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Published in:
Fuzzy Optimization and Decision Making

DOI:
10.1007/s10700-019-09302-y

Publication date:
2019

Citation for published version (APA):
Chen, Z., Lan, Y., Zhao, R., & Shang, C. (2019). Deadline-based incentive contracts in project management with cost salience. *Fuzzy Optimization and Decision Making*, *18*(4), 451-473. https://doi.org/10.1007/s10700-019-09302-y

Deadline-based incentive contracts in project management with cost salience

Zhihua Chen[a], Yanfei Lan[a,b,*], Ruiqing Zhao[a], Changjing Shang[b]

zhihuachen@tju.edu.cn, lanyf@tju.edu.cn, zhao@tju.edu.cn, cns@aber.ac.uk

[a] *College of Management and Economics, Tianjin University, Tianjin 300072, China*
[b] *Department of Computer Science, Aberystwyth University, Aberystwyth SY23 3DB, UK*

Abstract

The contractor's procrastinating behavior owing to the psychology of cost salience exposes the project manager to the risk of time delay, which brings a significant challenge in project manager's incentive contract design. This paper considers that a project manager pays a contractor over a menu of deadline-based incentive contracts to conduct a project which consists of two sequential tasks. The contractor is endowed with private cost salience information and unobservable efforts. The subjective assessments about the cost salience degree and the project variability are characterized as uncertain variables. Within the framework of uncertainty theory and principal-agent theory, we investigate the impacts of the existence of cost salience and information asymmetry on the incentive contract and the project manager's profit. We confirm that cost salience can impel the project manager to lower both the fixed payment under full information and the penalty/incentive rate under pure moral hazard. Interestingly, we find that moral hazard can weaken the extent of inverse impact caused by the existence of cost salience for the project manager. Our study also shows that, for mitigating the adverse impacts brought by moral hazard, the project manager is more profitable to provide effort incentive when the contractor's efforts are more productive or the project risk is in a higher level. Finally, other suggestions for mitigating the detrimental impacts brought by adverse selection are provided by numerical experiments.

Keywords: Uncertainty theory, Incentive mechanism, Project management, Information asymmetry, Cost salience

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1. Introduction

Completion on time is generally identified as the key indicator of project success. Thus, it is ideal that a project is completed without time delay. However, in practice,

*Corresponding author: Yanfei Lan (lanyf@tju.edu.cn, yal5@aber.ac.uk).

achieving this major objective is very difficult because of procrastinating behavior and uncertainty environment. For example, Assaf and Al-Hejji (2006) conducted a survey on time performance of different types of construction projects in Saudi Arabia. They concluded that, on account of the contractor's effort procrastination and project's volatilities, 70% of projects experienced time overrun and the average time overrun was between 10% and 30% of the original contract duration. However, in academic and industrial domain, project managers rarely consider the contractor's procrastinating behavior owing to the psychology of cost salience. In fact, the contractor has a tendency to procrastinate as he attaches greater salience to immediate-term costs when allocating efforts over time (Wu et al. 2014), which may enlarge the project duration. Therefore, from the perspective of the project manager, how to motivate the contractor with cost salience to complete the project in a shorter time has been an urgent issue under uncertainty environment.

Deadline-based incentive contract, as a contractual strategy to enhance project's time performance, has received an increasing recognition from researchers and practitioners (e.g., Tang et al. 2015 and Zhang 2016). Many state transportation departments use deadline-incentive contracts, for example, Washington State Department of Transportation (WSDOT) reports it has used deadline-based incentive contracts with favorable outcomes to reward subcontractors for early completion of a project phase and/or penalize a subcontractor for late completion or failure to meet the deadline (Walker 2010). Nevertheless, introducing the contractor's procrastinating behavior caused by the psychology of cost salience into the project management and deal with cost salience by the deadline-based incentive contracts rarely have been studied. The presence of the contractor's cost salience brings a significant challenge in project manager's incentive contract design, especially when the project contains sequential tasks because the contractor may think he can put off more work to the later task.

In particular, since the degree of tendency to procrastinate (i.e., the cost salience degree) is one kind of the contractor's own psychological states and his effort level also cannot be monitored by the project manager, the project manager neither knows the contactor's truthful cost salience degree nor observes his effort level, which results in adverse selection and moral hazard in project management. Furthermore, in the setting of hiring a new contractor to implement a project, there is usually no observed historical data about the project's volatilities and the contactor's cost salience degree. This fact leads to that the probability distribution cannot be estimated from the frequency due to the lack of them. Hence, probability theory is no longer applicable to be used to characterize these incomplete information. Whereas uncertainty theory founded by Liu (2007) has been proved to be appropriate to depict subjective assessment and model human uncertainty by inviting some domain experts to evaluate the belief degree that each event will occur. Thus, we characterize the project's volatilities and the contactor's private cost salience degree as uncertain variables and focus on the optimal time-incentives under dual asymmetric information in an uncertain principal-agent setting.

The above discussion gives rise to three research questions. First, what are the optimal deadline-based contracts the project manager should design with serial tasks in the presence of contractor's private cost salience information and unobservable efforts? Second, how does the existence of cost salience influence the project manager's profit and optimal solutions? Third, how do the contractor's private cost salience information and unobservable efforts affect the project manager's profit and the contracting strategies, respectively?

In this paper, we consider an agency problem in which a project manager desires to employ a contractor to conduct a project. The completion time of the project which consists of two serial tasks is determined by the contractor's efforts. Furthermore, as the contractor attaches greater cost salience to the present moment when allocating efforts over time, he has a tendency to procrastinate and delay work over two tasks. The contractor's cost salience degree is his private information and his efforts are unobservable to the project manager. The project manager must design the effective deadline-based contract for the contactor to urge him to reveal truthful cost salience degree and complete the project on time. To address these above proposed issues, the optimal solutions are studied initially without cost salience. Subsequently, we investigate the optimal solutions with cost salience under four information cases (full information, only moral hazard, only adverse selection and dual asymmetric information). Afterwards, we investigate the impacts of both the existence of cost salience and the asymmetric information on the optimal profits of the project manager. With the analytical results and numerical experiments, we establish the following main findings.

First, we characterize the optimal deadline-based incentive contracts for the project manager in the absence of cost salience and in the presence of cost salience under different information cases, respectively. We find that the presence of cost salience leads to lower fixed payment under full information and lower penalty/incentive rate under pure moral hazard for the first task. However, it makes no difference in the incentive contract for the second task irrespective of the information structure. The solutions also suggest that, under dual symmetric information and pure adverse selection, the project manager prefers to only provide the contractor with fixed compensations and no penalty/incentive rate. In contrast, under pure moral hazard, the project manager would like to distort the penalty/incentive rate upward in the first task so as to motivate the contractor to implement proper effort. Furthermore, under dual asymmetric information, we characterize the optimal menu of deadline-based incentive contracts so that the project manager can dynamically update the contracts based on the hazard rate and the project risk.

Second, by examining the impacts of cost salience on the project manager's profit, we identify the values of cost salience. The results confirm that, in the absence of cost salience, the project manager's profit is always higher than that with cost salience, i.e., the existence of cost salience always brings about a loss of profit for the project manager. Besides, the project manager suffers from greater loss along with the contractor's higher degree of cost salience. As an interesting finding, we show that moral hazard can weaken the extent of inverse impact caused by the existence of cost salience for the project manager. We also illustrate that lower effort productivity of the contractor in the first task is helpful for the project manager to reduce the loss caused by the cost salience. What is more, the cost salience's detrimental impacts are decreasing in the project marginal time revenue under full information and increasing in the project marginal time revenue under moral hazard.

