, D\} - C\hat{e}_{i,N}\right] = E_D[-C] = -C \leq 0$ that contractor i's expected payoff decreases in $\hat{e}_{i,N}$. To summarize, we show that contractor i's expected payoff increases in $\hat{e}_{i,N}$ if $\hat{e}_{i,N}$ is less than $\min\{\hat{e}_{-i,N}, e^*\}$, and decreases otherwise. Therefore, contractor i's best response to the least total production quantity by all other contractors $\hat{e}_{-i,N}$ is $b_i(\hat{e}_{-i,N}) = \min\{\hat{e}_{-i,N}, e^*\}$. By symmetry, all contractors prefer to produce the same total quantity between the lowest capacity $\underline{e}$, and the maximum beneficial capacity e^*, and therefore there exist multiple equilibria in which all contractors achieve the same total quantity between the lowest capacity $\underline{e}$, and the maximum beneficial capacity e^*. □

A.9. Proof of Proposition 2.7

Using backward induction, we start from the second period and we derive the subgame perfect equilibrium, and then we roll back to the first period to derive the equilibrium.

Second period. At the beginning of the second period, contractors' beginning states are $e_{1,1}$ and $e_{2,1}$ which are public information among both contractors. For ease of exposition, we relabel the contractor with the lowest effort as contractor 1 and the other contractor as contractor 2, i.e., $e_{1,1} \leq e_{2,1}$.

We first derive contractor i's best response to a given other contractor's effort $e_{-i,2}$. Contractor i's payoff $\pi_{i,2}(\hat{\boldsymbol{e}}_1 + (e_{1,2}, e_{2,2})) = \min\{e_{1,1} + e_{1,2}, e_{2,1} + e_{2,2}\} - \frac{C}{2} e_{i,2}^2$ increases in its effort when $e_{i,2} \leq \min\left\{\frac{1}{C}, e_{-i,1} + e_{-i,2} - e_{i,1}\right\}$ and decreases otherwise.

Therefore contractor i's best response is to exert $\underline{e}_2 + \min\left\{\delta, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}$ when $\frac{1}{C} \leq e_{-i,1} + e_{-i,2} - e_{i,1}$ and $\underline{e}_2 + \min\left\{\delta, \left(e_{-i,1} + e_{-i,2} - e_{i,1} - \underline{e}_2\right)^+\right\}$ otherwise. Equivalently the best response can be written as $b_{i,2}(e_{-i,2}) = \underline{e}_2 + \min\left\{\delta, \left(\min\left\{\frac{1}{C}, e_{-i,1} + e_{-i,2} - e_{i,1}\right\} - \underline{e}_2\right)^+\right\}$. Comparing the best response in the case of linear cost function with the convex cost function it is trivial to observe that the best responses when the cost function is convex is limited by $\frac{1}{C}$ meaning that contractors do not want to exert any effort beyond the beneficial effort $\frac{1}{C}$ at the second period. Therefore, in equilibrium contractor i exerts $e^*_{i,2} = \min\left\{\bar{e}_2, \underline{e}_2 + \left(P(\hat{\boldsymbol{e}}_1 + \boldsymbol{e}^*_2) - \underline{e}_2 - e_{i,1}\right)^+\right\}$ where $P(\hat{\boldsymbol{e}}_1 + \boldsymbol{e}^*_2) \in \left[\min\left\{e_{2,1} + \underline{e}_2, e_{1,1} + \underline{e}_2 + \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}, \min\left\{e_{1,1} + \bar{e}_2, e_{1,1} + \underline{e}_2 + \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}\right]$. Therefore, we have unique equilibrium $e^*_{1,2} = \min\left\{\bar{e}_2, \underline{e}_2 + \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}$ and $e^*_{2,2} = \underline{e}_2$ when $\left(\frac{1}{C} - \underline{e}_2\right)^+ \leq e_{2,1} - e_{1,1}$ and multiple equilibria otherwise.

Next, when $\left(\frac{1}{C} - \underline{e}_2\right)^+ \geq e_{2,1} - e_{1,1}$ we show that $P(\hat{\boldsymbol{e}}_1 + \boldsymbol{e}^*_1) = e_{2,1} + \underline{e}_2$ survives the maxmin criteria. The maxmin strategy is a strategy which maximizes the worst-case payoff, and results in the secure equilibrium. For contractor 1, the worst case occurs when contractor 2 exerts the lowest effort $\underline{e}_2$. In this case, the least total effort among contractors is limited by contractor 2's total effort $\hat{e}_{2,2} = e_{2,1} + \underline{e}_2$. In this scenario, contractor 1's payoff increases in its effort if $e_{1,2} \leq e_{2,1} + \underline{e}_2 - e_{1,1}$, and decreases in its effort otherwise, so contractor 1 can maximize its payoff by exerting $e^*_{1,2} = e_{2,1} + \underline{e}_2 - e_{2,1}$. Note that this is the worst case for contractor 2 since contractor 1's total effort is less than the total effort of contractor 2, i.e., $\mathrm{e}_{1,1} + e^*_{1,2} \leq \mathrm{e}_{2,1} + \underline{e}_2$.

In this case, contractor 2's payoff $\pi_{2,2}\big(\hat{\boldsymbol{e}}_1 + (e_{1,2}^*, e_{2,2})\big) = e_{1,1} + e_{1,2}^* - C\big(e_{2,1} + e_{2,2}\big)$ decreases in its effort and therefore it does not have incentive to exert anything above the lowest effort $\underline{e}_2$. Therefore $e_{2,2}^* = \underline{e}_2$ is an equilibrium action surviving the maxmin strategy.

To summarize, we have derived that $\left(e_{1,2}^*, e_{2,2}^*\right) = \left(\underline{e}_2 + \min\left\{e_{2,1} - e_{1,1}, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}, \underline{e}_2\right)$ is the equilibrium surviving the maxmin criteria. Next, we roll back to the first period to derive the equilibrium in the first period.

First period. Without loss of generality assume that contractor 2 has exerted more effort than contractor 1, i.e., $e_{1,1} \leq e_{2,1}$.

First, we derive contractor 2's best response to contractor 1's effort. Contractor 2's payoff $\pi_{2,1}\big((e_{1,1}, e_{2,1}) + (e_{1,2}^*, e_{1,2}^*)\big) = \min\{e_{1,1} + e_{1,2}^*, e_{2,1} + e_{2,2}^*\} - \frac{C}{2}{e_{2,1}}^2 - \frac{C}{2}{e_{2,2}^*}^2 = \min\Big\{e_{1,1} + \underline{e}_2 + \min\left\{e_{2,1} - e_{1,1}, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}, e_{2,1} + \underline{e}_2\Big\} - \frac{C}{2}{e_{2,1}}^2 - \frac{C}{2}\underline{e}_2^2$ where the last equality follows from substitution of $\left(e_{1,2}^*, e_{2,2}^*\right) = \left(\underline{e}_2 + \min\left\{e_{2,1} - e_{1,1}, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}, \underline{e}_2\right)$.

Therefore contractor 2's payoff increases in its effort when $e_{2,1} \leq \min\left\{\frac{1}{C}, e_{1,1} + \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}$ and decreases otherwise. Therefore, contractor 2's best response is to exert $\underline{e}_2$ when $\frac{1}{C} \leq \underline{e}_2$, $\frac{1}{C}$ when $\underline{e}_2 \leq \frac{1}{C} \leq \bar{e}_2$ and $\bar{e}_2$ when $\bar{e}_2 \leq \frac{1}{C}$. Note that contractor 2's best response is equivalent to its equilibrium effort as its best response is independent of contractor 1's effort $e_{1,1}$. Next, we derive contractor 1's best response in three cases: $\frac{1}{C} \leq \underline{e}_2$, $\underline{e}_2 \leq \frac{1}{C} \leq \bar{e}_2$ and $\bar{e}_2 \leq \frac{1}{C}$.

When $\frac{1}{C} \leq \underline{e}_2$ and therefore $e_{2,1}^* = \underline{e}_2$ contractor 1's payoff $\pi_{1,1}\big((e_{1,1}, e_{2,1}) + (e_{1,2}^*, e_{2,2}^*)\big) = \min\{e_{1,1} + e_{1,2}^*, e_{2,1} + e_{2,2}^*\} - \frac{C}{2}{e_{1,1}}^2 - \frac{C}{2}{e_{1,2}^*}^2 = \min\{e_{1,1} + \underline{e}_2, \underline{e}_2 + \underline{e}_2\} - \frac{C}{2}{e_{1,1}}^2 - \frac{C}{2}{\underline{e}_2}^2$ where the last equality follows from substitution of $\left(e_{1,2}^*, e_{2,2}^*\right) = \left(\underline{e}_2, \underline{e}_2\right)$. Therefore, contractor 1's payoff decreases in its effort. Therefore, contractor 1 exerts $e_{1,1}^* = \underline{e}_2$ in equilibrium.

When $\underline{e}_2 \leq \frac{1}{C} \leq \bar{e}_2$ and therefore $e_{2,1}^* = \frac{1}{C}$ contractor 1's payoff $\pi_{1,1}\big((e_{1,1}, e_{2,1}) + (e_{1,2}^*, e_{2,2}^*)\big) = \min\{e_{1,1} + e_{1,2}^*, e_{2,1} + e_{2,2}^*\} - \frac{C}{2}{e_{1,1}}^2 - \frac{C}{2}{e_{1,2}^*}^2 = \min\left\{\frac{1}{C} + \underline{e}_2, \frac{1}{C} + \underline{e}_2\right\} - \frac{C}{2}{e_{1,1}}^2 - \frac{C}{2}\left(\underline{e}_2 + \frac{1}{C} - e_{1,1}\right)^2$ where the last equality follows from substitution of $\left(e_{1,2}^*, e_{2,2}^*\right) = \left(\underline{e}_2 + \min\left\{\frac{1}{C} - e_{1,1}, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}, \underline{e}_2\right) = \left(\underline{e}_2 + \frac{1}{C} - e_{1,1}, \underline{e}_2\right)$. The last equality follows from the case that $\underline{e}_2 \leq \frac{1}{C}$ and the fact that $e_{1,1} \geq \underline{e}_2$. Therefore contractor 1's payoff increases in its effort when $e_{1,1} \leq \frac{\underline{e}_2}{2} + \frac{1}{2C}$ and decreases otherwise. Therefore, contractor 1 exerts $e_{1,1}^* = \frac{\underline{e}_2}{2} + \frac{1}{2C}$ in equilibrium.

