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Information systems outsourcing projects as a double moral hazard problem

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ABSTRACT

In the past two decades many organizations have turned to other organizations to satisfy their information systems needs. Information systems outsourcing arrangements cover the spectrum from agreements involving the delivery of all information services to those providing specific services such as systems development, communications management, desktop computing provision and maintenance, and so on.

In this paper we model information systems outsourcing arrangements as a non-cooperative game with two players: a company and an outsourcing vendor. The game between the two players has an inherent double moral hazard problem as the success of the information system outsourcing project depends on the actions of both players, which are costly for them and are not directly contractible. Both parties make their decisions taking into account the effects that these decisions have on the other player's actions. In our analysis, we compare the solution obtained without a moral hazard problem (the first-best solution) to the one obtained under a double moral hazard setting (the second-best solution). We demonstrate some results based on the assumption that increases in the productivity of the vendor lead to increases in the productivity of the company. Further we establish that outsourcing contracts should provide no separate payment for failure to the outsourcing vendor although effectively many of them do. We also provide a sharing rule for providing appropriate incentives for the vendor and examine the dynamics associated with this sharing rule. Finally, we further provide for the characterization of response functions and the ensuing Nash solution including the optimal outsourcing fee. This allows for the nuanced consideration of the degree of interaction between the effort of one party and the productivity of the effort of the other party. This particular interaction has not been explored formally in the extant research literature.

1. Introduction

Information services (systems) outsourcing occurs when an organization contracts with another organization for the provision of some or all of its information service needs. Such needs may include the provision of new applications systems, the complete overhaul of the organization's information infrastructure, or simply running the organization's present information systems. Since many information services are difficult to assess and are delivered over an extended period of time it is difficult to ensure that the outsourcing vendor (henceforth simply 'vendor') acts in the best interest of the outsourcing company (henceforth simply 'company'). There are a variety of responses that are appropriate in this type of situation. One approach is to design incentives so that the vendor will be motivated to act in best interests of the company.

Over the past two decades considerable attention has been directed towards the outsourcing phenomenon in general and the information services outsourcing phenomenon in particular (for an excellent review of the IT outsourcing literature over the last two decades see [1]). Michell and Fitzgerald [2], for example, describe the selection process of the IT outsourcing vendor. A variety of authors have discussed, in general terms, the relative advantages and disadvantages of outsourcing. Early on, Gupta and Gupta [3] argue that outsourcing can lead to a reduction in costs but may also lead to a loss of control and an uncertain level of service. In a similar vein Kelly [4] argues that, in addition to the factors identified by Gupta and Gupta, outsourcing may lead to a loss of strategic direction for the company. Fink [5] discusses the security and control considerations in information systems outsourcing. In a later work Aubert et al. [6] state that "Some argue that outsourcing IT leads to lower costs, economies of scale, access to socialized resources, and new business ventures." (p. 4)

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Aubert et al. [6] further identify a variety of risks associated with outsourcing including hidden costs, contractual difficulties, service debasement, and loss of organizational competencies. A much more extensive review of research investigating benefits associated with outsourcing is provided by Dibbern, Goles, Hirschheim, and Jayatilaka [26]. Clearly the nature and significance of the benefits and risks associated with outsourcing are contingent on both the nature and the range of activities which are outsourced.

Papers directed towards the theoretical analysis of the economics of outsourcing span about the same period as those addressing the outsourcing phenomenon in general. However, typically this research is presaged by seminal work in the economics domain. Information system outsourcing represents a stylized setting where creation of a good or service is outsourced to one individual or organization by another independent individual or organization. To the extent that efficient markets exist these transactions are relatively uncontroversial. However, when it is difficult to specify ex-ante the specifications for the product or service and there are significant uncertainties associated with the development of the product or service, and associated costs, outsourcing may become challenging.

Williamson [7] recognized that prior work in classical economics did not provide an explanation as to why transactions would be performed within the organization rather than mediated through the market. As such, his work on transaction cost economics (TCE) recognized the potential existence of opportunism on the part of the individual, or organization, providing outsourcing services and the need for monitoring to reduce the likelihood of opportunistic behavior. Clearly *sans* monitoring TCE faces significant information asymmetries.