Third, by comparing the manager's profit under different information cases, we are able to pinpoint interesting interplays between the asymmetric information and the manager's profit. By examining the information rent induced by the contractor's private information about his cost salience degree, we find that it is more favorable to the project manager to screen the contractor's cost salience degree with higher effort productivity, higher project marginal time revenue, higher coefficient of risk aversion and lower project risk in the first task. What is more, compared to the case without moral hazard, the project manager is more beneficial to learn the contractor's truthful cost salience degree under moral hazard. With regard to the impacts of contractor's unobservable efforts, we find that, for mitigating the adverse impacts brought by moral hazard, the project manager is more profitable and willing to provide incentive mechanism for contracting on the contractor's efforts and impelling his optimal efforts when the efforts are more productive or the project risk is in a higher level.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature. In Section 3, we describe the problem formulation and notations. Section 4, as a benchmark, we first analyze the optimal solutions without cost salience under full information and under moral hazard, respectively. In Section 5, we correspondingly discuss the solutions with cost salience under four information cases. Section 6 illustrates the impacts of cost salience's existence, private information about the cost salience and unobservable efforts on the project manager's profits. We present this paper's conclusion in Section 7. All the proofs are relegated to the "Appendix".

2. Literature Review

This paper is related to three streams of literature: time-incentive literature in project management, the psychology literature on procrastination behavior and the literature on uncertain principal-agent problems.

The time-incentive problem in project management has been studied extensively by both academics and practitioners. According to Bubshait (2003), clients can provide time incentive for early completion. Kwon et al. (2010) investigate how the time-based contract can achieve optimal project channel coordination. Tang et al. (2015) examine two time-related incentive project management contracts when the manager conducts a reverse auction. Chen et al. (2015) propose a new time-incentive payment contract for stochastic projects defined by a series of stages or tasks and that contract can be used to find the optimal due date. Kerkhove and Vanhoucke (2016) provide a quantitative framework for selecting the optimal environment to adopt duration incentive contract. Zhang (2016) explores the value of deadlines from the agency-theoretic perspective and derives conditions under which the firm should impose such deadlines. We complement this line of literature by taking the agent's procrastinating behavior caused by the psychology of cost salience into consideration and analyzing how to design deadline-based incentive contract to overcome it and avoid time delay.

Past research has studied the source of procrastination in the psychology literature. O'Donoghue and Rabin (1999) posit that procrastination results from people's psychological tendency to overvalue current utilities, i.e., individuals tend to defer work because they attach a greater salience to the present moment, amplifying the costs of immediate effort. Ariely and Wertenbroch (2002) find that people recognize their self-control problems and attempt to control their procrastination by setting deadlines for themselves. Steel (2007) conducts meta-analysis of procrastination's possible causes and effects and finds that strong and consistent predictors of procrastination are task delay, self-efficacy, and impulsiveness. Ericson (2017) shows that anticipated reminders can induce additional procrastination, lowering both welfare and the probability the task is completed. Ferrari and Roster (2018) suggest that general procrastination tendencies may enable a lifelong pattern of responses to one's environment that become increasingly maladaptive throughout the life cycle. Although economists typically point out procrastination as a strong behavioral regulator because of cost salience, fewer researchers explicitly take this psychological bias into formal modeling consideration in the time-based project, especially when the psychological bias is individual's private information. Our study introduces the contractor's psychological state of cost salience into project management and discusses the impacts of cost salience on the project manager's contractual strategy and profit.

The last stream of literature focuses on how to use uncertainty theory to develop the principal-agent models. Uncertainty theory is founded by Liu (2007) who gives the basic concepts. Recent years, uncertainty theory has become a branch of axiomatic mathematics for dealing with modeling human uncertainty. Liu (2013) proposes an insurance risk model with uncertain claims. Liu et al. (2015) view the foreign exchange rate as an uncertain processes and discuss the uncertain currency option problems. Gao et al. (2016) employ the theory of uncertain Shapley value to analyze a profit allocation problem of supply chain alliance. The concerns of using uncertainty theory to develop the principal-agent model have been elaborated in a number of papers. Mu et al. (2013) establish an uncertain principal-agent model to maximize the expected utility of the enterprise under incentive feasible mechanism, in which the rural migrant worker's profit is characterized as an uncertain variable. Fu et al. (2018) consider an agency problem where a firm employs a manager to implement a R&D project and both the subjective assessments about the manager's risk aversion degree and the project variability are characterized as uncertain variables. Zhou et al. (2018) study a model of principal-agent problem under loss aversion and inequity aversion under uncertainty theory. Chen et al. (2018) investigate the impacts of risk attitude and outside option on compensation contracts under different information structures. Different from these studies, we characterize the project's volatilities and the contactor's private cost salience degree as uncertain variables and investigate the impact of dual asymmetric information on performance in an uncertain principal-agent setting.

3. Model Formulation

Consider a risk-neutral project manager (she) engages a risk-averse contractor (he) to complete a new project that consists of two tasks. The two tasks must be performed in sequence for technological reasons and the completion time in each task which influences the project's value mainly depends on the contractor's effort level. The contractor's effort division over the course of the project is not contractible upfront by the manager. What is more, the contractor has a tendency to procrastinate, as he has psychological bias of attaching greater salience to immediate-term costs when allocating efforts over time (Wu et al. 2014). In reality, however, the manager cannot distinguish the contractor's exact cost salience degree. Therefore, it is necessary for the project manager to design an incentive contract to induce the contractor to exert proper effort for shortening the project duration and report truthful cost salience degree for avoiding procrastinate.

3.1. Project's completion time

The project is conducted by two serial tasks both of which can be accelerated the contractor's effort levels. Moreover, the uncertain completion time T_i of the task i depends on the contractor's an unobservable effort e_i as well as the project risk. Thus, we define the project duration of task i as

$$T_i = t_{0i} - t_{1i}e_i + \varepsilon_i, \quad i = 1, 2,$$

where the uncertain component ε_i with mean 0 and variance σ_i^2 represents the risk of task i associated with development and commercialization of the project. In the context of conducting new project without historical data, the project manager cannot distinguish the project's accurate risk and has to invite some domain experts to evaluate the belief degree that each event will occur. Thus, we characterize the project's volatilities as uncertain variables. Furthermore, we assume ε_1 and ε_2 are independent. The parameter $t_{0i} > 0$ denotes the maximum possible project duration and the coefficient $t_{1i} > 0$ measures the marginal impact of the contractor's effort on reducing the completion time of task i, $i = 1, 2$.

Because the project consists of two serial tasks, task 2 is started immediately after task 1 is complete. Therefore, the project's total completion time $T = T_1 + T_2$. When the project is completed, the project manager will subsequently receive a project's value $V(T)$. We follow the usual modeling assumptions of the time-cost trade-off literature (Tang et al. 2015 and Yang et al. 2016) and assume that the project's value $V(T)$ to the manager is a linear, decreasing function of the project completion time T. So that $V(T) = a - bT$ where $a > 0$ indicates the base revenue of the project and $b > 0$ means the marginal revenue/loss the project manager gains when the project duration is reduced/increased by one time unit.

3.2. Cost salience and effort procrastination

When invited to accomplish a project with serial tasks, the contractor usually has a tendency to procrastinate, since he would attach greater salience to the immediate-term costs when allocating efforts over time (Wu et al. 2014). As shown in Akerlof (1991): Suppose one can finish a task freely at an earlier time or at a later time with a benefit of v and a cost of c. Finishing the task at the earlier time brings a net payoff of only $v - \theta c$ where $\theta > 1$ captures that the individual would attach greater psychological salience to the immediate cost, while the net payoff of finishing at the later time is $v - c$. As a consequence, the individual prefers to delay work whenever possible. Furthermore, a bigger θ imposes higher impact of cost salience on the individual utility and results in the individual's procrastination more likely.

In our model, the contractor has a convex cost $c(e_i) = e_i^2/2$ by inputting effort level e_i in task i, $i = 1, 2$. The assumption of a quadratic cost function is made not only for expositional convenience but also in accordance with the practical fact, which has been used in Dutta (2008) and Xiao and Xu (2012). Owing to the cost salience, the contractor would overvalue the effort cost in task 1 which is completed in the earlier time relative to task 2. As a result, the contractor's effort cost valued behaviorally by himself is $\theta e_1^2/2 + e_2^2/2$. Moreover, the contractor's cost salience factor θ is generally his private information and the project manager does not know the exact degree. Thus, the project manager can only make the subjective assessment about the contractor's cost salience which is characterized by an uncertain variable X with distribution $F(x)$ on the interval $[\underline{\theta}, \overline{\theta}]$, where $0 \leqslant \underline{\theta} < \overline{\theta} < +\infty$. Let $f(x) = \mathrm{d}F(x)/\mathrm{d}x$. We further impose the hazard rate

(HR) $h(x) = F(x)/f(x)$ as an increasing function so that the project revenue is increasing in the contractor's effort level. This monotonicity condition has been commonly used in the private information agency literature (Mu et al. 2013), and many distributions, including the linear, the zigzag, the normal, and any other distribution with single-peak (see Liu 2007 for details), have this property.