When $\bar{e}_2 \leq \frac{1}{C}$ and therefore $e_{2,1}^* = \bar{e}_2$ contractor 1's payoff $\pi_{1,1}\big((e_{1,1}, e_{2,1}) + (e_{1,2}^*, e_{2,2}^*)\big) = \min\{e_{1,1} + e_{1,2}^*, e_{2,1} + e_{2,2}^*\} - \frac{C}{2}{e_{1,1}}^2 - \frac{C}{2}{e_{1,2}^*}^2 = \min\{\underline{e}_2 + \bar{e}_2, \bar{e}_2 + \underline{e}_2\} - \frac{C}{2}{e_{1,1}}^2 - \frac{C}{2}\left(\underline{e}_2 + \bar{e}_2 - e_{1,1}\right)^2$ where the last equality follows from substitution of $\left(e_{1,2}^*, e_{2,2}^*\right) = \left(\underline{e}_2 + \bar{e}_2 - e_{1,1}, \underline{e}_2\right)$. Therefore contractor 1's payoff increases in its effort when $e_{1,1} \leq \frac{\underline{e}_2 + \bar{e}_2}{2}$ and decreases otherwise. Therefore, contractor 1 exerts $e_{1,1}^* = \frac{\underline{e}_2 + \bar{e}_2}{2}$ in equilibrium.

To summarize in the first period, $e^*_{1,1} = e^*_{2,1} = \underline{e}_2$ when $\frac{1}{C} \leq \underline{e}_2$, $e^*_{1,1} = \frac{\underline{e}_2}{2} + \frac{1}{2C}$ and $e^*_{2,1} = \frac{1}{C}$ when $\underline{e}_2 \leq \frac{1}{C} \leq \bar{e}_2$, $e^*_{1,1} = \frac{\underline{e}_2 + \bar{e}_2}{2}$ and $e^*_{2,1} = \bar{e}_2$ when $\bar{e}_2 \leq \frac{1}{C}$. Equivalently the equilibrium effort can be written as $e^*_{2,1} = \underline{e}_2 + \min\left\{\delta, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}$ and $e^*_{1,1} = \underline{e}_2 + \frac{\min\left\{\delta, \left(\frac{1}{C} - \underline{e}_2\right)^+\right\}}{2}$. □

A.10. Proof of Lemma 3.1

Using backward induction, we start from the second period. After deriving supplier best response in the second period, we roll back to the first period. We consider three cases where $T \in \{0,1,2\}$.

Case 1. When $T = 0$, as the supplier earns the reward R no matter what its final score is, it is trivial to derive that the supplier always exerts low effort, A_2.

Case 2. When $T = 1$, starting from the second period, the supplier might have score 0 or 1 by the end of the first period, therefore we consider two cases where $S_1 = 0$ and $S_1 = 1$. When $S_1 = 0$ supplier exerts high effort if its payoff-to-go from exerting high effort $\pi_2(0, H)$ is higher than exerting low $\pi_2(0, L)$, i.e., $\pi_2(0, H) = pR + (1-p)0 - C \geq qR + (1-q)0 = \pi_2(0, L)$. Therefore, the supplier exerts high if $\Delta \geq \frac{1}{p-q}$ and low otherwise. When $S_1 = 1$ we note that the supplier exerts low as it has already reached the target and its payoff-to-go from exerting low is $\pi_2(1, L) = qR + (1-q)R$.

Rolling back to the first period, we consider two cases where $\Delta \geq \frac{1}{p-q}$ and $\Delta \leq \frac{1}{p-q}$. When $\Delta \geq \frac{1}{p-q}$, the supplier exerts high effort if its payoff-to-go from exerting high effort $\pi_1(0, H)$ is higher than exerting low $\pi_1(0, L)$, i.e., $\pi_1(0, H) = p\pi_2(1, L) + (1-p)\pi_2(0, H) - C \geq$

$q\pi_2(1,L)+(1-q)\pi_2(0,H)=\pi_1(0,L)$. Note that $\pi_2(1,L)=qR+(1-q)R$ and $\pi_2(0,H)=pR+(1-p)0-C$. Therefore, the supplier exerts high if $\Delta \geq \frac{1-p+q}{(p-q)(1-p)}$ and low otherwise.

When $\Delta \leq \frac{1}{p-q}$ the supplier exerts high effort if its payoff-to-go from exerting high effort $\pi_1(0,H)$ is higher than exerting low $\pi_1(0,L)$, i.e., $\pi_1(0,H)=p\pi_2(1,L)+(1-p)\pi_2(0,L)-C \geq q\pi_2(1,L)+(1-q)\pi_2(0,L)=\pi_1(0,L)$. Note that $\pi_2(1,L)=qR+(1-q)R$ and $\pi_2(0,L)=qR+(1-q)0$. Therefore, the supplier exerts high if $\frac{1}{(p-q)(1-q)} \leq \Delta$ and low otherwise. As in this case $\Delta \leq \frac{1}{p-q} \leq \frac{1}{(p-q)(1-q)}$ the supplier best response is to exert low effort.

To summarize, when target is 1 the supplier best response is to exert A_2 when $\Delta \leq \frac{1}{p-q}$, exert A_6 when $\frac{1}{p-q} < \Delta \leq \frac{1-p+q}{(p-q)(1-p)}$ and exert A_5 when $\frac{1-p+q}{(p-q)(1-p)} < \Delta$.

Case 3. When target is 2 starting from the second period, the supplier might have score 0 or 1 by the end of the first period, therefore we consider two cases where $S_1=0$ and $S_1=1$. When $S_1=0$ we note that the supplier always receives 0 no matter what it exerts in the second period as it has no chance of reaching the target of 2 and its payoff-to-go from exerting low is $\pi_2(0,L)=0$. When $S_1=1$ the supplier exerts high effort if its payoff-to-go from exerting high effort $\pi_2(1,H)$ is higher than exerting low $\pi_2(1,L)$, i.e., $\pi_2(1,H)=pR+(1-p)0-C \geq qR+(1-q)0=\pi_2(1,L)$. Therefore, the supplier exerts high if $\Delta \geq \frac{1}{p-q}$ and low otherwise.

Rolling back to the first period, we consider two cases where $\Delta \geq \frac{1}{p-q}$ and $\Delta \leq \frac{1}{p-q}$. When $\Delta \geq \frac{1}{p-q}$, the supplier exerts high effort if its payoff-to-go from exerting high effort $\pi_1(0,H)$ is higher than exerting low $\pi_1(0,L)$, i.e., $\pi_1(0,H)=p\pi_2(1,H)+(1-p)\pi_2(0,L)-C \geq$

$q\pi_2(1,H) + (1-q)\pi_2(0,L) = \pi_1(0,L)$. Note that $\pi_2(1,H) = pR + (1-p)0 - c$ and $\pi_2(0,L) = 0$. Therefore, the supplier exerts high if $\Delta \geq \frac{1+p-q}{(p-q)p}$ and low otherwise.

When $\Delta \leq \frac{1}{p-q}$ the supplier exerts high effort if its payoff-to-go from exerting high effort $\pi_1(0,H)$ is higher than exerting low $\pi_1(0,L)$, i.e., $\pi_1(0,H) = p\pi_2(1,L) + (1-p)\pi_2(0,L) - C \geq q\pi_2(1,L) + (1-q)\pi_2(0,L) = \pi_1(0,L)$. Note that $\pi_2(1,L) = qR + (1-q)0$ and $\pi_2(0,L) = 0$. Therefore, the supplier exerts high if $\frac{1}{(p-q)q} \leq \Delta$ and low otherwise. As in this case $\Delta \leq \frac{1}{p-q} \leq \frac{1}{(p-q)q}$ the supplier best response is to exert low effort.

To summarize, we have that supplier best response is to exert A_2 when $\Delta \leq \frac{1}{p-q}$, exert A_4 when $\frac{1}{p-q} \leq \Delta \leq \frac{1+p-q}{(p-q)p}$ and exert A_3 when $\frac{1+p-q}{(p-q)p} \leq \Delta$. □

A.11. Proof of Proposition 3.1

In proof of this proposition we use results from Lemma 3.1 and we consider 4 cases where $\mathit{\Delta} \leq \frac{1}{p-q}$, $\frac{1}{p-q} < \mathit{\Delta} \leq \min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\}$, $\min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} < \mathit{\Delta} \leq \max\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\}$ and $\max\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} < \mathit{\Delta}$.

Case 1. When $\mathit{\Delta} \leq \frac{1}{p-q}$ based on Lemma 3.1, for any target $T \in \{0,1,2\}$ the supplier optimal action is to exert A_2 that leads to 0 high effort proportion. Therefore, when $\mathit{\Delta} \leq \frac{1}{p-q}$ the optimal target is $T^* \in \{0,1,2\}$ that leads to $\bar{e}^*(A_2) = 0$.

Case 2. When $\frac{1}{p-q} < \mathit{\Delta} \leq \min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\}$ based on Lemma 3.1 supplier best response is A_2 that leads to $\bar{e}(A_2) = 0$ when $T = 0$, A_6 that leads to $\bar{e}(A_6) = \frac{1-q}{2}$ when $T = 1$ and

A_4 that leads to $\bar{e}(A_4) = \frac{q}{2}$ when $T = 2$. Therefore, the manufacturer can maximize supplier high effort proportion by setting the target at $T^* = 2$ when $q \geq \frac{1}{2}$ and $T^* = 1$ otherwise. This result follows from the fact that $\bar{e}(A_4) = \frac{q}{2} \geq \frac{1-q}{2} = \bar{e}(A_6)$ when $q \geq \frac{1}{2}$.

Case 3. When $\min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} < \Delta \leq \max\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\}$. First, note that $\min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} = \frac{1+p-q}{(p-q)p}$ when $p + q \geq 1$.

When $p + q \geq 1$ and therefore $\min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} = \frac{1+p-q}{(p-q)p}$ based on Lemma 3.1 supplier's best response is A_2 that leads to $\bar{e}(A_2) = 0$ when $T = 0$, A_6 that leads to $\bar{e}(A_6) = \frac{1-q}{2}$ when $T = 1$ and A_3 that leads to $\bar{e}(A_3) = \frac{1+p}{2}$ when $T = 2$, and therefore the optimal target to set is $T^* = 2$ that leads to $\bar{e}(A_3) = \frac{1+p}{2}$ as $\bar{e}(A_3) = \frac{1+p}{2} \geq \frac{1-q}{2} = \bar{e}(A_6)$.

When $p + q < 1$ and therefore $\min\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} = \frac{1-p+q}{(p-q)(1-p)}$ based on Lemma 3.1 supplier's best response is A_2 that leads to $\bar{e}(A_2) = 0$ when $T = 0$, A_5 that leads to $\bar{e}(A_5) = \frac{2-p}{2}$ when $T = 1$ and A_4 that leads to $\bar{e}(A_4) = \frac{q}{2}$ when $T = 2$, and therefore the optimal target to set is $T^* = 1$ that leads to $\bar{e}(A_5) = \frac{2-p}{2}$ as $\bar{e}(A_5) = \frac{2-p}{2} \geq \frac{q}{2} = \bar{e}(A_4)$. The last inequality follows the fact that $p + q \leq 2$ as $p, q \leq 1$.