Recently Jiang et al. [8] have utilized a real option-based approach to investigating a generic outsourcing situation (in their case related to the Beijing Olympic Games). This approach has not, however, been focused on information systems outsourcing even though Jiang et al.'s analysis embraces two key characteristics of information systems outsourcing namely uncertainty and rapidly time-sensitive costs.

An alternative modeling approach involves the principle/agent approach with information asymmetries. In the following section we will review the research literature that represents previous examples of attempts to use economics derived models of information systems and indicate the location of our research in the domain.

2. A review of the research literature

2.1. The information systems and economics literature

One of the first papers to attempt to develop an economic framework for analyzing outsourcing contracts is Richmond et al. [9]. Their analysis uses the concept of incomplete contracting and focuses on systems development. It differentiates between a user group and a development group that may be located in the same organization (in-sourcing) or in a different organization (outsourcing). In contrast with our approach, they use simulations, instead of closed-form solutions, to investigate whether in-sourcing dominates outsourcing. They note that while in some cases in-sourcing dominates outsourcing this is not always the case.

Wang et al. [10] provide a formal analysis of contractual structures for custom software developments though without explicitly representing double moral hazard. They also consider a somewhat more nuanced consideration as to the nature of in-sourcing by introducing central management as a communications mediator and budget balancer. As with earlier work modeling the systems development process, they use a two-stage model. In their subsequent analysis the authors both provide intuitions derived from their formal modeling approach and also numerical analysis. They demonstrate a mechanism that can achieve the first-best solution for internal sourcing in situations where there are information asymmetries between the user group and the development group. They further note that in order for outsourcing to dominate internal sourcing the external developer must have considerable cost advantages.

As we have indicated above one common approach to modeling situation where one party develops a product or service for another is the principal/agent model. In the first instance it would appear that the challenge for the principal is that the agent may not exert optimal effort. Thus, this approach incorporates a single moral hazard dimension to outsourcing. Elitzur and Wensley [11] utilize a principal/agent game-theoretic approach to model information systems outsourcing arrangements. Their approach makes the traditional assumptions with respect to the principal/agent model. Their study focuses on designing contracts to deal with two types of moral hazard—one relating to the effort expended by the outsourcing vendor in providing the outsourced service and one relating to the outsourcing vendor's potential use of confidential information for his own benefit. They further establish a variety of propositions with respect to optimal contract characteristics in this situation.

Whang [12] has also investigated the outsourcing of information systems development from an economic perspective. In particular, he models information systems development as a multi-stage process. However, Whang [12] does not take into account important uncertainties with respect to the development project relating to changing requirements and the revision of estimates of the cost and value of the development project. Further, given the analytic approach adopted by Whang [12], he is unable to take into account information asymmetries or moral hazard issues that arise as a result.

Subsequent to Richmond et al. [9] and Whang [12] a considerable body of literature has grown up that addresses the application of many different research approaches to many different aspects of the outsourcing phenomenon.

Interestingly, in spite of an increasing body of research literature focused on the outsourcing phenomenon few researchers have extended game-theoretic modeling approaches along the lines initiated by Richmond et al. [9] and Elitzur and Wensley [11] who, as noted above, investigated a situation involving information asymmetries and, in the latter case, single moral hazard issues that arise as a result of these asymmetries.[1] Neither has the information systems research literature explored the nature and impact of information asymmetries further in a principled way or focused further on moral hazard issues arising from such information asymmetries.

2.2. A focused review of the economics literature addressing double moral hazard

One of the main directions for the development of principal/agent models of information systems outsourcing would be to investigate situations where double moral hazard is likely to occur. We provide a more extended rationale for this later on when we introduce the particular model but, in essence, information systems outsourcing arrangements are characterized by the fact that both parties exert effort that is unobservable by the other party. This gives rise to a

[1] An extensive review of this literature can be found in Dibbern et al. (2004). However, as we have noted, in their classification only papers by Richmond et al. [9], Whang [12], and Elitzur and Wensley [11] are referred to in the context of extant research having a 'theoretical economic approach'.

setting where the parties involved not sharing the same information in relevant respects. Given that the quality of the resulting system depends on the effort expended by both parties such information asymmetries potentially result in a situation characterized by double moral hazard. The economics research literature provides a rich stream of research that investigates information asymmetries in a wide variety of different contexts and has provided insights into single and double moral hazard in many different areas. Of particular relevance to the analysis presented below, focused on the nature and impact of double moral hazard on information systems outsourcing, is work investigating double moral hazard and its impact on contractual relationships in general [13], warranty provisions [14], professional services [15], sharecropping and franchising [16], joint production projects [17], and management consulting/professional services [18]. We review each of these contributions separately below. Our intention in the following section is to review some of the related economic literature, which addresses the issue of double moral hazard and indicate the location of our research in the domain. Although the economic literature reviewed below does not investigate the phenomenon of information systems outsourcing the stylized approaches could well be applied to information systems outsourcing.