3.3. Compensation scheme

Note that the contractor's real cost salience is unknown and his effort is unobservable to the project manager, thus, neither his cost salience nor effort is contractible. Because the project completion time is verifiable and contractible, for impelling the contractor to induce short completion time and improved performance, we consider the contractor's incentive compensation to be contingent on the observable completion time T_1 and T_2. Different from Wu et al. (2014) who considered how to reduce the quality loss because of cost salience, we intend to study how to reduce the complete time in the presence of cost salience. In the following, we will examine the deadline-based incentive project management contracts when the contractor conducts unobservable efforts in two serial tasks with private cost salience information. For tractability and practically, we shall focus on the case of linear incentives/disincentives compensation form for easily implementing in practice and obtaining closed-form expressions of project manager's optimal contracting strategies and expected payoff.

The contractor receives a payment $W_i(\theta, T_i) = \alpha_i(\theta) - \beta_i(\theta)(T_i - d_i)$ for task i from the manager upon finishing the project, where $\alpha_i(\theta)$ is the fixed wage, $\beta_i(\theta) \geqslant 0$ is the penalty/incentive rate and d_i is the due date (or deadline), $i = 1, 2$. Such a typical deadline-based incentive contract has been used extensively in building construction, software development and new product development projects (Tang et al. 2015). For example, to repair the Santa Monica Freeway within $d = 180$ days after the Northridge earthquake in 1994, the City of Los Angeles (the project manager) provided C.C. Mayers, Inc. (the contractor) with an incentive (disincentive) of \$200,000 per day for early (late) completion and a fixed payment \$10,000,000. In this case, the contractor's payment takes the form of $15,000,000 - 200000(T - 180)$. Finally, the winning contractor C.C. Mayers, Inc. completed the repair 74 days before the 180-day deadline by exerting extra efforts (e.g., extra crews and extra equipment) and earned a \$14.5 million bonus (Boarnet 1998).

The sequence of events illustrated in Figure 1 is as follows: (1) the contractor privately learns his own type of cost salience; (2) the project manager offers a menu of compensation contracts; (3) the contractor decides whether to accept the contract or not; (4) if the contractor accepts the contract, he reports his cost salience information to the project manager and exerts efforts to complete the project; (5) the project manager pays the contractor according to the realized project duration and the chosen contract.

Figure 1: Sequence of events

3.4. The incentives problem

The project manager's expected profit is the project's value net of the compensation payed to the contractor, which can be written as

$$E[V(T) - W_1(\theta, T_1) - W_2(\theta, T_2)].$$

We assume the contractor's risk preference is constant absolute risk-averse (CARA). In our linear contracting framework, the contractor's expected utility can be conveniently represented by his certainty equivalent value which takes the familiar mean-variance form. Let $\mathrm{CE}_i(\theta, \tilde{\theta})$ denote the contractor's certainty equivalent in the task i when he self-selects the contract $(\alpha_i(\tilde{\theta}), \beta_i(\tilde{\theta}))$ by reporting his cost salience $\tilde{\theta}$, but his true type is θ, i=1,2.

$$\mathrm{CE}_i(\theta, \tilde{\theta}) = \alpha_i(\tilde{\theta}) - \beta_i(\tilde{\theta})(T_i - d_i) - \frac{1}{2}\rho\beta_i(\tilde{\theta})^2\sigma_i^2 - \frac{[1 + (i-2)(1-\theta)]e_i^2}{2}, \quad i = 1, 2,$$

where $\rho > 0$ is the contractor's coefficient of risk aversion.

By the same way, the contractor's certainty equivalent value in the task i by reporting his cost salience θ truthfully is given by

$$\mathrm{CE}_i(\theta, \theta) = \alpha_i(\theta) - \beta_i(\theta)(T_i - d_i) - \frac{1}{2}\rho\beta_i(\theta)^2\sigma_i^2 - \frac{[1 + (i-2)(1-\theta)]e_i^2}{2}, \quad i = 1, 2.$$

Because the contractor's efforts in two tasks are unobservable to the project manager, the manager should also design an incentive mechanism to make the contractor exert optimal efforts in both tasks. The contractor's objective is to induce an execution plan (e_1, e_2) that minimizes the sum of effort cost of completing the project. The incentive compatibility constraints for moral hazard are given by

$$e_i = \arg\max_{\hat{e}_i \geqslant 0} \mathrm{CE}_i(\theta, \theta), \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2. \quad \text{(IC1)}$$

Furthermore, from the perspective of project manager, to ensure the contractor to reveal his cost salience θ truthfully rather than claim to possess some other levels of $\tilde{\theta}$, the incentive compatibility constraints for adverse selection should be introduced by

$$\mathrm{CE}_i(\theta, \theta) \geqslant \mathrm{CE}_i(\theta, \tilde{\theta}), \quad \forall \theta, \tilde{\theta} \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2. \quad \text{(IC2)}$$

The contractor accepts the project manager's contract if and only if his expected utility exceeds the reservation utility obtained from the outside option which is assumed to be zero. Thus, the contractor's individual rationality constraints are given by

$$\mathrm{CE}_i(\theta,\theta) \geqslant 0, \quad \forall\theta \in [\underline{\theta},\overline{\theta}], \quad i=1,2. \quad \text{(IR)}$$

4. Optimal Solutions without Cost Salience

To explore the impacts of the contractor's psychological preference for delaying work on the deadline-based contract and the project manager's profit, as a benchmark, we first study the optimal solutions without cost salience. In the following, according to whether the project manager can observe the contractor's efforts or not, two information scenarios are established.

4.1. Optimal solution without cost salience under perfect information

In this scenario, the contractor does not have cost salience ($\theta = 1$) and his efforts are observable to the project manager, which transforms our analysis into a dual symmetric information problem. Thus, the project manager's objective is to maximize her profit by offering a first-best contract (α_i, β_i, e_i), $i = 1, 2$. Consequently, the project manager's problem is

$$\begin{cases} \max\limits_{(\alpha_i,\beta_i,e_i)} E[V(T) - W_1(\theta,T_1) - W_2(\theta,T_2)] \\ \text{subject to:} \\ \quad \mathrm{CE}_i(\theta,\theta) \geqslant 0, \quad \forall\theta \in [\underline{\theta},\overline{\theta}], \quad i=1,2. \quad \text{(IR)} \end{cases}$$

Proposition 1. *Under dual symmetric information without cost salience, the contractor's optimal effort levels for task 1 and task 2 is $e_1 = bt_{11}$ and $e_2 = bt_{12}$, respectively. The optimal fixed compensations $\alpha_1 = \frac{b^2t_{11}^2}{2}$ and $\alpha_2 = \frac{b^2t_{12}^2}{2}$ and the optimal penalty/incentive rates $\beta_1 = \beta_2 = 0$.*

As shown in Proposition 1, because the project manager can observe the contractor's efforts, the manager can require him to exert the optimal effort level which is equal to his effort productivity multiplied by the project revenue earned by unit reduced time. In this case, the project manage does not need to give the contractor penalty/incentive rate ($\beta_1 = \beta_2 = 0$). Moreover, as the contractor's individual rationality constraint is binding, which leads to the fixed wage paid to the contractor in each task is equal to his cost of effort. Based on Proposition 1, we can derive the manager's optimal expected profit in the following corollary.