Case 4. When $\max\left\{\frac{1+p-q}{(p-q)p}, \frac{1-p+q}{(p-q)(1-p)}\right\} < \Delta$ based on Lemma 3.1 supplier's best response is A_2 that leads to $\bar{e}(A_2) = 0$ when $T = 0$, A_5 that leads to $\bar{e}(A_5) = \frac{2-p}{2}$ when $T = 1$ and A_3 that leads to $\bar{e}(A_3) = \frac{1+p}{2}$ when $T = 2$. Therefore, the manufacturer can maximize high effort proportion by setting the target at $T^* = 2$ when $p \geq \frac{1}{2}$ and $T^* = 1$ otherwise. This result follows from the fact that $\bar{e}(A_3) = \frac{1+p}{2} \geq \frac{2-p}{2} = \bar{e}(A_5)$ when $q \geq \frac{1}{2}$. □

A.12. Proof of Corollary 3.1.

The proof trivially follows from Proposition 4.1. □

A.13. Proof of Lemma 3.2

First, we derive the symmetric equilibria. Next, we prove that there does not exist any asymmetric equilibria and finally we derive mixed strategy Nash equilibria.

Symmetric Equilibria: Using backward induction, we start from second. After deriving supplier best response in the second period, we roll back to the first period. Given the other player's action at $e_{-i,1}(0), e_{-i,2}(0), e_{-i,2}(1)$ we will find player $i's$ best response at period n when its score is $S_{i,n-1}$ denoted as $b_{i,n}(S_{i,n-1})$. We denote $P_0 = \text{Prob}\big(S_{-i,2} = 0 \big| e_{-i,1}\big(S_{-i,0} = 0\big) = x_1, e_{-i,2}\big(S_{-i,1} = 0\big) = x_2, e_{-i,2}\big(S_{-i,1} = 1\big) = x_3\big)$, $P_1 = \text{Prob}\big(S_{-i,2} = 1 \big| e_{-i,1}\big(S_{-i,0} = 0\big) = x_1, e_{-i,2}\big(S_{-i,1} = 0\big) = x_2, e_{-i,2}\big(S_{-i,1} = 1\big) = x_3\big)$ and $P_2 = \text{Prob}\big(S_{-i,2} = 2 \big| e_{-i,1}\big(S_{-i,0} = 0\big) = x_1, e_{-i,2}\big(S_{-i,1} = 0\big) = x_2, e_{-i,2}\big(S_{-i,1} = 1\big) = x_3\big)$ as the probability that the other supplier final score is 0,1 and 2 respectively.

Second period: Supplier i exerts high effort when its score is $S_{i,1}$ =0 if its payoff from exerting high effort $\pi_{i,2}(0,H) = P_0\left(pR_1 + (1-p)\frac{(R_1+R_2)}{2}\right) + P_1\left(p\frac{R_1+R_2}{2} + (1-p)R_2\right) + P_2(R_2) - C$ is more than its pay off from exerting low effort $\pi_{i,2}(0,L) = P_0\Big(qR_1 +$

$(1-q)\frac{(R_1+R_2)}{2}\Big) + P_1\left(q\frac{R_1+R_2}{2} + (1-q)R_2\right) + P_2(R_2)$. Therefore, $b_{i,2}(0) = H$ when $\widetilde{\Delta} \geq \frac{1}{(p-q)(1-P_2)}$ and $b_{i,2}(0) = L$ otherwise.

Supplier i exerts high effort when its score is $S_{i,1}$ =1 if its payoff from exerting high effort $\pi_{i,2}(1,H) = P_0(R_1) + P_1\left(pR_1 + (1-p)\frac{R_1+R_2}{2}\right) + P_2\left(p\frac{R_1+R_2}{2} + (1-p)R_2\right) - C$ is more than its payoff from exerting low effort $\pi_{i,2}(1,L) = P_0(R_1) + P_1\left(qR_1 + (1-q)\frac{R_1+R_2}{2}\right) + P_2\left(q\frac{R_1+R_2}{2} + (1-q)R_2\right)$. Therefore, $b_{i,2}(0) = H$ when $\widetilde{\Delta} \geq \frac{1}{(p-q)(1-P_0)}$ and $b_{i,2}(0) = L$ otherwise.

First period: Here we consider four cases: $\widetilde{\Delta} \leq \min\{\frac{1}{(p-q)(1-P_2)}, \frac{1}{(p-q)(1-P_0)}\}$, $\frac{1}{(p-q)(1-P_0)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-P_2)}$, $\frac{1}{(p-q)(1-P_2)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-P_0)}$ and $\max\{\frac{1}{(p-q)(1-P_2)}, \frac{1}{(p-q)(1-P_0)}\} \leq \widetilde{\Delta}$.

Case 1. When $\widetilde{\Delta} \leq \min\left\{\frac{1}{(p-q)(1-P_2)}, \frac{1}{(p-q)(1-P_0)}\right\}$ supplier i exerts high effort when its score is $S_{i,0}$ =0 if its payoff from exerting high effort $\pi_{i,1}(0,H) = p\pi_{i,2}(1) + (1-p)\pi_{i,2}(0) - C = p\left(P_0(R_1) + P_1\left(qR_1 + (1-q)\frac{R_1+R_2}{2}\right) + P_2\left(q\frac{R_1+R_2}{2} + (1-q)R_2\right)\right) + (1-p)\Big(P_0\Big(qR_1 + (1-q)\frac{(R_1+R_2)}{2}\Big) + P_1\left(q\frac{R_1+R_2}{2} + (1-q)R_2\right) + P_2(R_2)\Big) - C$ is more than its pay off from exerting low effort $\pi_{i,1}(0,L) = q\pi_{i,2}(1) + (1-q)\pi_{i,2}(0) = q\Big(P_0(R_1) + P_1\Big(qR_1 + (1-q)\frac{R_1+R_2}{2}\Big) + P_2\left(q\frac{R_1+R_2}{2} + (1-q)R_2\right)\Big) + (1-q)\Big(P_0\left(qR_1 + (1-q)\frac{(R_1+R_2)}{2}\right) + P_1\Big(q\frac{R_1+R_2}{2} + (1-q)R_2\Big) + P_2(R_2)\Big)$. Therefore, $b_{i,1}(0) = H$ when $\widetilde{\Delta} \geq \frac{1}{(p-q)(1-qP_0-(1-q)P_2)}$ and $b_{i,1}(0) = L$ otherwise. Next, we show that $b_{i,1}(0) = H$ is not possible as $\widetilde{\Delta} \geq \frac{1}{(p-q)(1-qP_0-(1-q)P_2)}$ is not possible in the case that $\widetilde{\Delta} \leq \min\left\{\frac{1}{(p-q)(1-P_2)}, \frac{1}{(p-q)(1-P_0)}\right\}$. It follows from $\widetilde{\Delta} \leq \min\left\{\frac{1}{(p-q)(1-P_2)}, \frac{1}{(p-q)(1-P_0)}\right\}$ that $1 - \frac{1}{(p-q)\Delta} \leq P_2$ and $1 - \frac{1}{(p-q)\Delta} \leq P_0$ and therefore $(1 - q)\left(1 - \frac{1}{(p-q)\Delta}\right) + q\left(1 - \frac{1}{(p-q)\Delta}\right) = 1 - \frac{1}{(p-q)\Delta} \leq (1-q)P_2 + qP_0$. With simplification of the last inequality we derive that $\widetilde{\Delta} \leq \frac{1}{(p-q)(1-qP_0-(1-q)P_2)}$ and therefore $b_{i,1}(0) = L$.

Similarly, we can trivially derive supplier i's best response in the other three cases. The proof is omitted for space and here we only provide the result.

Case 2. When $\frac{1}{(p-q)(1-P_0)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-P_2)}$ supplier best response is $b_{i,1}(0) = H$ when $\widetilde{\Delta} \geq \frac{1}{(p-q)\left(1-\frac{p}{1+p-q}P_0-\frac{1-q}{1+p-q}P_2\right)}$ $b_{i,1}(0) = L$ otherwise.

Case 3. When $\frac{1}{(p-q)(1-P_2)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-P_0)}$ supplier best response is $b_{i,1}(0) = H$ when $\widetilde{\Delta} \geq \frac{1}{(p-q)\left(1-\frac{q}{1-p+q}P_0-\frac{1-p}{1-p+q}P_2\right)}$ $b_{i,1}(0) = L$ otherwise.

Case 4. When $\max\{\frac{1}{(p-q)(1-P_2)}, \frac{1}{(p-q)(1-P_0)}\} \leq \widetilde{\Delta}$ supplier best response is $b_{i,1}(0) = H$.

Next, we will derive the symmetric equilibria using the suppliers' best response. We have 6 symmetric equilibria. We denote symmetric equilibria A_iA_i as both contractors exert A_i.

$\boldsymbol{A_1A_1}$: Taking action A_1 the probability of ending at score 2 and 0 are $P_2 = p^2$ and $P_0 = (1-p)^2$ respectively, and based on the best response this action is an equilibrium if $\max\{\frac{1}{(p-q)(1-p^2)}, \frac{1}{(p-q)(1-(1-p)^2)}\} \leq \widetilde{\Delta}$.

$\boldsymbol{A_2A_2}$: Taking action A_2 the probability of ending at score 2 and 0 are $P_2 = q^2$ and $P_0 = (1-q)^2$ respectively, and based on the best response this action is an equilibrium if $\widetilde{\Delta} \leq \min\left\{\frac{1}{(p-q)(1-q^2)}, \frac{1}{(p-q)(1-(1-q)^2)}\right\}$.

$\boldsymbol{A_3A_3}$: Taking action A_3 the probability of ending at score 2 and 0 are $P_2 = p^2$ and $P_0 = (1-p)(1-q)$, and based on the best response this action is an equilibrium if $\frac{1}{(p-q)(1-(1-p)(1-q))} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ and when $\widetilde{\Delta} \geq \frac{1}{(p-q)\left(1-\frac{p}{1+p-q}(1-p)(1-q)-\frac{1-q}{1+p-q}p^2\right)} = \frac{1+\mathrm{p}-\mathrm{q}}{(\mathrm{p}-\mathrm{q})(1+\mathrm{qp}-\mathrm{q})}$. Note that these conditions are only satisfied (The set is not empty) when $p^2 \geq (1-p)(1-q)$ which we denote as E_1.

$\boldsymbol{A_4A_4}$: Taking action A_4 the probability of ending at score 2 and 0 are $P_2 = qp$ and $P_0 = (1-q)^2$ respectively, and based on the best response this action is an equilibrium if $\frac{1}{(p-q)(1-(1-q)^2)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-qp)}$ and when $\widetilde{\Delta} \leq \frac{1}{(p-q)\left(1-\frac{p}{1+p-q}(1-q)^2-\frac{1-q}{1+p-q}qp\right)} = \frac{1+\mathrm{p}-\mathrm{q}}{(\mathrm{p}-\mathrm{q})(1+\mathrm{qp}-\mathrm{q})}$. Note that these conditions are only satisfied (The set is not empty) when $(1-q)^2 \leq qp$ which we denote as E_2.