Cooper and Ross [14] develop a principal/agent model, which provides for double moral hazard in order to investigate the structuring of warranties. As with the traditional stylized approach, double moral hazard arises as a result of unobservable effort by both parties when the efforts of both parties are positively related to the quality of performance of the product. One interesting feature of Cooper and Ross's approach is that they provide a framework for investigating the interaction between the effort expended by the manufacturer of the product and the effort expended by the user of the product in maintaining the product and using it appropriately. Cooper and Ross [14] provide a variety of qualitative results but, in contrast with our work, they do not investigate the structure of optimal contracts. We note below that we have adapted Cooper and Ross's approach since it provides a way of stylizing the information systems outsourcing situation, which is both more nuanced that previous analyses and therefore potentially provides more insight.

In later work addressing double moral hazard the focus is on the nature of optimal contracts. For example, Bhattacharyya and Lafontaine [16] investigate both formally and empirically situations involving double moral hazard and revenue/profit sharing using simple linear sharing rules. It is interesting to note that they derive a result from their formal analysis that the optimal share function is a function of the exponents of the technology production function and the disutility-of-effort functions of the parties involved assuming a Cobb–Douglas production function. As will be noted below, our analysis, in contrast, implies that the optimal contract in a double moral hazard situation will have a fixed fee of zero and a markedly different sharing rule as suggested by Bhattacharyya and Lafontaine.

Agarwal [13] develops a two-stage model wherein both parties are risk averse and agree to an enforceable contract with terms addressing how the outcome of their joint action is to be shared and a fixed payment. The second stage of the model involves both parties choosing a level of effort and a monitoring regime. Agarwal [13] establishes that when mutual monitoring is allowed, share contracts may not be the only type of contracts that can be optimal. He further shows that when the outcome cannot be observed by one of the parties, the optimal contract will involve a fixed payment to that party. We would note that the assumption of risk aversion is likely to be less supportable in the case of information systems outsourcing than in the general share contracts that Agarwal [13]is seeking to model.

Kim and Wang [17] consider a setting where a principal hires an agent to undertake a joint project governed by a wage contract established by the principal. They provide an extensive model-based analysis of a double moral hazard problem where the agent is risk averse while the principal is risk neutral. They note that in this situation, where the agent is risk averse, the optimal incentive contract is non-linear. They further note that a linear contract is not optimal as the agent's risk aversion approaches zero. However, as we have noted above, in the case of information systems outsourcing the market tends to be dominated by relatively few outsourcing organizations and hence it would seem appropriate to assume that both agent and principal are risk neutral.

Homburg and Stabel [18] analyze professional service agreements where they note that:

> [T]he details of the required service are often unclear at the beginning and many relevant details are thus not conclusively established when a project commences. Contracts are therefore frequently incomplete with respect to the service output as well as to the input of the contracting parties. (p. 130)

and further note that:

> [B]ecause of their complexity and intangibility, it is often difficult to observe the effort of a contracting party and to define verifiable performance measures for evaluating the service output. (p. 130)

Homburg and Stabel [18] primarily investigate a number of empirical hypotheses with respect to whether the contract between the professional service provider and the professional service consumer is performance-based (variable-cost) or outcome-based (fixed cost). Generally speaking, the data they analyze provides support for the proposition that the less verifiable the agent's performance the more likely the contract between professional service provider and professional service consumer is an outcome-based (fixed cost) contract. They also note that when it is the case that reputation and trust can be developed between professional service provider and professional service consumer, moral hazard problems are mitigated. As we have noted above, reputation may have a limited effect on the extent of double moral hazard problems that may arise in an information systems outsourcing context. We might also note that the knowledge and experience that may be offered by the types of professional service firm investigated by Homburg and Stabel [18] may be significantly more structured, coherent, and generally agreed to than that relating to information systems outsourcing.