Corollary 1. *Under dual symmetric information without cost salience, the project manager's optimal expected profit*

$$\Pi_1 = a - b(t_{10} + t_{20}) + \frac{b^2}{2}\left(t_{11}^2 + t_{12}^2\right).$$

4.2. Optimal solution without cost salience under moral hazard

In this scenario, the contractor does not have cost salience and his efforts are unobservable to the project manager, which transforms our analysis into a moral hazard problem. Thus, the project manager's problem is

$$\begin{cases} \max\limits_{(\alpha_i,\beta_i)} E[V(T) - W_1(\theta, T_1) - W_2(\theta, T_2)] \\ \text{subject to:} \\ \quad e_i = \arg\max\limits_{\hat{e}_i \geqslant 0} \mathrm{CE}_i(\theta, \theta), \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2 \quad \text{(IC1)} \\ \quad \mathrm{CE}_i(\theta, \theta) \geqslant 0, \qquad\qquad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2. \quad \text{(IR)} \end{cases}$$

Using the first-order condition for the optimal effort levels and substituting the contractor's participation constraint into the manager's objective function, we obtain an unconstrained decision problem. Solving for the optimal penalty/incentive rates and fixed compensations leads to the following optimal solution:

Proposition 2. *Under moral hazard without cost salience, the manager's optimal effort levels* $e_i = \frac{bt_{1i}^3}{t_{1i}^2+\rho\sigma_i^2}$*, i=1,2. The optimal fixed compensations* $\alpha_i = \frac{bt_{1i}^2(t_{0i}-d_i)}{t_{1i}^2+\rho\sigma_i^2} - \frac{b^2t_{1i}^4(t_{1i}^2-\rho\sigma_i^2)}{2(t_{1i}^2+\rho\sigma_i^2)^2}$ *and the optimal penalty/incentive rates* $\beta_i = \frac{bt_{1i}^2}{t_{1i}^2+\rho\sigma_i^2}$*, i=1,2.*

Proposition 2 provides us with closed form of the optimal deadline-based incentive contract under moral hazard without cost salience. Note that the optimal penalty/incentive rate β_i is decreasing in risk attitude ρ and the task risk σ_i, $i = 1, 2$, the project manager prefers lowing the optimal penalty/incentive rate to motivate the contractor when he is more risk averse and the task is in higher risk. What is more, the optimal penalty/incentive rate β_i increase in effort productivity t_{1i}, $i = 1, 2$. Thus, the project manager would raise the optimal penalty/incentive rate when the contractor's effort productivity in each task is higher. Based on Proposition 2, we can derive the manager's optimal expected profit in the following corollary.

Corollary 2. *Under moral hazard without cost salience, the project manager's optimal expected profit*

$$\Pi_2 = a - b(t_{10} + t_{20}) + \frac{1}{2}b^2 \sum_{i=1}^{2} \frac{t_{1i}^4}{t_{1i}^2 + \rho\sigma_i^2}.$$

5. Optimal Solutions with Cost Salience

In this section, we consider the contractor has cost salience. To explore the impact of information asymmetry on the project manager's contractual strategies and revenue, in the following, we would investigate the optimal solutions in four information cases.

5.1. Optimal solution with cost salience under dual symmetric information

In this scenario, the contractor has cost salience ($\theta > 1$) which is a public information and the contractor's efforts are observable to the project manager, which transforms our analysis into a dual symmetric information problem in the presence of cost salience. Consequently, the project manager's problem is

$$\begin{cases} \max\limits_{(\alpha_i,\beta_i,e_i)} E[V(T) - W_1(\theta, T_1) - W_2(\theta, T_2)] \\ \text{subject to:} \\ \quad \text{CE}_i(\theta,\theta) \geqslant 0, \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2. \quad \text{(IR)} \end{cases}$$

Proposition 3. *Under dual symmetric information with cost salience, the manager's optimal effort levels for task 1 and task 2 is* $e_1 = \frac{bt_{11}}{\theta}$ *and* $e_2 = bt_{21}$*, respectively. The optimal fixed compensation* $\alpha_1 = \frac{b^2 t_{11}^2}{2\theta}$ *for task 1 and* $\alpha_2 = \frac{b^2 t_{12}^2}{2}$ *for task 2 and the optimal penalty/incentive rates* $\beta_1 = \beta_2 = 0$.

Proposition 3 suggests that the optimal effort level (e_2), the fixed payment (α_2) for the second task and the optimal penalty/incentive rates (β_1 and β_2) under dual symmetric information with cost salience are the same as those under dual symmetric information without cost salience. That is, the contractor's cost salience makes no difference in these strategic decisions under full information. However, compared with the optimal solutions without cost salience under full information, the project manager would let the contractor exert lower effort (lower e_1) and offer a lower fixed payment (lower α_1) for the first task because of the existence of cost salience ($\theta > 1$). Based on Proposition 3, we can derive the manager's optimal expected profit in the following corollary

Corollary 3. *Under dual symmetric information with cost salience, the project manager's optimal expected profit*

$$\Pi_3 = a - b(t_{10} + t_{20}) + \frac{b^2}{2}\left(t_{12} + \frac{t_{11}^2}{\theta}\right).$$

5.2. Optimal solution with cost salience under pure moral hazard

In this scenario, the contractor's cost salience degree is public information but his efforts are unobservable to the project manager, which transforms our analysis into a pure moral hazard problem. Consequently, the project manager's problem is to choose the optimal incentive contract to maximize the project's profit net of compensation expenses.

$$\begin{cases} \max\limits_{(\alpha_i,\beta_i)} E[V(T) - W_1(\theta, T_1) - W_2(\theta, T_2)] \\ \text{subject to:} \\ \quad e_i = \arg\max\limits_{\hat{e}_i \geqslant 0} \text{CE}_i(\theta,\theta), \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2 \quad \text{(IC1)} \\ \quad \text{CE}_i(\theta,\theta) \geqslant 0, \qquad\qquad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2. \quad \text{(IR)} \end{cases}$$

Proposition 4. *Under moral hazard with symmetric cost salience information, the optimal fixed compensation* $\alpha_1 = \frac{bt_{11}^2(t_{01}-d_1)}{t_{11}^2+\theta\rho\sigma_1^2} - \frac{b^2t_{11}^6-\theta\rho\sigma_1^2b^2t_{11}^4}{2\theta(t_{11}^2+\theta\rho\sigma_1^2)^2}$ *and* $\alpha_2 = \frac{bt_{12}^2(t_{02}-d_2)}{t_{12}^2+\rho\sigma_2^2} - \frac{b^2t_{12}^4(t_{12}^2-\rho\sigma_2^2)}{2(t_{12}^2+\rho\sigma_i^2)^2}$*. The optimal penalty/incentive rates* $\beta_1 = \frac{bt_{11}^2}{t_{11}^2+\theta\rho\sigma_1^2}$ *and* $\beta_2 = \frac{bt_{12}^2}{t_{12}^2+\rho\sigma_2^2}$*. And the manager's optimal effort levels* $e_1 = \frac{bt_{11}^3}{\theta(t_{11}^2+\theta\rho\sigma_1^2)}$ *and* $e_2 = \frac{bt_{12}^3}{t_{11}^2+\rho\sigma_2^2}$*.*

The solution shows that, compared to that in the absence of cost salience under pure moral hazard, the project manager would like to lower the optimal penalty/incentive rate for the second task and the contractor would make less effort for the second task. The other contract strategies have no change. Besides, compared to the solution with cost salience under dual symmetric information, the project manager prefers to distort the optimal penalty/incentive rate up to be positive for motivating the contractor to exert optimal effort. According to the result in Proposition 4, the manager's optimal expected profit is obtained in the following corollary.

Corollary 4. *Under moral hazard with symmetric cost salience information, the project manager's optimal expected profit*

$$\Pi_4 = a - b(t_{10} + t_{20}) + \frac{b^2t_{12}^4}{2(t_{12}^2 + \rho\sigma_2^2)} + \frac{b^2t_{11}^4}{2\theta(t_{11}^2 + \theta\rho\sigma_1^2)}.$$

5.3. Optimal solution with cost salience under pure adverse selection

In this scenario, the contractor's cost salience is his private information but his efforts are observable to the project manager, which transforms our analysis into an information screening problem. In order to reveal the contractor's cost salience degree, the project manager has to design a menu of incentive contacts to screen it. Consequently, the project manager's problem is

$$\begin{cases} \max\limits_{(\alpha_i(x),\beta_i(x),e_i)} E[V(T) - W_1(\theta, T_1) - W_2(\theta, T_2)] \\ \text{subject to:} \\ \quad \mathrm{CE}_i(\theta,\theta) \geqslant \mathrm{CE}_i(\theta,\tilde{\theta}), \quad \forall\theta \in [\underline{\theta},\overline{\theta}], \quad i = 1,2 \quad \text{(IC2)} \\ \quad \mathrm{CE}_i(\theta,\theta) \geqslant 0, \qquad\qquad \forall\theta \in [\underline{\theta},\overline{\theta}], \quad i = 1,2. \quad \text{(IR)} \end{cases}$$

We can derive the closed form of the optimal deadline-based incentive contract and the contractor's optimal efforts e_1 and e_2, both of which are formalized in Proposition 5 below.