$\boldsymbol{A_5A_5}$: Taking action A_5 the probability of ending at score 2 and 0 are $P_2 = qp$ and $P_0 = (1-p)^2$ respectively, and based on the best response this action is an equilibrium if $\frac{1}{(p-q)(1-qp)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-(1-p)^2)}$ and when $\widetilde{\Delta} \geq \frac{1}{(p-q)\left(1-\frac{q}{1-p+q}(1-p)^2-\frac{1-p}{1-p+q}qp\right)} = \frac{1-\mathrm{p}+\mathrm{q}}{(\mathrm{p}-\mathrm{q})(1+\mathrm{qp}-\mathrm{p})}$. Note that these conditions are only satisfied (The set is not empty) when $(1-p)^2 \geq qp$ which we denote as E_3.

$\boldsymbol{A_6A_6}$: Taking action A_5 the probability of ending at score 2 and 0 are $P_2 = q^2$ and $P_0 = (1-q)(1-p)$ respectively, and based on the best response this action is an equilibrium if $\frac{1}{(p-q)(1-q^2)} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)\left(1-(1-q)(1-p)\right)}$ and when $\widetilde{\Delta} \geq \frac{1}{(p-q)\left(1-\frac{q}{1-p+q}(1-q)(1-p)-\frac{1-p}{1-p+q}q^2\right)} = \frac{1-p+q}{(p-q)(1+qp-p)}$. Note that these conditions are only satisfied (The set is not empty) when $q^2 \leq (1-p)(1-q)$ which we denote as E_4.

Next, we show that there does not exist any asymmetric equilibria.

Asymmetric Equilibria: We show an equilibrium such that a supplier acts A_i and the other supplier takes a different action A_j (i.e., $i \neq j$), namely, A_iA_j, cannot be an equilibrium. Consider an asymmetric strategy of A_1A_2. For A_1 to be the best response to A_2 we should have $\max\{\frac{1}{(p-q)(1-q^2)}, \frac{1}{(p-q)(1-(1-q)^2)}\} \leq \widetilde{\Delta}$ and for A_2 to be the best response to A_1 we should have $\widetilde{\Delta} \leq \min\{\frac{1}{(p-q)(1-p^2)}, \frac{1}{(p-q)(1-(1-p)^2)}\}$, but $\min\left\{\frac{1}{(p-q)(1-p^2)}, \frac{1}{(p-q)(1-(1-p)^2)}\right\} \leq \max\{\frac{1}{(p-q)(1-q^2)}, \frac{1}{(p-q)(1-(1-q)^2)}\}$ and therefore there does not exist any $\widetilde{\Delta}$ that leads to the asymmetric equilibrium of A_1A_2. The last inequality follows from the assumption that $q \leq p$ and therefore $\frac{1}{(p-q)(1-(1-p)^2)} \leq \frac{1}{(p-q)(1-(1-q)^2)}$. The other cases are similar but simpler and are omitted for space.

Mixed Strategy Nash Equilibrium: We denote $\mu_{-i,n}\left(S_{-i,n-1}\right)$ as the probability that supplier $-i$ exerts high effort at period n when its cumulative score is $S_{-i,n-1}$. Using backward induction, we will find $\mu_{-i,n}\left(S_{-i,n-1}\right)$ that makes supplier i indifferent between exerting high or low effort at any state. Recall that P_0, P_1 and P_2 are the probability that the other supplier final score is 0, 1 and 2 and therefore $P_0 = \mu_{-i,1}(0)(1-p)\left[\mu_{-i,2}(0)(1-p) + \left(1-\mu_{-i,2}(0)\right)(1-q)\right] + \Big(1-$

$\mu_{-i,1}(0)\Big)(1-q)\left[\mu_{-i,2}(0)(1-p)+\left(1-\mu_{-i,2}(0)\right)(1-q)\right]$, $\quad P_2=\mu_{-i,1}(0)p\left[\mu_{-i,2}(1)p+\left(1-\mu_{-i,2}(1)\right)q\right]+\left(1-\mu_{-i,1}(0)\right)q\left[\mu_{-i,2}(1)p+\left(1-\mu_{-i,2}(1)\right)q\right]$ and $P_1=1-(P_0+P_2)$.

Period 2: When supplier score is $S_{i,1}=0$ supplier i is indifferent between exerting high or low effort if its payoff from exerting low effort $\pi_{i,2}(0,L)=P_0\left(qR_1+(1-q)\frac{(R_1+R_2)}{2}\right)+P_1\left(q\frac{R_1+R_2}{2}+(1-q)R_2\right)+P_2(R_2)$ and its payoff from exerting high effort, $\pi_{i,2}(0,H)=P_0\left(pR_1+(1-p)\frac{(R_1+R_2)}{2}\right)+P_1\left(p\frac{R_1+R_2}{2}+(1-p)R_2\right)+P_2(R_2)-C$ are equal. It follows from $\pi_{i,2}(0,L)=\pi_{i,2}(0,H)$ that $p_2=1-\left(\frac{2C}{(R_1-R_2)(p-q)}\right)$.

When supplier score is $S_{i,1}=1$ supplier i is indifferent between exerting high or low effort if its payoff from exerting low effort $\pi_{i,2}(1,L)=P_0(R_1)+P_1\left(qR_1+(1-q)\frac{R_1+R_2}{2}\right)+P_2\left(q\frac{R_1+R_2}{2}+(1-q)R_2\right)$ and its payoff from exerting high effort is $\pi_{i,2}(1,H)=P_0(R_1)+P_1\left(pR_1+(1-p)\frac{R_1+R_2}{2}\right)+P_2\left(p\frac{R_1+R_2}{2}+(1-p)R_2\right)-C$ are equal. It follows from $\pi_{i,2}(1,L)=\pi_{i,2}(1,H)$ that $p_0=1-\left(\frac{2c}{(R_1-R_2)(p-q)}\right)$.

Period 1: Supplier i is indifferent between exerting high or low effort if its payoff from exerting low effort $\pi_{i,1}(0,L)=q\pi_{i,2}(1)+(1-q)\pi_{i,2}(0)=q\Big(P_0(R_1)+P_1\Big(pR_1+(1-p)\frac{R_1+R_2}{2}\Big)+P_2\left(p\frac{R_1+R_2}{2}+(1-p)R_2\right)-C\Big)+(1-q)\Big(P_0\left(pR_1+(1-p)\frac{(R_1+R_2)}{2}\right)+P_1\left(p\frac{R_1+R_2}{2}+(1-p)R_2\right)+P_2(R_2)-C\Big)$ and its payoff from exerting high effort $\pi_{i,1}(0,H)=p\pi_{i,2}(1)+(1-p)\pi_{i,2}(0)-C=p\Big(P_0(R_1)+P_1\left(pR_1+(1-p)\frac{R_1+R_2}{2}\right)+P_2\Big(p\frac{R_1+R_2}{2}+(1-$

$p)R_2\Big) - C\Big) + (1-p)\left(P_0\left(pR_1 + (1-p)\frac{(R_1+R_2)}{2}\right) + P_1\left(p\frac{R_1+R_2}{2} + (1-p)R_2\right) + P_2(R_2) - \right.$

$\left.C\right) - C$ are equal. It follows from $\pi_{i,1}(0,L) = \pi_{i,2}(0,H)$ that $P_1 = 1 - 2\left(1 - \left(\frac{2C}{(R_1 - R_2)(p-q)}\right)\right)$.

Next, we will find $\mu_{-i,n}(S_{-i,n-1})$ that makes supplier i indifferent between exerting high or low effort at any state. It follows from $P_0 = \mu_{-i,1}(0)(1-p)\left[\mu_{-i,2}(0)(1-p) + \left(1 - \mu_{-i,2}(0)\right)(1-q)\right] + \left(1-\mu_{-i,1}(0)\right)(1-q)\left[\mu_{-i,2}(0)(1-p) + \left(1-\mu_{-i,2}(0)\right)(1-q)\right]$ and $p_0 = 1 - \left(\frac{2c}{(R_1 - R_2)(p-q)}\right)$ that $\mu_{-i,2}(0) = \frac{1-q}{p-q} - \frac{1-\left(\frac{2C}{(R_1 - R_2)(p-q)}\right)}{(p-q)\left(\mu_{-i,1}(0)(1-p)+\left(1-\mu_{-i,1}(0)\right)(1-q)\right)}$. It follows from $P_2 = 1 - \left(\frac{2C}{(R_1 - R_2)(p-q)}\right)$ and $P_2 = \mu_{-i,1}(0)p\left[\mu_{-i,2}(1)p + \left(1-\mu_{-i,2}(1)\right)q\right] + \left(1 - \mu_{-i,1}(0)\right)q\left[\mu_{-i,2}(1)p + \left(1-\mu_{-i,2}(1)\right)q\right]$ that we have $\mu_{-i,2}(1) = \frac{1-\left(\frac{2C}{(R_1 - R_2)(p-q)}\right)}{(p-q)\left(\mu_{-i,1}(0)p+\left(1-\mu_{-i,1}(0)\right)q\right)} - \frac{q}{p-q}$.

Next, we find the high effort proportion when there is a mixed strategy. The high effort proportion is $\bar{e} = \frac{1}{2}\left(\mu_{-i,1}(0) + \mu_{-i,2}(0)\left[\mu_{-i,1}(0)(1-p) + \left(1-\mu_{-i,1}(0)\right)(1-q)\right] + \mu_{-i,2}(1)\left[\mu_{-i,1}(0)p + \left(1-\mu_{-i,1}(0)\right)q\right]\right) = \frac{1-2q}{2(p-q)}$.