Another stream of research is represented by Sharma [15] who identifies ways in which moral hazard problems may be mitigated. He provides a detailed qualitative analysis of professional service relationships with particular emphasis on knowledge asymmetries. One of the overall objectives of his analysis is to demonstrate ways in which such relationships may be analyzed using methods derived from the principal-agent and ways in which characteristics of such relationships do not conform to assumptions underlying the principal-agent analyses. In particular, he argues that opportunism may be mitigated through non-contractual aspects of professions, such as reputation. This research has potential applications to information systems outsourcing though it is appropriate to note that reputation seems to have only a limited currency in information systems outsourcing since often large outsourcing firms continue to win large outsourcing contracts even when a significant number of their earlier outsourcing agreement have ended in partial or complete failure. It would also appear that one of the effects of such failures is to adopt different contract structures such as those linked explicitly to the value added by the outsourced system to the company contracting for the system.

The analysis presented in this paper considers outsourcing as a more general case of the agency problem including elements of asymmetric information and moral hazard. In particular, we argue that the success of the outsourcing relationship depends not just on what the vendor does but also on the company's mission critical actions.[2] As the actions that should be taken by the company are costly, and not directly contractible (as are the vendor's actions), the setting entails a double moral hazard situation. This injects an element of reality to the setting that results in a richer model than the one described by Elitzur and Wensley [11], which is considered as a one-sided moral hazard only. That is, their analysis considered the moral hazard associated with misrepresentation by the outsourcing vendor. The approach presented in this paper, considering, as it does, the moral hazard arising as a result of interactions between the company and the vendor is consistent with the conclusions reached by Bahli and Rivard [19] who confirmed that the nature of the client and supplier are important factors to be considered when assessing IT outsourcing risk. Clearly, a significant area of risk with respect to both the supplier and client is the failure to exert optimal effort during the outsourcing relationship. While previous studies such as Gavious and Rabinowitz [20] consider the dynamics of the mechanism of outsourcing, the analysis in the current study considers the strategic behavior of the players and its impact on the specification of appropriate optimal contracts between the parties.

In the following section we present a discussion of the background for the analysis. This is followed by a section describing the model that we propose to analyze. The model is then analyzed in detail and various results presented. This section is followed by a section that provides a comparison of first-best solutions and second-best solutions. The penultimate section investigates an approach to linking the analysis provided in this paper with transaction cost economics. The final section provides a summary and a discussion of conclusions.

3. Background

Game theory provides a framework to investigate different approaches to ensuring that arrangements between two parties are as efficient as possible. We assume that in outsourcing arrangements parties act in their own best interests. Thus, the parties will only cooperate when it benefits them. Given that outsourcing vendors and companies are generally independent arm's-length entities this seems to be a reasonable assumption.

Outsourcing arrangements usually involve the parties making sequential moves. For example, in the case of a consummated outsourcing arrangement, the outsourcing company requests that the outsourcing vendor submit a bid; the outsourcing company accepts the bid; and then the outsourcing vendor provides a service or a portfolio of services. Finally, outsourcing arrangements are usually made between parties who have access to different information sets. Thus information is not symmetric; it is rather asymmetric. The essence of asymmetric information is that one party has useful private information that is not directly available to the other party in the arrangement. As indicated above, one of the first studies to use a double moral hazard perspective is Cooper and Ross [14], which examines the implications of double moral hazard for warranties. As such, in contrast with Cooper and Ross [14], who focus on the failure of a product and a warranty to insure against it, our model focuses on an information systems outsourcing situation where the effort expended by the company in providing accurate information and requirements to the vendor and the effort expended by the vendor in providing the service or building the system to meet the company's requirements where rather than addressing it considers a situation where we consider. Our approach, with its recognition of the double moral hazard inherent in outsourcing contracts is consistent with Willcocks and Lacity [21] who argue that one of the risks of information systems outsourcing is "lack of active management of the supplier on contract and relationship dimensions" (p. 164). That is, in managing the relationship between the vendor and the company it is important to recognize moral hazard relating to the behavior of both parties. Furthermore, the approach here attempts to capture some of the aspects of the interaction approach to information systems outsourcing that was suggested by Kern and Willcocks [22,23].