Proposition 5. *Under pure adverse selection with cost salience, the contractor's optimal effort levels for task 1 and task 2 are* $e_1 = \frac{bt_{11}}{\overline{\theta}}$ *and* $e_2 = bt_{12}$*, respectively. The optimal fixed wages* $\alpha_1 = \frac{b^2t_{11}^2}{2\overline{\theta}^2}$ *for task 1 and* $\alpha_2 = \frac{b^2t_{12}^2}{2}$ *for task 2. The optimal penalty/incentive rates* $\beta_1 = \beta_2 = 0$*.*

As seen in Proposition 5, the project manager would require the contractor to carry out the optimal effort based on the project revenue in unit decreased time and his effort productivity in each task. We can find the deadline-based incentive contract only consists of fixed wages which are equal to the contractor's cost of efforts. Moreover, compared to the case under dual asymmetric information, the difference in the optimal solution is that the project manager would adjust the optimal effort level and the fixed wage in the first task to be lower. Based on Proposition 5, we can derive the manager's optimal expected profit in the following corollary.

Corollary 5. *Under pure adverse selection with cost salience, the project manager's optimal expected profit*

$$\Pi_5 = a - b(t_{10} + t_{20}) + b^2 \left(\frac{t_{12}^2}{2} + \frac{t_{11}^2}{2\overline{\theta}} \right).$$

5.4. Optimal solution with cost salience under dual asymmetric information

In this scenario, the contractor's cost salience is his private information and his efforts are unobservable to the project manager, which transforms our analysis into dual asymmetric information problem. Consequently, to guarantee the contractor report real cost salience degree and make proper efforts, the project manager's problem is

$$\begin{cases} \max\limits_{(\alpha_i(x),\beta_i(x))} E[V(T) - W_1(\theta, T_1) - W_2(\theta, T_2)] \\ \text{subject to:} \\ \quad e_i = \arg\max\limits_{\hat{e}_i \geqslant 0} \mathrm{CE}_i(\theta, \theta), \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2 \quad \text{(IC1)} \\ \quad \mathrm{CE}_i(\theta, \theta) \geqslant \mathrm{CE}_i(\theta, \tilde{\theta}), \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2 \quad \text{(IC2)} \\ \quad \mathrm{CE}_i(\theta, \theta) \geqslant 0, \quad \forall \theta \in [\underline{\theta}, \overline{\theta}], \quad i = 1, 2. \quad \text{(IR)} \end{cases}$$

The following proposition characterizes the optimal menu of deadline-based incentive contracts that the project manager should follow and the contractor's optimal effort levels in the presence of dual asymmetric information.

Proposition 6. *Under dual asymmetric information, the optimal fixed compensation* $\alpha_1 = \int_{\theta}^{\overline{\theta}} \frac{t_{11}^3(2b\theta - t_{11}h(\theta))}{4\theta^3(t_{11}^2 + \theta\rho\sigma_1^2)} \mathrm{d}\theta + \frac{t_{11}(2b\theta - t_{11}h(\theta))(t_{01} - d_1)}{2\theta(t_{11}^2 + \theta\rho\sigma_1^2)} - \frac{t_{11}^2(t_{11}^2 - \theta\rho\sigma_1^2)(2b\theta - t_{11}h(\theta))^2}{8\theta^3(t_{11}^2 + \theta\rho\sigma_1^2)^2}$ *and* $\alpha_2 = \frac{bt_{12}^2(t_{02} - d_2)}{t_{12}^2 + \rho\sigma_2^2} - \frac{b^2 t_{12}^4(t_{12}^2 - \rho\sigma_2^2)}{2(t_{12}^2 + \rho\sigma_2^2)^2}$. *The optimal penalty/incentive rates* $\beta_1 = \frac{t_{11}(2b\theta - t_{11}h(\theta))}{2\theta(t_{11}^2 + \theta\rho\sigma_1^2)}$ *and* $\beta_2 = \frac{bt_{12}^2}{t_{12}^2 + \rho\sigma_2^2}$. *The manager's optimal effort levels* $e_1 = \frac{t_{11}^2(2b\theta - t_{11}h(\theta))}{2\theta^2(t_{11}^2 + \theta\rho\sigma_1^2)}$ *and* $e_2 = \frac{bt_{12}^3}{t_{11}^2 + \rho\sigma_2^2}$.

Proposition 6 presents the qualitative solutions for the penalty/incentive and fixed parameters of the deadline-based contract as well as the contractor's optimal efforts even in the presence of both adverse selection and moral hazard. An important outcome of our solution is the manner where the both hazard rate $h(x)$ which is linked to adverse selection and project risk σ_1^2 which is linked to moral hazard enter the incentive term.

Hence we are able to clarify how adverse selection and moral hazard impact incentives for the time-based projects. First, as seen in Proposition 6, the penalty/incentive rate for task 1 decreases in the hazard rate $h(x)$. That is, in order to prevent the contractor from concealing true information and mimicking other degrees of cost salience, the project manager would bring down the penalty/incentive rate for avoiding such strategic manipulation. Second, the penalty/incentive rate for task 1 also decreases in the project risk in task 1. Thus, the project manager should reduce the penalty/incentive rate if the project's volatility is higher. That is because the risk-averse contractor exerts low effort under high risk, which in turn causes the project manager just provides low incentive for him. Proposition 6 also offers an important observation regarding the contractor's compensation and optimal effort for task 2 which are the same as that under pure moral hazard with symmetric cost salience. Thus, the adverse selection has no impact on the contract strategy and the effort level for the second task. Thus, it unnecessary to consider the private information for the project manager when designing contract strategy of the second task. The following corollary characterizes the manager's optimal expected profit under dual asymmetric information with cost salience.

Corollary 6. *Under dual asymmetric information with cost salience, the project manager's optimal expected profit*

$$\Pi_6 = a - b(t_{10} + t_{20}) + \frac{b^2 t_{12}^4}{2(t_{12}^2 + \rho\sigma_2^2)} + \frac{1}{8}\int_{\underline{\theta}}^{\overline{\theta}} \frac{(2\theta b t_{11} - t_{11}^2 h(\theta))^2}{\theta^3(t_{11}^2 + \theta\rho\sigma_1^2)} f(\theta)\mathrm{d}\theta.$$

6. Impacts of Cost Salience and Information Asymmetry

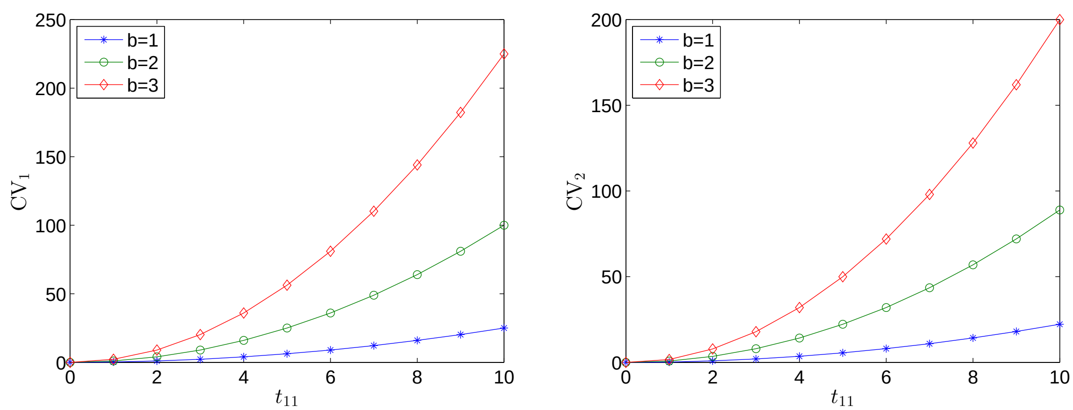
In this section, first, we examine the effects of the existence of cost salience on the project manager's profits. We also investigate the contractor's private information about his cost salience degree on the project manager's profits. Finally, we determine how the contractor's unobservable efforts influence the project manager's profits. We aim at discovering several important managerial insights that how to diminish the impacts of cost salience and information asymmetry.