Next, we organize the equilibrium effort decisions on the relative reward axis $\widetilde{\Delta}$. Based on the conditions on the symmetric equilibria we will have seven cases:

Case 1. When $\frac{1}{2} \leq q$ and E_2 holds then we test the possibility of all equilibria. A_1A_1 is an equilibrium when $\max\left\{\frac{1}{(p-q)(1-p^2)}, \frac{1}{(p-q)(1-(1-p)^2)}\right\} = \frac{1}{(p-q)(1-p^2)} \leq \widetilde{\Delta}$. Note that the equality follows from the case that $p \geq \frac{1}{2}$ as $q \geq \frac{1}{2}$ in case 1. A_2A_2 is an equilibrium when $\widetilde{\Delta} \leq$

$\min\left\{\frac{1}{(p-q)(1-q^2)}, \frac{1}{(p-q)(1-(1-q)^2)}\right\} = \frac{1}{(p-q)(1-(1-q)^2)}$. Note that the equality follows from the case that $q \geq \frac{1}{2}$. A_3A_3 is an equilibrium when $\max\left\{\frac{1}{(p-q)\left(1-(1-p)(1-q)\right)}, \frac{1+p-q}{(p-q)(1+qp-q\,)}\right\} = \frac{1+p-q}{(p-q)(1+qp-q\,)} \leq \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$, and E_1 holds. Note that the left equality follows from $\frac{1}{(p-q)\left(1-(1-p)(1-q)\right)} \leq \frac{1+p-q}{(p-q)(1+qp-q\,)}$ and to show this inequality holds note that the LHS nominator is smaller than the RHS nominator (i.e., $1 \leq 1+p-q$ as $q < p$) and the RHS dominator is smaller than the LHS dominator (i.e., $(p-q)(1+\mathrm{qp}-\mathrm{q}) \leq (\mathrm{p}-\mathrm{q})\big(1-(1-p)(1-q)\big)$ as $\frac{1}{2} \leq q$). It also follows from E_2: $(1-q)^2 \leq qp$ that E_1: $(1-p)(1-q) \leq p^2$ holds. A_4A_4 is an equilibrium when $\frac{1}{(p-q)(1-(1-q)^2)} \leq \widetilde{\Delta} \leq \min\left\{\frac{1}{(p-q)(1-qp)}, \frac{1+p-q}{(p-q)(1+qp-q\,)}\right\} = \frac{1+p-q}{(p-q)(1+qp-q\,)}$ and E_2 holds. Note that the right equality follows from $\frac{1+\mathrm{p}-\mathrm{q}}{(\mathrm{p}-\mathrm{q})(1+\mathrm{qp}-\mathrm{q}\,)} \leq \frac{1}{(p-q)(1-qp)}$ and by simplifying this inequality we derive $(1-q)^2 \leq qp$ which holds in this case (Recall that E_2: $(1-q)^2 \leq qp$). A_5A_5 is an equilibrium when $\max\left\{\frac{1-p+q}{(p-q)(1+qp-p\,)}, \frac{1}{(p-q)(1-qp)}\right\} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)(1-(1-p)^2)}$ and E_3 holds, but It follows from E_2: $(1-q)^2 \leq qp$ that E_3: $(1-p)^2 \geq qp$ does not hold and therefore A_5A_5 is not possible in this case. A_6A_6 is an equilibrium when $\max\left\{\frac{1}{(p-q)(1-q^2)}, \frac{1-p+q}{(p-q)(1+qp-p\,)}\right\} \leq \widetilde{\Delta} \leq \frac{1}{(p-q)\left(1-(1-q)(1-p)\right)}$ and E_4 holds, but we have $(1-p)(1-q) \leq (1-q)^2 \leq q^2$ (the left inequality follows from $q \leq p$ and the right inequality follows from $\frac{1}{2} \leq q$) and therefore E_4: $(1-p)(1-q) \geq q^2$ does not hold. As E_4 does not hold, A_6A_6 is not an equilibrium in this case. Next, we organize these equilibria on the relative reward axis $\widetilde{\Delta}$.

The equilibrium actions are A_2A_2, A_4A_4, A_3A_3 and A_1A_1 when $\tilde{\Delta} \leq \frac{1}{(p-q)(1-(1-q)^2)}$, $\frac{1}{(p-q)(1-(1-q)^2)} < \tilde{\Delta} \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \tilde{\Delta} \leq \frac{1}{(p-q)(1-p^2)}$ and $\frac{1}{(p-q)(1-p^2)} < \tilde{\Delta}$ respectively. The other cases are similar but simpler and are omitted for space. □

A.14. Proof of Proposition 3.2

In Lemma 3.2, we derive the suppliers' best responses to the announced reward scheme by the manufacturer. We observe that the high effort proportion increases in the relative reward $\tilde{\Delta} = \frac{R_1-R_2}{2c}$ and therefore in the gap between R_1 and R_2. Given the manufacturer's limited budget i.e., $R_1 + R_2 \leq 2R$, manufacturer can maximize suppliers' high effort proportion by assigning all the reward to the supplier with the highest final score i.e., $R_1 = 2R$ and $R_2 = 0$. □

A.15. Proof of Proposition 3.3

We compare the equilibrium high effort proportion under the Absolute approach with Relative approach. Consider the case that $q \geq \frac{1}{2}$ and E_2 holds. Under the absolute approach, the equilibrium high effort proportions are 0, $\frac{q}{2}$ and $\frac{1+p}{2}$ when $\Delta \leq \frac{1}{p-q}$, $\frac{1}{p-q} < \Delta \leq \frac{1+p-q}{(p-q)p}$ and $\frac{1+p-q}{(p-q)p} < \Delta$ respectively. Under the Relative approach, the equilibrium high effort proportions are 0, $\frac{q}{2}$, $\frac{1+p}{2}$ and 1 when $\Delta \leq \frac{1}{(p-q)(1-(1-q)^2)}$, $\frac{1}{(p-q)(1-(1-q)^2)} < \Delta \leq \frac{1+p-q}{(p-q)(1+qp-q)}$, $\frac{1+p-q}{(p-q)(1+qp-q)} < \Delta \leq \frac{1}{(p-q)(1-p^2)}$ and $\frac{1}{(p-q)(1-p^2)} < \Delta$ respectively. Organizing these equilibrium high effort proportions on the relative reward axis, we derive that the Absolute approach leads to a higher high effort proportion when $\Delta \leq \frac{1}{(p-q)(1-(1-q)^2)}$ and otherwise Relative approach leads to a higher high effort proportion. Note that the result follows from $\frac{1}{p-q} \leq \frac{1}{(p-q)(1-(1-q)^2)}$ and $\frac{1+p-q}{(p-q)p} \leq \frac{1+p-q}{(p-q)(1+qp-q\ )}$.

The other cases are similar but simpler and are omitted for space. □

APPENDIX B

EXPERIMENTAL INSTRUCTIONS

B.1. Instruction for Information Feedback Treatment with Two Contractors (I_2^1)[3]

You are about to participate in an experimental study of decision-making. If you follow these instructions carefully and make good decisions, you will earn money that will be paid to you in cash at the end of the session. If you have a question at any time, please raise your hand and the experimenter will come to your station and answer it. We ask that you not talk with one another for the duration of the experiment.

The monetary unit in this experiment is called Experimental Currency Unit (ECU). You will accumulate your earnings throughout periods. Your objective is to earn as much as you can. After the experiment, your earnings in terms of ECU will be converted to US dollars at the rate of 100 [50] ECU for $1 and paid to you in private and in cash, in addition to a $5 show up fee.

How to earn money

The session consists of 20 periods. In each period you will be matched with a different person in the room. Both of you will work on a project which requires each of you to work on two tasks. At the beginning of each period, you and the other player will simultaneously decide how much effort to exert on the first task. You will then observe each other's effort level in the first task, and will simultaneously decide how much effort to exert on the second task. [You will then

[3] Underlined sentences are unique to the information feedback treatment (I_2^1 and I_4^5) instruction and should be deleted or replaced with the sentences in the square brackets for the no information feedback treatment instruction. The instructions are available upon request for treatments I_2^0 (I_4^0), I_4^1 and I_2^5.

simultaneously decide how much effort to exert on the second task without observing each other's effort level in the first task. Note that you only observe your own effort on the first task, and your effort is only revealed to the other player after the end of the second task.] Your effort level in each task may be any number from 55 to 115 (up to two decimal places) and costs you 0.75 ECU per unit. Your *total* effort is the sum of your efforts in the two tasks.

The *project progress* is defined as the smaller one of the two *total* efforts chosen by you and the other player. The revenue you and the other player earn from the project depends on the minimum of the *project progress* and 170. So the earnings are determined as follows:

Your Earnings = (minimum of *project progress* and 170) – 0.75 × your *total* effort

Your safety level on the second task, which is the effort level guaranteed to contribute to the project progress, is determined as follows. On one hand, if your effort on the first task is lower than the other player's, your safety level is the difference between the two efforts in the first tasks plus the minimum required effort (55). On the other hand, if your effort on the first task is higher than the other player's, your safety level is the minimum required effort (55). If your effort on the second task was below your safety level, you could have increased the project progress and therefore your earnings by exerting a higher effort.

Example:

Suppose that your effort is X1 in the first task, and is X2 in the second task, so the total effort is X1+X2. Similarly, suppose that the other player's effort is Y1 in the first task, and is Y2 in the second task, so the total effort is Y1+Y2.

- If (X1+X2) ≥ (Y1+Y2), the project progress is (Y1+Y2).
- If (Y1+Y2) ≥ (X1+X2), the project progress is (X1+X2).
- If project progress ≤ 170, then you get project progress - 0.75× (X1+X2), and the other player gets project progress - 0.75× (Y1+Y2).
- If project progress ≥ 170, then you get 170 - 0.75× (X1+X2), and the other player gets 170 - 0.75× (Y1+Y2).

How you will be paid

At the end of the session, the computer will sum up your total earnings for all periods, convert them to US dollars, add them to your $5 show up fee, and display your total earnings for the session. Please use this information to fill out the checkout form and wait quietly until the monitor calls you to come to the front of the room to be paid your earnings in private and in cash. After you have been paid, you will be free to leave the laboratory.

B.2. Instruction for Information Feedback Treatment with Four Contractors (I_4^5)

You are about to participate in an experimental study of decision-making. If you follow these instructions carefully and make good decisions, you will earn money that will be paid to you in cash at the end of the session. If you have a question at any time, please raise your hand and the experimenter will come to your station and answer it. We ask that you not talk with one another for the duration of the experiment.

The monetary unit in this experiment is called Experimental Currency Unit (ECU). You will accumulate your earnings throughout rounds. Your objective is to earn as much as you can. After the experiment, your earnings in terms of ECU will be converted to US dollars at the rate of 50 ECU for $1 and paid to you in private and in cash, in addition to a $5 show up fee.

How to earn money

The session consists of 20 rounds. In each round you will be matched with three different people in the room. All of you will work on a project which requires each of you to work on six tasks. At the beginning of each round, you and the other players will simultaneously decide how much effort to exert on the first task. <u>You will then observe each other’s effort level in the first task and will simultaneously decide how much effort to exert on the second task. Similarly, you will first observe the efforts on the second task before making your decision on the third task, and so on for all six tasks.</u> [You will then simultaneously decide how much effort to exert on the second task without observing each other’s effort level in the first task. Similarly, without observing each other’s effort level in the second task, you will make your decision on the third task, and so on for all six tasks. Note that you only observe your own effort on the pervious tasks, and your effort is only revealed to others after the end of the sixth task.] Your effort level in each task may be any number from 18.33 to 38.33 (up to two decimal places) and costs you 0.75 ECU per unit. Your *total* effort is the sum of your efforts in the six tasks.

The *project progress* is defined as the smallest of the four *total* effort levels chosen by you and the other three players. The revenue you and the other players earn from the project depends on the minimum of the *project progress* and 170. So, the earnings are determined as follows:

Your Earnings = (minimum of *project progress* and 170) – 0.75 × your *total* effort

Your safety level on each task, which is the effort level guaranteed to contribute to the project progress, is determined as follows. For any task:

- If your total effort up to that task is *lower* than the lowest total effort of the other players' up to that task, your *safety level* is the difference between your total effort and the smallest total efforts of other plyers' plus the minimum required effort (18.33).
  - For example, suppose your total effort level after task 1 was 30 and it was the lowest total effort level in your group, while the next lowest effort level was 35. In this case your safety level is 18.33 + (35-30) = 23.33.
- If your total effort up to that task is *higher* than the smallest total effort of the other players' up to that task, your *safety level* is the minimum required effort (18.33).
  - For example, suppose your total effort level after task 1 was 30 and yours was not the lowest in the group, and the lowest level was 20. In this case your safety level is 18.33

So you can see that if your effort at any task was *below* your *safety level*, you could have increased the project progress and therefore your earnings by exerting a higher effort.

Example:

Suppose at the end of the six tasks, the total effort levels for the four players are:

- Player 1: 150
- Player 2: 171
- Player 3: 172
- Player 4: 175

Because Player 1's total effort level is the lowest, the project progress is 150, and the earnings are:

- Player 1: $150 – 0.75 \times 150 = 37.5$
- Player 2: $150 – 0.75 \times 171 = 21.75$
- Player 3: $150 – 0.75 \times 172 = 21$
- Player 4: $150 – 0.75 \times 175 = 18.75$

Now, suppose instead Player 1's total effort level was still the lowest in the group, but it was 171. In this case the project progress is 170 because $171 > 170$ and the earnings are:

- Player 1: $170 – 0.75 \times 171 = 41.75$
- Player 2: $170 – 0.75 \times 171 = 41.75$
- Player 3: $170 – 0.75 \times 172 = 41$
- Player 4: $170 – 0.75 \times 175 = 38.75$

How you will be paid

At the end of the session, the computer will sum up your total earnings for all rounds, convert them to US dollars, add them to your $5 show up fee, and display your total earnings for the session. Please use this information to fill out the checkout form and wait quietly until the monitor calls you to come to the front of the room to be paid your earnings in private and in cash. After you have been paid, you will be free to leave the laboratory.

B.3. Instructions (Absolute Approach, A_{13})

You are about to participate in an experimental study of decision-making. If you follow these instructions carefully and make good decisions, you will earn money that will be paid to you in cash at the end of the session. If you have a question at any time, please raise your hand and the experimenter will come to your station and answer it. We ask that you not talk with one another for the duration of the experiment.

The monetary unit in this experiment is called Experimental Currency Unit (ECU). You will accumulate your earnings throughout rounds. Your objective is to earn as much as you can. After the experiment, your earnings in terms of ECU will be converted to US dollars at the rate of 100 ECU for $1 and paid to you in private and in cash, in addition to a $5 show up fee.

Overview

The experiment has 20 rounds. You will be in the role of a supplier and make decisions in a sequence of rounds. The manufacturer has been computerized. In each round, you and the manufacturer start a new contract to produce and deliver some product. Each contract lasts for 2 periods. In each period, you produce and deliver one batch. The manufacturer checks the product quality upon receiving your delivery and may or may not find the quality acceptable. Your management effort can affect product quality. In each period you have a choice between HIGH or LOW effort. LOW effort costs you 0 ECU and HIGH effort costs you 10 ECU. If you choose HIGH effort, there is a 70% chance that the manufacturer will find the batch acceptable and there is a 30% chance that the manufacturer will find it unacceptable; if you choose LOW effort, there is a 30% chance that the manufacturer will find the batch acceptable and 70% chance that the manufacturer will find it unacceptable.

How to earn money

The manufacturer tracks your delivered quality with a score. Your score is set to zero at the beginning of each round. In each of the 2 following periods, if the manufacturer finds the supplier quality acceptable, your score increases by 1; otherwise, your score remains unchanged. At the end of each round, the manufacturer reviews your final score and pays you a bonus of 13 ECU if your final score is higher than or equal to a target score of 1.

Procedure

At the beginning of each round, you will start with a balance of 30 ECU. In each period, your balance reduces by 10 ECU if you choose HIGH effort, and your balance remains unchanged if you choose LOW effort.

The computer will simulate the process through which the manufacturer checks the quality for each batch, and it informs you whether the manufacturer finds it acceptable or not. Your score increases by 1 for each acceptable batch. At the end of each round, if you receive the bonus, it will be added to your total balance of that round.

How you will be paid

At the end of the session, the computer will sum up your total earnings for all rounds, convert them to US dollars, add them to your $5 show up fee, and display your total earnings for the session. Please use this information to fill out the checkout form and wait quietly until the monitor calls you to come to the front of the room to be paid your earnings in private and in cash. After you have been paid, you will be free to leave the laboratory.

B.4. Instruction[4] (Relative Approach, R_{13})

You are about to participate in an experimental study of decision-making. If you follow these instructions carefully and make good decisions, you will earn money that will be paid to you in cash at the end of the session. If you have a question at any time, please raise your hand and the experimenter will come to your station and answer it. We ask that you not talk with one another for the duration of the experiment.

The monetary unit in this experiment is called Experimental Currency Unit (ECU). You will accumulate your earnings throughout rounds. Your objective is to earn as much as you can. After the experiment, your earnings in terms of ECU will be converted to US dollars at the rate of 100 ECU for $1 and paid to you in private and in cash, in addition to a $5 show up fee.

Overview

The experiment has 20 rounds. You will be in the role of the supplier and make decisions in a sequence of rounds. In each round you will be matched with a different person in the room, also in the role of a supplier. The manufacturer has been computerized. In each round, you, the other supplier, and the manufacturer start a new contract to produce and deliver some product. Each contract lasts for 2 periods. In each period, each supplier will produce and deliver one batch. The

[4] The instructions are available upon request for treatments A_{26}, A_{45}, R_{26} and R_{45}.

manufacturer checks the product quality upon receiving your deliveries and may or may not find the quality acceptable. The manufacturer's decision on the quality of your product is independent of its decision about the other supplier product. After the inspection the manufacturer informs each supplier whether it finds its batch acceptable or not. Your management effort can affect product quality. In each period you have a choice between HIGH or LOW effort. LOW effort costs you 0 ECU and HIGH effort costs you 10 ECU. If you choose HIGH effort, there is a 70% chance that the manufacturer will find the batch acceptable and there is a 30% chance that the manufacturer will find it unacceptable; if you choose LOW effort, there is a 30% chance that the manufacturer will find the batch acceptable and 70% chance that the manufacturer will find it unacceptable.

How to earn money

The manufacturer separately tracks suppliers' delivered quality with a score. Both suppliers' score is set to zero at the beginning of each round. In each of the two periods, if the manufacturer finds the supplier quality acceptable, its score increases by 1; otherwise, its score remains unchanged. At the end of each round, the manufacturer reviews suppliers' final scores. The manufacturer pays a bonus of 26 ECU to the supplier with the higher score, and 0 ECU to the supplier with the lower score. If both suppliers reach the same score, the manufacturer pays a bonus of 13 ECU to each supplier.

Procedure

At the beginning of each round, you will start with a balance of 30 ECU. In each period, your balance reduces by 10 ECU if you choose HIGH effort, and your balance remains unchanged if you choose LOW effort.

The computer will simulate the process through which the manufacturer checks the quality for each batch, and it informs you whether the manufacturer finds it acceptable or not. At the end of each round, if you receive the bonus, it will be added to your total balance of that round.

How you will be paid

At the end of the session, the computer will sum up your total earnings for all rounds, convert them to US dollars, add them to your $5 show up fee, and display your total earnings for the session. Please use this information to fill out the checkout form and wait quietly until the monitor calls you to come to the front of the room to be paid your earnings in private and in cash. After you have been paid, you will be free to leave the laboratory.

B.5. Experiment Instructions of Chapter 4

This is an experiment to study decision-making. You will play the role of the supplier and make decisions in a sequence of rounds. The buyer has been computerized.

The monetary unit in this experiment is called Experimental Currency Unit (ECU). You will accumulate your earnings throughout rounds. Your objective is to earn as much as you can. You will receive $5 for participating in this experiment. After the experiment, your earnings in terms of ECU will be converted to US dollars at the rate of 200 ECU for $1. If you follow the instructions carefully, you could earn a considerable amount of money.

You are **NOT allowed** to communicate with the other participants during the experiment. If you have any questions, please raise your hand and the experimenter will come to you.

Overview

The experiment has **twenty** rounds. In each round, you and the buyer start a new contract to produce and deliver some product. Each contract lasts for 10 periods. In each period, you produce and deliver one batch. The buyer checks the product quality upon receiving your delivery and may or may not find the quality acceptable. Your management **effort** can affect product quality. In each period you have a choice between HIGH or LOW effort. LOW effort costs you 0 ECU and high effort costs you 4 ECU. If you choose HIGH effort, there is a 70% chance that the buyer will find the batch acceptable and there is a 30% chance that the buyer will find it unacceptable; if you choose LOW management effort in the period, there is a 30% chance that the buyer will find the batch acceptable and 70% chance that the buyer will find it inacceptable.

The buyer tracks your delivered quality with a score. Your score is set to zero at the beginning of each round. In each of the 10 following periods, if the buyer finds the products acceptable, your score increases by 1; otherwise, your score remains unchanged. At the end of each round, the buyer reviews your final score and pays you a bonus of 120 ECU if your final score is higher than or equal to a target score of 7.

Procedure

At the beginning of each round, you will start with a balance of 50 ECU. In each period, your balance reduces by 4 ECU if you choose HIGH effort, and your balance remains unchanged if you choose LOW effort.

The computer will simulate the process through which the buyer checks the quality for each batch, and it informs you whether the buyer finds it acceptable or not. Your score increases by 1 for each acceptable batch. At the end of each round, if you receive the bonus, it will be added to your total balance of that round.

How you will be paid

At the end of the session, the computer will sum up your total earnings for all rounds, convert them to US dollars, add them to your $5 show up fee, and display your total earnings for the session. Please use this information to fill out the checkout form.