6.1. The impacts of cost salience on the project manager's profit

When the project manager does not have the cost salience, he does not prefer to distort his effort between two tasks. In contrast, if the project manager amplifies the costs of the present effort, he would have the tendency to delay work. How is the project performance susceptible to the manager's procrastinating behavior? We would derive the effect of the existence of cost salience by comparing the project manager's profits with cost salience and that without cost salience. Specifically, we denote $\mathrm{CV}_1 = \Pi_1 - \Pi_3$ and $\mathrm{CV}_2 = \Pi_2 - \Pi_4$ as the values of cost salience under full information and the profit difference under moral hazard, respectively.

Proposition 7. *The existence of cost salience induces a loss of the project manager's profit. Moreover, as the contractor attaches greater cost salience to the present moment, the project manager would suffer from greater loss. However, moral hazard can weaken the extent of inverse impact caused by the existence of cost salience for the project manager.*

Proposition 7 shows that the manager's procrastinating behavior is always harmful to the project manager. That is because, first, the cost salience makes the contractor exert less effort in the first task, which extends the project's duration and then cut down the manager's profit; second, the cost salience makes the contractor amplify his cost of effort so that the manager has to pay more than before. Furthermore, the larger the contractor's cost salience degree, the more likely the contractor to procrastinate. It brings about that the manager is forced to bear the project delay, which induces a loss of the project manager's profit. In addition, we demonstrate that the loss induced by the presence of cost salience is lower under moral hazard than that under full information. That is, moral hazard can weaken the extent of inverse impact caused by the existence of cost salience for the project manager. This result is expected from the project manager's perspective as it is difficult to monitor the contractor's efforts in most cases.



(a) The effects of t_{11} and b on CV_1

(b) The effects of t_{11} and b on CV_2

Figure 2: The values of cost salience with $\sigma_1 = 0.5$ and $\rho = 2$

Fig. 2 presents two numerical examples regarding the influence of t_{11} and b on the values of cost salience. With respect to the effect of the existence of cost salience under full information, the loss of project manager's profit is increasing in both contract's effort marginal impact t_{11} in the first task and the marginal revenue b the project manager gains by unit time. This phenomena can be explained by Corollaries 1 and 3 in which the project manager's expected profits increase in t_{11} and b and the difference of the profits is positive. Regarding to the impact caused by the presence of cost salience under moral hazard, the loss induced by the existence of cost salience is increasing in b. Interestingly, it is increasing in t_{11} when t_{11} is lower and decreasing when t_{11} is higher. This result holds because under moral hazard the contractor can adjust his own effort level based on his effort marginal impact t_{11}. When t_{11} is smaller, the contractor intends to procrastinate so as to reduce effort cost. However, when t_{11} is bigger, the contractor would input more effort to the first task in order to complete project earlier and receive more payment, in which case the cost salience does not make a difference in the contractor's effort. Hence, when t_{11} is bigger under moral hazard, the effect of the existence of cost salience becomes smaller. Comparing with Fig. 2(a) and Fig. 2(b) also verifies that inverse impact caused by the existence of cost salience for the project manager is lower under moral hazard than that under perfect information.

6.2. The value of the contractor's unobservable effort

Under moral hazard, the effort levels e_1 and e_2 in both tasks become his decision variables rather than that of the manager. As a result, the manager cannot get the same solution under moral hazard as that under no moral hazard. We refer to the difference in the project manager's profits as the value of unobservable effort.

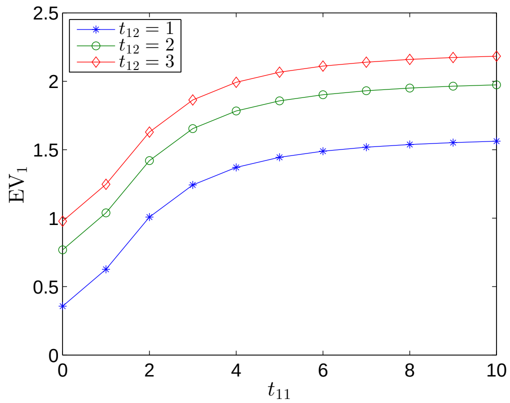
According to whether the project manager can observe the contractor's efforts or not, we define two forms of the value of unobservable effort. In specific, when the contractor's cost salience level is public information, we denote the value of information about his unobservable efforts as $\mathrm{EV}_1 = \Pi_3 - \Pi_4$, where Π_3 and Π_4 are given in Corollaries 3 and 4, respectively. Similarly, when the contractor's truthful cost salience is not known by the project manager, the value of information about his private effort is defined by $\mathrm{EV}_2 = \Pi_5 - \Pi_6$, where Π_5 and Π_6 are given in Corollaries 5 and 6, respectively.

We derive the result regarding the impact of the contractor's moral hazard on the project manager's profit which is expressed in the following proposition.

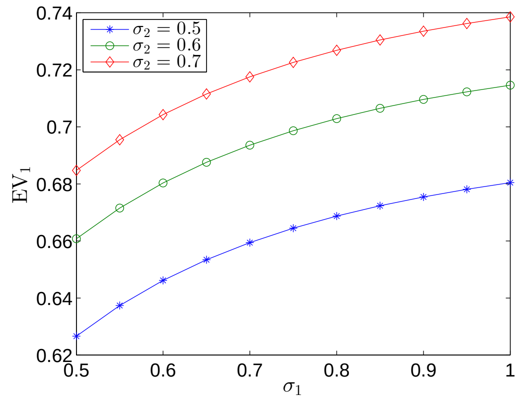
Proposition 8. *No matter whether cost salience is public information or not, moral hazard is always detrimental to the project manager.*

Fig. 3 numerically depicts the values of unobservable efforts under symmetric cost salience information. As shown in Fig. 3(a), the value of unobservable efforts is always increasing in t_{11} and t_{12}. If the effort marginal output is in a high level, the manager will suffer more loss if the contractor shirk effort due to moral hazard. Therefore, the higher the effort marginal output in task 1 or task 2 is, the more preferable the project manager is to provide effort incentive. Fig. 3(b) shows that the value of unobservable effort under symmetric cost salience information increases as the project risk in each task improves. Hence, for mitigating the adverse impacts brought by moral hazard, the project manager is more willing to contract on the contractor's efforts when the project risk is in a higher level.

Fig. 4 visually shows the influence of t_{11}, t_{12}, σ_1 and σ_2 on EV_2. It is obvious that the value of unobservable efforts under asymmetric cost salience information increases



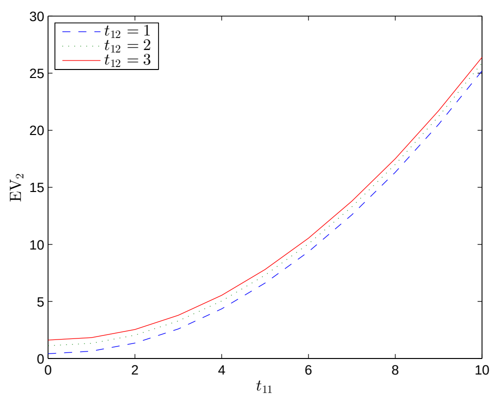
(a) The effects of t_{11} and t_{12} on EV_1



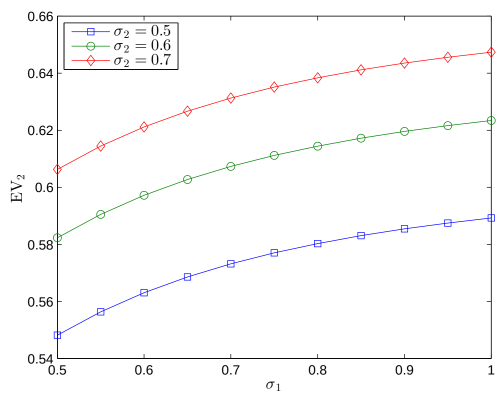
(b) The effects of σ_1 and σ_2 on EV_1

Figure 3: The values of unobservable efforts under symmetric cost salience information

Notes. Parameters are as follows: $b = 1$, $\sigma_1 = 0.5$, $\sigma_2 = 0.5$ and $\rho = 10$ in Fig. 3(a); $b = 1$, $t_{11} = 1$, $t_{12} = 1$ and $\rho = 10$ in Fig. 3(b).