APPENDIX C

ADDITIONAL EXPERIMENTAL RESULTS

Table C.1. Experiment Results (Two-Contractor Treatment)

Treatment I_2^0 (Setting 1. One-period decision making)						
	Cohorts					
	1	2	3	4	5	6
Mean	123.56	117.23	145.13	114.96	112.18	116.08
Standard Error	0.77	1.83	1.22	1.11	0.69	1.42
Min	118.45	110.0	136.5	110.0	110.0	110.0
Max	130.4	134.99	157.75	128.97	119.52	136.0
Treatment I_2^0 (Setting 2. Two-period decision making)						
	Cohorts					
	1	2	3	4	5	6
Mean	112.39	113.87	112.92	111.14	NA	NA
Standard Error	0.95	0.5	1.39	0.5	NA	NA
Min	110.0	110.01	110.0	110.0	NA	NA
Max	125.62	118.76	133.75	119.75	NA	NA
Treatment I_2^1						
	Cohorts					
	1	2	3	4	5	6
Mean	149.53	157.87	145.46	159.95	160.0	163.71
Standard Error	1.64	2.03	1.66	0.82	1.78	1.58
Min	135.6	142.95	134.0	153.0	148.2	148.5
Max	162.0	172.0	159.98	166.4	170.6	170.0
Treatment I_2^6						
	Cohorts					
	1	2	3	4	5	6
Mean	170.42	161.08	168.66	165.48	NA	NA
Standard Error	0.28	1.32	0.87	1.28	NA	NA
Min	169.16	148.69	157.76	149.76	NA	NA
Max	174.99	169.33	173.99	170.75	NA	NA

Table C.2. Experiment Results (Four-Contractor Treatment)

Treatment I_4^0 (Setting 1. One-period decision making)						
	Cohorts					
	1	2	3	4	5	6
Mean	110.25	110.0	110.0	110.1	NA	NA
Standard Error	0.18	0.0	0.0	0.08	NA	NA
Min	110.0	110.0	110.0	110.0	NA	NA
Max	113.33	110.02	110.0	111.56	NA	NA
Treatment I_4^0 (Setting 2. Six-period decision making)						
	Cohorts					
	1	2	3	4	5	6
Mean	110.36	110.29	110.11	110.27	NA	NA
Standard Error	0.38	0.21	0.08	0.22	NA	NA
Min	109.98	109.98	109.98	109.98	NA	NA
Max	117.65	113.62	111.32	114.47	NA	NA
Treatment I_4^1						
	Cohorts					
	1	2	3	4	5	6
Mean	110.22	112.27	112.23	112.19	NA	NA
Standard Error	0.17	0.74	0.84	1.36	NA	NA
Min	110.0	110.0	110.0	110.0	NA	NA
Max	113.33	120.67	121.67	135.0	NA	NA
Treatment I_4^5						
	Cohorts					
	1	2	3	4	5	6
Mean	135.62	131.32	151.51	136.91	NA	NA
Standard Error	1.41	1.12	1.92	1.68	NA	NA
Min	121.34	120.68	127.91	122.58	NA	NA
Max	143.21	139.39	159.57	146.85	NA	NA

Table C.3. Absolute Approach

Reward	13 ECU				26 ECU				45 ECU			
Cohort	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max
1	0.3	0.07	0	1	0.35	0.05	0	0.5	0.35	0.09	0	1
2	0.23	0.07	0	1	0.42	0.08	0	1	0.65	0.05	0.5	1
3	0.07	0.04	0	0.5	0.53	0.07	0	1	0.45	0.03	0	0.5
4	0.1	0.05	0	0.5	0.53	0.07	0	1	0.57	0.08	0	1
5	0.1	0.05	0	0.5	0.47	0.07	0	1	0.38	0.05	0	0.5
6	0.07	0.04	0	0.5	0.53	0.06	0	1	0.62	0.08	0	1
7	0.47	0.07	0	1	0.65	0.05	0.5	1	0.38	0.06	0	1
8	0.35	0.06	0	1	0.45	0.05	0	1	0.75	0.06	0.5	1
9	0.2	0.08	0	1	0.47	0.08	0	1	0.47	0.04	0	1
10	0.03	0.02	0	0.5	0.42	0.08	0	1	0.33	0.07	0	1
11	0.2	0.06	0	0.5	0.1	0.06	0	1	0.35	0.06	0	1
12	0.33	0.08	0	1	0.53	0.06	0	1	1	0	1	1
13	0.25	0.07	0	1	0.45	0.08	0	1	0.55	0.08	0	1
14	0.62	0.09	0	1	0.47	0.06	0	1	0.4	0.07	0	1
15	0.2	0.06	0	0.5	0.3	0.08	0	1	0.55	0.09	0	1
16	0.33	0.08	0	1	0.55	0.08	0	1	0.53	0.07	0	1
17	0.07	0.05	0	1	0.38	0.06	0	1	0.6	0.08	0	1
18	0.55	0.05	0	1	0.6	0.05	0.5	1	0.68	0.07	0	1
19	0.15	0.05	0	0.5	0.45	0.06	0	1	0.42	0.07	0	1
20	0.7	0.08	0	1	0.7	0.06	0.5	1	0.78	0.06	0.5	1
21	0.42	0.08	0	1	0.5	0.07	0	1	0.55	0.05	0	1
22	0.4	0.06	0	1	0.65	0.05	0.5	1	0.62	0.08	0	1
23	0.25	0.07	0	1	0.33	0.07	0	1	0.12	0.05	0	0.5
24	0.28	0.08	0	1	0.28	0.06	0	0.5	NA	NA	NA	NA

Table C.4. Relative Approach

Reward	13 ECU				26 ECU				45 ECU			
Cohort	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max
1	0.54	0.04	0	1	0.61	0.03	0	1	0.84	0.02	0	1
2	0.34	0.04	0	1	0.72	0.03	0	1	0.78	0.03	0	1
3	0.67	0.03	0	1	0.83	0.03	0	1	0.77	0.03	0	1
4	0.47	0.03	0	1	0.78	0.03	0	1	0.78	0.03	0	1

Table C.5. Experimental Results on Low and High Reliability Treatment

Treatment	p=4 and T=3				p=4 and T=4			
Subject	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max
1	0.275	0.0416	0.1	0.7	0.625	0.0475	0.3	1
2	0.41	0.0481	0.1	0.8	0.695	0.0432	0.2	1
3	0.425	0.026	0.2	0.6	0.335	0.0509	0	0.7
4	0.085	0.0274	0	0.4	0.325	0.0331	0	0.6
5	0.16	0.0351	0	0.6	0.84	0.0366	0.4	1
6	0.57	0.0333	0.3	1	0.635	0.0466	0.2	0.9
7	0.25	0.0516	0	0.6	0.625	0.0575	0	1
8	0.215	0.0357	0	0.5	0.48	0.0746	0	1
9	0.56	0.0413	0.2	1	0.405	0.0426	0.2	1
10	0.475	0.0575	0.1	0.9	0.445	0.0478	0.1	0.8
11	0.155	0.042	0	0.5	0.235	0.0472	0	0.8
12	0.515	0.0431	0.2	0.8	0.41	0.0458	0.1	0.9
13	0.515	0.0499	0.1	0.9	0.37	0.0317	0	0.5
14	0.355	0.0467	0	0.8	0.65	0.0531	0.2	1
15	0.455	0.0426	0.1	0.8	0.18	0.0462	0	0.8
16	0.27	0.0585	0	0.7	0.755	0.0564	0	1
17	0.18	0.0427	0	0.7	0.125	0.0228	0	0.4
18	0.46	0.0426	0.2	1	0.72	0.0479	0.3	1
19	0.31	0.0416	0	0.6	0.355	0.0655	0	1
20	0.545	0.0535	0.2	0.9	0.635	0.0604	0.1	1
Treatment	p=4 and T=5				p=4 and T=7			
Subject	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max
1	0.46	0.0499	0	0.9	0.525	0.0736	0	1
2	0.5	0.0481	0	0.9	0.61	0.0747	0.1	1
3	0.455	0.0462	0.2	0.8	0.47	0.0877	0	1
4	0.815	0.0335	0.6	1	0.44	0.069	0.1	1
5	0.335	0.0319	0	0.5	0.29	0.027	0.1	0.5
6	0.55	0.0521	0.2	0.9	0.07	0.0417	0	0.6
7	0.205	0.0756	0	1	0.455	0.0679	0	1
8	0.81	0.0289	0.6	1	0.33	0.0471	0	0.7
9	0.715	0.0477	0.2	1	0.105	0.0467	0	0.7
10	0.415	0.0723	0	1	0.485	0.0431	0.1	0.8
11	0.245	0.0535	0	0.8				

12	0.84	0.0303	0.6	1				
13	0.08	0.0367	0	0.6				
14	0.14	0.0686	0	0.9				
15	0.415	0.0539	0.1	0.9				
16	0.3	0.0384	0	0.8				
17	0.235	0.0302	0.1	0.6				
18	0.56	0.0554	0.2	0.9				
19	0.765	0.0494	0.3	1				
20	0.41	0.0332	0.2	0.7				
Treatment	p=7 and T=4				p=7 and T=7			
Subject	Mean	Std. Err.	Min	Max	Mean	Std. Err.	Min	Max
1	0.345	0.0489	0	0.7	0.8	0.0348	0.4	1
2	0.345	0.0444	0	0.7	0.83	0.0349	0.5	1
3	0.355	0.0531	0	0.9	0.745	0.0489	0.3	1
4	0.535	0.0379	0.4	0.9	0.845	0.0256	0.6	1
5	0.405	0.0505	0.1	0.9	0.74	0.0387	0.3	1
6	0.45	0.032	0.2	0.8	0.51	0.0973	0	1
7	0.355	0.04	0.1	0.8	0.505	0.0776	0	1
8	0.58	0.0337	0.4	0.9	0.82	0.0526	0.1	1
9	0.385	0.0327	0.1	0.7	0.785	0.0393	0.4	1
10	0.45	0.0366	0.2	0.8	0.83	0.0219	0.6	1
11	0.525	0.0323	0.3	0.9	0.81	0.0369	0.4	1
12	0.6	0.0476	0.4	1	0.745	0.0246	0.6	1
13	0.44	0.0343	0.2	0.7	0.795	0.0456	0.3	1
14	0.295	0.0444	0	0.6	0.795	0.0373	0.5	1
15	0.565	0.0514	0.2	1	0.765	0.0477	0.3	1
16	0.555	0.0366	0.4	0.9	0.945	0.017	0.8	1
17	0.465	0.0466	0.2	0.8	0.735	0.0372	0.4	1
18	0.315	0.031	0	0.6	0.635	0.0412	0.3	1
19	0.48	0.0367	0.3	0.9	0.85	0.0564	0.1	1
20	0.61	0.0452	0.4	1	0.795	0.0344	0.5	1
Treatment	p=7 and T=9							
Subject	Mean	Std. Err.	Min	Max				
1	0.525	0.0736	0	1				
2	0.21	0.0657	0	1				
3	0.61	0.0747	0.1	1				
4	0.04	0.0285	0	0.5				

5	0.47	0.0877	0	1				
6	0.03	0.0179	0	0.3				
7	0.44	0.069	0.1	1				
8	0.37	0.0665	0	1				
9	0.29	0.027	0.1	0.5				
10	0.455	0.0526	0.1	0.8				
11	0.07	0.0417	0	0.6				
12	0.69	0.0672	0.2	1				
13	0.455	0.0679	0	1				
14	0.305	0.0841	0	1				
15	0.33	0.0471	0	0.7				
16	0.69	0.0475	0.2	1				
17	0.105	0.0467	0	0.7				
18	0.025	0.025	0	0.5				
19	0.485	0.0431	0.1	0.8				
20	0.485	0.0534	0.1	0.8				

REFERENCES

Anderson, S.P., J.K. Goeree, C.A. Holt. 2001. Minimum-effort coordination games: Stochastic potential and logit equilibrium. *Games and Economic Behavior*. **34**(2) 177-199.

Baiman, S., P.E. Fischer, M.V. Rajan. 2000. Information, contracting, and quality costs. *Management Science*. **46**(6) 776-789.

Bayiz, M., C.J. Corbett. 2005. Coordination and incentive contracts in project management under asymmetric information. *Available at SSRN 914227*.

Benjaafar, S., E. Elahi, K.L. Donohue. 2007. Outsourcing via service competition. *Management Science*. **53**(2) 241-259.

Berger, J., D. Pope. 2011. Can losing lead to winning? *Management Science*. **57**(5) 817-827.

Berninghaus, S.K., K.-M. Ehrhart. 1998. Time horizon and equilibrium selection in tacit coordination games: experimental results. *Journal of Economic Behavior & Organization*. **37**(2) 231-248.

Bolton, G.E., E. Katok, A. Ockenfels. 2004. How effective are electronic reputation mechanisms? An experimental investigation. *Management science*. **50**(11) 1587-1602.

Bowman, R.J. 2006. Home depot turns its attention to supplier performance managment. *Global Logistics & Supply Chain Strategies*. **10**(6).

Brandts, J., D.J. Cooper. 2006. Observability and overcoming coordination failure in organizations: An experimental study. *Experimental Economics*. **9**(4) 407-423.

Buser, T. 2016. The impact of losing in a competition on the willingness to seek further challenges. *Management Science*. **62**(12) 3439-3449.

Cachon, G.P., C.F. Camerer. 1996. Loss-avoidance and forward induction in experimental coordination games. *The Quarterly Journal of Economics*. **111**(1) 165-194.

Cachon, G.P., F. Zhang. 2007. Obtaining fast service in a queueing system via performance-based allocation of demand. *Management Science*. **53**(3) 408-420.

Camerer, C., T.H. Ho. 1999. Experience-weighted attraction learning in normal form games. *Econometrica*. **67**(4) 827-874.

Carlsson, H., M. Ganslandt. 1998. Noisy equilibrium selection in coordination games. *Economics Letters*. **60**(1) 23-34.

Charness, G., D. Masclet, M.C. Villeval. 2013. The dark side of competition for status. *Management Science*. **60**(1) 38-55.

Chen, H., S.H. Ham, N. Lim. 2011. Designing multiperson tournaments with asymmetric contestants: An experimental study. *Management Science*. **57**(5) 864-883.

Chen, H., N. Lim. 2013. Should managers use team-based contests? *Management Science*. **59**(12) 2823-2836.

Chen, R., Y. Chen. 2011. The potential of social identity for equilibrium selection. *The American Economic Review*. **101**(6) 2562-2589.

Chen, S., H. Lee. 2016. Incentive alignment and coordination of project supply chains. *Management Science*.

Chen, T., T. Klastorin, M.R. Wagner. 2015. Incentive contracts in serial stochastic projects. *Manufacturing & Service Operations Management*. **17**(3) 290-301.

Chen, Y., S.X. Li, T.X. Liu, M. Shih. 2014. Which hat to wear? Impact of natural identities on coordination and cooperation. *Games and Economic Behavior*. **84** 58-86.

Choice, R. 2012. *The growing trend of sustainability scorecards: Why it makes sense to get on board*.

Cooper, R., D.V. DeJong, R. Forsythe, T.W. Ross. 1992. Communication in coordination games. *The Quarterly Journal of Economics* 739-771.

Crawford, V.P. 1995. Adaptive dynamics in coordination games. *Econometrica: Journal of the Econometric Society* 103-143.

Davis, A.M., K. Hyndman. 2017. An experimental investigation of managing quality through monetary and relational incentives. *Management Science*.

Dechenaux, E., D. Kovenock, R.M. Sheremeta. 2015. A survey of experimental research on contests, all-pay auctions and tournaments. *Experimental Economics*. **18**(4) 609-669.

Deck, C., N. Nikiforakis. 2012. Perfect and imperfect real-time monitoring in a minimum-effort game. *Experimental Economics*. **15**(1) 71-88.

Devetag, G. 2005. Precedent transfer in coordination games: An experiment. *Economics Letters*. **89**(2) 227-232.

Devetag, G., A. Ortmann. 2007. When and why? A critical survey on coordination failure in the laboratory. *Experimental economics*. **10**(3) 331-344.

Douthit, J.D., L.W. Kearney, D.E. Stevens. 2012. Can agent cheap talk mitigate agency problems in the presence of a noisy performance measure? An experimental test in a single-and multi-period setting. *Journal of Management Accounting Research*. **24**(1) 135-158.

Elmaghraby, W.J. 2000. Supply contract competition and sourcing policies. *Manufacturing & Service Operations Management*. **2**(4) 350-371.

Fan, J., J. Gómez-Miñambres. 2016. Non-binding goals in teams: A real-effort coordination experiment. *Working paper*.

Farlow, D., G. Schmidt, A. Tsay, C.A. Holloway. 1996. Supplier management at Sun Microsystems (A). *Palo Alto, CA: Stanford University Graduate School of Business, OIT-16-A and OIT-16-B, March*.

Fischbacher, U. 1999. *Z-Tree 1.1. 0: Zurich toolbox for readymade economic experiments: Experimenter's manual*. Institute for Empirical Research in Economics, University of Zurich.

Gill, D., Z. Kissová, J. Lee, V.L. Prowse. 2015. First-place loving and last-place loathing: How rank in the distribution of performance affects effort provision.

Goeree, J.K., C.A. Holt. 2005. An experimental study of costly coordination. *Games and Economic Behavior*. **51**(2) 349-364.

Gonzalez, R., G. Wu. 1999. On the shape of the probability weighting function. *Cognitive psychology*. **38**(1) 129-166.

Greising, D., J. Johnsson. 2007. Behind Boeing's 787 delays. *Chicago Tribune*. **10** 2007.

Harsanyi, J.C. 1995. A new theory of equilibrium selection for games with complete information. *Games and Economic Behavior*. **8**(1) 91-122.

Harsanyi, J.C., R. Selten. 1988. A general theory of equilibrium selection in games. *MIT Press Books*. **1**.

Hu, B., A. Qi. 2017. Optimal procurement mechanisms for assembly.

Hyndman, K., D. Honhon. 2015. Flexibility in long-term relationships: An experimental study. *Working paper, https://www.hyndman-honhon.com/uploads/1/0/9/9/109960863/hh.pdf*.

Katok, E., D. Thomas, A. Davis. 2008. Inventory service-level agreements as coordination mechanisms: The effect of review periods. *Manufacturing & Service Operations Management*. **10**(4) 609-624.

Kerzner, H.R. 2013. *Project management: a systems approach to planning, scheduling, and controlling*. John Wiley & Sons.

Klotz, D.E., K. Chatterjee. 1995. Dual sourcing in repeated procurement competitions. *Management science*. **41**(8) 1317-1327.

Knez, M., C. Camerer. 1994. Creating expectational assets in the laboratory: Coordination in "Weakest-Link" games. *Strategic Management Journal*. **15**(S1) 101-119.

Kräkel, M. 2008. Emotions in tournaments. *Journal of Economic Behavior & Organization*. **67**(1) 204-214.

Kulp, S.L., V. Narayanan, R.L. Verkleeren. 2004. *Metalcraft supplier scorecard*. Harvard Business School.

Kwon, H.D., S.A. Lippman, K.F. McCardle, C.S. Tang. 2010. Project management contracts with delayed payments. *Manufacturing & Service Operations Management*. **12**(4) 692-707.

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

Lee, H.H., C. Li. 2017. Supplier quality management: Investment, inspection, and incentives. *Production and Operations Management*.

Li, H., H. Zhang, C.H. Fine. 2013. Dynamic business share allocation in a supply chain with competing suppliers. *Operations Research*. **61**(2) 280-297.

Lim, N. 2010. Social loss aversion and optimal contest design. *Journal of Marketing Research*. **47**(4) 777-787.

McKelvey, R.D., T.R. Palfrey. 1995. Quantal response equilibria for normal form games. *Games and economic behavior*. **10**(1) 6-38.

Mishra, B.K., A. Prasad. 2004. Centralized pricing versus delegating pricing to the salesforce under information asymmetry. *Marketing Science*. **23**(1) 21-27.

Mu, L., M. Dawande, X. Geng, V. Mookerjee. 2015. Milking the quality test: Improving the milk supply chain under competing collection intermediaries. *Management Science*. **62**(5) 1259-1277.

Owen, D.B. 1980. A table of normal integrals: A table. *Communications in Statistics-Simulation and Computation*. **9**(4) 389-419.

PMI, A. 2013. Guide to the Project Management Body of Knowledge (PMBOK Guide). *PMI Standard. Project Management Institute*. **53** 54.

Price, C.R., R.M. Sheremeta. 2011. Endowment effects in contests. *Economics Letters*. **111**(3) 217-219.

Rahmani, M., G. Roels, U.S. Karmarkar. 2015. Collaborative work dynamics in projects with co-production. *Available at SSRN 2686860*.

Riechmann, T., J. Weimann. 2008. Competition as a coordination device: Experimental evidence from a minimum effort coordination game. *European Journal of Political Economy*. **24**(2) 437-454.

Sako, M., S. Helper. 1998. Determinants of trust in supplier relations: Evidence from the automotive industry in Japan and the United States. *Journal of Economic Behavior & Organization*. **34**(3) 387-417.

Sheremeta, R.M. 2010. Experimental comparison of multi-stage and one-stage contests. *Games and Economic Behavior*. **68**(2) 731-747.

Tang, C.S., J.D. Zimmerman. 2009. *Managing new product development and supply chain risks: The Boeing 787 case*. Taylor & Francis.

Tavares, L.V. 2002. A review of the contribution of operational research to project management. *European Journal of Operational Research*. **136**(1) 1-18.

Van Huyck, J.B., R.C. Battalio, R.O. Beil. 1990. Tacit coordination games, strategic uncertainty, and coordination failure. *The American Economic Review*. **80**(1) 234-248.

Van Huyck, J.B., R.C. Battalio, R.O. Beil. 1993. Asset markets as an equilibrium selection mechanism: Coordination failure, game form auctions, and tacit communication. *Games and Economic Behavior*. **5**(3) 485-504.

Ware, N., S. Sing, D. Banwet. 2012. Supplier selection problem: A state-of-the-art review. *Management Science Letters*. **2**(5) 1465-1490.

Weber, R.A. 2006. Managing growth to achieve efficient coordination in large groups. *The American Economic Review*. **96**(1) 114-126.

Williams, T. 2003. The contribution of mathematical modelling to the practice of project management. *IMA Journal of Management Mathematics*. **14**(1) 3-30.

Xu, X., Y. Zhao. 2012. Incentives and coordination in project-driven supply chains. *Working paper, http://zhao.rutgers.edu/Xu-Zhao-11-23-2013.pdf*.

Zeckhauser, R. 1970. Medical insurance: A case study of the tradeoff between risk spreading and appropriate incentives. *Journal of Economic theory*. **2**(1) 10-26.

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