(a) The effects of t_{11} and t_{12} on EV_2



(b) The effects of σ_1 and σ_2 on EV_2

Figure 4: The values of unobservable efforts under asymmetric cost salience information

Notes. Parameters are as follows: $b = 1$, $\sigma_1 = 0.5$, $\sigma_2 = 0.5$ and $\rho = 20$ in Fig. 4(a); $b = 1$, $t_{11} = 1$, $t_{12} = 1$ and $\rho = 10$ in Fig. 4(b).

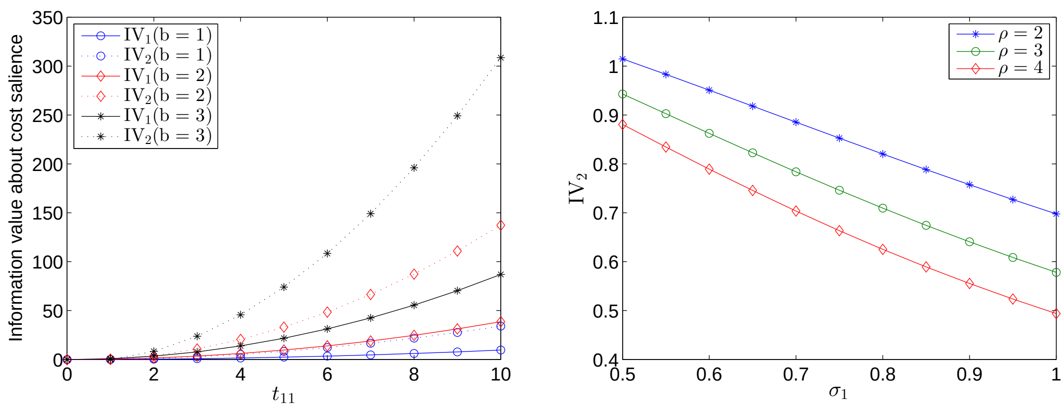
in both the effort marginal output in each task and the project risks in both tasks, i.e., incremental parameters (t_{11}, t_{12}, σ_1 and σ_2) would enlarge the inverse impact induced by moral hazard. As a result, with regard to more productive efforts (higher t_{11} and t_{12}) and greater project risks (higher σ_1 and σ_2) under asymmetric cost salience information, an incentive mechanism for contracting on the contractor's efforts and impelling him to exert optimal efforts is more desirable for the project manager.

6.3. The value of information about the contractor's private cost salience

In the setting of symmetric cost salience, the contractor's cost salience degree is public information. However, under asymmetric cost salience information, the project manager must provide the contractor with information rent so as to prevent him from misreporting his type of cost salience. The informational rent, which can be interpreted as the value of the contractor's private information about his cost salience degree, is reflected by the difference between the project manager's profits under symmetric cost salience cases and those under asymmetric cost salience cases.

According to whether the project manager observes the contractor's efforts or not, we define two forms of the value of information about the contractor's private cost salience. In specific, when the contractor's efforts are observable, we denote the value of information about the contractor's private cost salience information as $\text{IV}_1 = \Pi_3 - \Pi_5$, where Π_3 and Π_5 are given in Corollaries 3 and 5, respectively.

Similarly, when the contractor's efforts are unobservable, the value of information about the contractor's private cost salience information is defined by $\text{IV}_2 = \Pi_4 - \Pi_6$, where Π_4 and Π_6 are given in Corollaries 4 and 6, respectively.



(a) The effects of t_{11} and b on IV_1 and IV_2 (b) The effects of σ_1 and ρ on IV_2

Figure 5: The values of information about cost salience

Notes. Parameters are as follows: $\sigma_1 = 0.5$ and $\rho = 2$ in Fig. 5(a); $b = 1$ and $t_{11} = 2$ in Fig. 5(b).

We conduct two numerical experiments to display the value of information about the contractor's private cost salience information and demonstrate the influence of parameters on the information value. Specifically, Fig. 5(a) illustrates the impacts of t_{11} and b on the information value with and without observable efforts. The implication of this figure is twofold. First, no matter whether the project manager can observe the contractor's efforts, the information value is increasing in t_{11} and b. In other words, regardless of whether the contractor's effort is observable or not, the project manager is always willing to learn the contractor's truthful cost salience degree when t_{11} or b is bigger. Second, the information value with moral hazard is higher than that without moral hazard ($\text{IV}_1 < \text{IV}_2$). Therefore, when the contractor's efforts are unobservable, it is more beneficial for the project manager to screen the contractor's cost salience degree. Fig. 5(b) reveals the impact of σ_1 and ρ on IV_2. The result shows that the information value under moral hazard is decreasing in both the project risk in the first task and the contractor's coefficient of risk aversion.

This suggests that from the project manager's perspective, on the one hand, acquiring the contractor's cost salience information becomes more valuable when the project risk in the first task is low. On the other hand, a much less conservative contractor with private information is disadvantageous to the project manager. In this situation, the project manager ought to know the contractor's cost salience information more accurately.

7. Conclusion and Future Research

From the perspective of project manager, this paper studies how to design the optimal deadline-based incentive contract for a contractor who is endowed with private cost salience information and unobservable efforts. With regard to the effects of the existence of cost salience on the incentive contracts, as cost salience gives rise to effort procrastination, we show that cost salience can let project manager weaken the fixed payment under full information and penalty/incentive rate under moral hazard. In the premise of having cost salience, compared to the contract strategy under dual symmetric information, the project manager should offer a low fixed wage and revise the penalty/incentive rate upwards under pure moral hazard. Furthermore, under both moral hazard and adverse selection, we pinpoint qualitative interplays between deadline-based incentive contract structure and the effects of dual asymmetric information.

We also characterize the effects of the existence of cost salience and information asymmetry. The results suggest that the presence of cost salience induces a loss of the project manager's profit. Moreover, the greater the manager attaches salience to the present moment, the higher the loss will be. Specially, moral hazard is helpful to the project manager to mitigate the negative impact caused by the contractor's cost salience. In addition, lower effort productivity in the first task and lower project marginal time revenue are also advantage to the project manager to cut down the loss caused by cost salience. Afterwards, with regard to the impact of moral hazard on the project manager's profit, we show that the project manager is more willing to contract on the contractor's efforts and provide effort incentive in higher effort productivity or higher project risk of either task no matter whether cost salience is public information or not. Lastly, by highlighting the role of asymmetric information about cost salience degree, we find that it is more preferable for the project manager to screen the contractor's real cost salience degree and decrease the extent of information asymmetry so as to reduce information rent when the contractor has higher effort productivity in the first task, less conservative or the project has lower risk in the first task.

Our model does not take the project quality into consideration. The contractor's effort procrastination caused by cost salience may result in remedying quality issues that surface later (Wu et al. 2014). It would be interesting and worthwhile to combine time-incentive and quality-incentive in order to not only shorten the project completion time but also improve the project quality.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant Nos. 71771166 and 71771165, Tianjin Natural Science Foundation under Grant No. 18JCQNJC04200, and partly by a Sêr Cymru II COFUND Fellowship, UK.

Appendix. Proofs

Proof of Proposition 1. Based on the expected value criterion, the project manager's expected profit can be written as

$$E[V(T) - W_1(1,T_1) - W_2(1,T_2)] = a - b\sum_{i=1}^{2}[t_{0i} - t_{1i}e_i] - \sum_{i=1}^{2}\left[\alpha_i - \beta_i(T_i - d_i)\right].$$

Because the project manager's expected profit is decreasing in the fixed payments α_1 and α_2, at optimality, the individual rationality constraints for the contractor should be binding, i.e., $\mathrm{CE}(1,1) = 0$. Thus, we can rewrite the project manager's problem as

$$\begin{cases} \max\limits_{(\alpha_i,\beta_i,e_i)} a - b\sum_{i=1}^{2}[t_{0i} - t_{1i}e_i] - \sum_{i=1}^{2}\left[\alpha_i - \beta_i(T_i - d_i)\right] \\ \text{subject to:} \\ \quad \alpha_i - \beta_i(T_i - d_i) - \frac{1}{2}\rho\beta_i^2\sigma_i^2 - \frac{e_i^2}{2} = 0, \quad i = 1,2. \end{cases}$$

By substituting the fixed payments into the objective function, we obtain the project manager's expected profit:

$$a - b(t_{01} - t_{11}e_1 + t_{02} - t_{12}e_2) - \frac{e_1^2}{2} - \frac{e_2^2}{2} - \frac{1}{2}\rho\beta_1^2\sigma_1^2 - \frac{1}{2}\rho\beta_2^2\sigma_2^2,$$

which is decreasing in β_1 and β_2 and concave in e_1 and e_2. Thus, the project manager would set both β_1 and β_2 to zero for getting a maximum profit. Besides, we can yield the contractor's optimal effort levels $e_1 = bt_{11}$ and $e_2 = bt_{12}$ by using the first-order condition. Following the determinate individual rationality constraints which are binding, the corresponding optimal fixed payments α_1 and α_2 for the contractor can be derived immediately. The proof of the proposition is complete.

Proof of Proposition 2. Under moral hazard, the contractor will choose his efforts e_i in task i to maximize his own utility

$$\alpha_i - \beta_i(T_i - d_i) - \frac{1}{2}\rho\beta_i^2\sigma_i^2 - \frac{\hat{e}_i^2}{2},$$

which is concave in $\hat{e}_i$, $i = 1, 2$. The maximum is completely characterized by the first-order condition and we derive $e_1 = t_{11}\beta_1$ and $e_1 = t_{12}\beta_2$. Furthermore, because the project manager's profit is decreasing in the fixed payments, at optimality, the individual rationality constraints should be binding. Therefore, by substituting e_1 and e_2 into the individual rationality constraints and then substituting the fixed payments (α_1 and α_2) and the effort levels (e_1 and e_2) into the objective function, the project manager's expected profit can be rewritten as

$$a - b(t_{01} + t_{02}) + \sum_{i=1}^{2} \left[bt_{1i}^2\beta_i - \frac{1}{2}t_{1i}^2\beta_i^2 - \frac{1}{2}\rho\beta_i^2\sigma_i^2 \right].$$

By the first-order condition regarding to β_1 and β_1, we can obtain $\beta_1 = \frac{bt_{11}^2}{t_{11}^2+\rho\sigma_1^2}$ and $\beta_2 = \frac{bt_{12}^2}{t_{12}^2+\rho\sigma_2^2}$. Based on the binding individual rationality constraints, the optimal fixed payments (α_1 and α_2) can be obtained immediately. The proof of the proposition is complete.

Proof of Proposition 3. Similar to the Proof of Proposition 1.

Proof of Proposition 4. Similar to the Proof of Proposition 2.

Proof of Proposition 5. Let $\mathrm{CE}(\theta, \theta) = \mathrm{CE}_1(\theta, \theta) + \mathrm{CE}_2(\theta, \theta)$. The incentive compatibility constraints for adverse selection can be written as

$$\mathrm{CE}(\theta, \theta) \geqslant \mathrm{CE}(\theta, \tilde{\theta}), \quad \forall \theta, \tilde{\theta} \in [\underline{\theta}, \overline{\theta}],$$

which means that $\mathrm{CE}(\theta, \tilde{\theta})$ obtains its maximal value at $\mathrm{CE}(\theta, \theta)$, i.e., the contractor can obtain his maximal profit $\mathrm{CE}(\theta, \tilde{\theta})$ if and only if $\theta = \tilde{\theta}$. Thus, $\mathrm{CE}(\theta, \tilde{\theta})$ satisfies the first-order condition (i.e., local incentive compatibility constraint) $\frac{\partial \mathrm{CE}(\theta,\tilde{\theta})}{\partial \tilde{\theta}} \mid_{\tilde{\theta}=\theta} = 0$ and the second-order condition $\frac{\partial^2 \mathrm{CE}(\theta,\tilde{\theta})}{\partial \tilde{\theta}^2} \mid_{\tilde{\theta}=\theta} \leqslant 0$. The local incentive compatibility constraint

$$\sum_{i=1}^{2} \left[\frac{\mathrm{d}\alpha_i(\theta)}{\mathrm{d}\theta} - (t_{0i} - t_{1i}e_i - d_i)\frac{\mathrm{d}\beta_i(\theta)}{\mathrm{d}\theta} - \rho\sigma_i^2\beta_i(\theta)\frac{\mathrm{d}\beta_i(\theta)}{\mathrm{d}\theta} \right] = 0, \quad \forall \theta \in [\underline{\theta}, \overline{\theta}].$$

Differentiating $\mathrm{CE}(\theta, \theta)$ with respect to θ yields

$$\sum_{i=1}^{2} \left[\frac{\mathrm{d}\alpha_i(\theta)}{\mathrm{d}\theta} - (t_{0i} - t_{1i}e_i - d_i)\frac{\mathrm{d}\beta_i(\theta)}{\mathrm{d}\theta} - \rho\sigma_i^2\beta_i(\theta)\frac{\mathrm{d}\beta_i(\theta)}{\mathrm{d}\theta} \right] - \frac{e_1^2}{2} = -\frac{e_1^2}{2} \leqslant 0.$$

Thus, the individual rationality constraint is equivalent to

$$\mathrm{CE}(\overline{\theta}, \overline{\theta}) \geqslant 0.$$

The constraint is binding under the optimal mechanism because the project manager will reap the redundant profit, so that $\mathrm{CE}(\overline{\theta}, \overline{\theta}) = 0$. Because $\mathrm{CE}(\overline{\theta}, \overline{\theta}) = 0$ and $\frac{\mathrm{dCE}(\theta,\theta)}{\mathrm{d}\theta} = -e_1^2/2$, we can derive

$$\mathrm{CE}(\theta, \theta) = \mathrm{CE}(\overline{\theta}, \overline{\theta}) + \int_{\theta}^{\overline{\theta}} \frac{e_1^2}{2}\mathrm{d}\theta = \frac{e_1^2}{2}(\overline{\theta} - \theta).$$

Combining the definition of $\mathrm{CE}(\theta, \theta)$ yields

$$\sum_{i=1}^{2}\left[\alpha_i - \beta_i(T_i - d_i) - \frac{1}{2}\rho\beta_i^2\sigma_i^2\right] - \frac{\theta e_1^2}{2} - \frac{e_2^2}{2} = \frac{e_1^2}{2}(\overline{\theta} - \theta).$$

By substituting the fixed wages into the objective function, we can derive

$$a - b(t_{01} - t_{11}e_1 + t_{02} - t_{12}e_2) - \frac{\overline{\theta}e_1^2}{2} - \frac{e_2^2}{2} - \frac{1}{2}\rho\beta_1^2\sigma_1^2 - \frac{1}{2}\rho\beta_2^2\sigma_2^2,$$

which is decreasing in β_1 and β_2 and concave in e_1 and e_2. Thus, the project manager would set both β_1 and β_2 to zero for getting a maximum profit. Besides, we can yield the contractor's optimal effort levels $e_1 = bt_{11}/\overline{\theta}$ and $e_2 = bt_{12}$ by using the first-order condition. Following the determinate individual rationality constraints which are binding, the corresponding optimal fixed payments α_1 and α_2 for the contractor can be derived immediately. The proof of the proposition is complete.

Proof of Proposition 6. Similar to the Proof of Proposition 5.

Proof of Proposition 7. The result is derived directly by comparing the project manager's profits which are shown in Corollaries 1-4.

Proof of Proposition 8. The result is derived directly by comparing the project manager's profits which are shown in Corollaries 3-6.

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