As we have noted above, our model, in contrast to Cooper and Ross [14] is specifically tailored to the outsourcing setting that embeds the germane aspects and variables pertaining to this setting. It also differs from that of Bhattacharyya and Lafontaine [16] in making no assumptions about underlying production functions and from [18] in allowing for the explicit modeling of the existence and extent of 'integrativity' between the effort expended by the provider of outsourcing services and the consumer of these services.

4. The model

We consider the case where a company contracts with an outsourcing vendor (henceforth, vendor) to develop a particular information system application or set of applications. The quality of the application is represented by the variable q which is a decision variable for the vendor. The cost of quality for the vendor is a function $C(q)$. The cost function, $C(q)$, includes development costs as a fixed cost. The effort that the company expends e, in working with the outsourcing vendor costs the company $S(e)$. In essence, e, captures what Willcocks and Lacity [21] would call "… active management of the supplier on contract and relationship dimensions" (p. 164). We assume that $C(q)$ and $S(e)$ are strictly increasing, twice continuously differentiable and convex. Since the application directly and critically supports the business, the probability of the supported business being successful, π, is a function of the quality of the software and the level of effort made by the company (i.e., $\pi(e,q)$). One could argue that, as opposed to what we stated above, the choice of e and q should not be independent and indeed, as we use a game-theoretic approach, the choices of e and q interact through the response functions of the players that will be explored in the Moral Hazard Setting section below (Section 5.2). As such, this interaction is achieved not directly but through the response functions, which is a limitation of this model.

We further assume that the probability of success, π, increases in e and q, i.e., $\pi_e > 0$ and $\pi_q > 0$. In essence, the model states that each party's effort will increase the probability of success but, at the same time, this effort is costly and thus each player could shirk in effort relying on the other player's effort ('the free rider' or moral hazard problem, in this case a two-sided one). In the following analysis we assume that the sign of the cross derivative π_{eq} is positive.[3] This assumption essentially states that if the vendor improves the quality by building a system with

[2] Homburg and Stebel [18] refer to the property of 'intergrativity' in the context of professional service provision. Integrativity may be interpreted as the extent to which the productivity of the effort expended by the provider of outsourcing services is dependent on the effort expended by the consumer of outsourcing services. We would note that, in our analysis, integrativity is explicitly modeled.

[3] That is, the marginal productivity of effort is positively influenced by an increase in q and vice versa.

extensive functionality then the company's benefit from investing more effort communicating with the vendor to achieve this functionality is increasing. Thus, actions that result in improving the productivity of the vendor also improve the productivity of an additional effort made by the company. Similarly, if the company provides the vendor with extensive access to company personnel, business processes and documentation, then the vendor is better off by providing higher quality to maximize his payoff. This would seem to be a common situation. We further assume that π is concave with respect to e and q. Further, we assume that if the business is successful the company gains a payoff of H while if it is not successful the associated payoff is L where, $L<H$.

Let us assume that the company pays the vendor a flat fee W and in addition an amount P for success and G for failure.[4] The time line of the resulting game is as follows:

1. The company writes a contract outlining W, P, and G.
2. The company and vendor, simultaneously and independently, set e and q, respectively.
3. The outcome of outsourcing is realized: success or failure
4. The players receive their payoffs.

We consider two concepts of solution; first-best and second-best.

The first-best solution represents the case of vertical integration, the vendor is actually internal to the company and thus, quality is observable.[5] Consequently, this situation has no moral hazard and the payment to the vendor, an internal department, is just enough to cover its costs. In this case, both the quality and effort are decision variables of the company and, thus, it is able to maximize its payoff with respect to both.

Outsourcing, as opposed to vertical integration, falls into a second-best solution, where the vendor is an independent company and the quality of the services provided, q, is unobservable by the company. Similarly, the effort exerted by the company with respect to the information system being outsourced, e, is unobservable by the vendor. Thus, only the company knows the value of e and only the vendor knows the value of q. Although both parties know at the end of the game whether the project is a success or a failure, neither one can determine *ex-post* the level of effort (quality) made by the other player. Consequently this setting embeds a double moral hazard situation. This situation is more complex than the first-best situation and includes two main stages. In the first stage the company sets the contract, i.e., the payment to the vendor for a failure, or, alternatively, for a success. In the second stage both parties, simultaneously exert effort and provide quality. While in the first-best case the solution is obtained by solving an optimization problem, in the second-best situation we use the backward induction technique to find the sub-game perfect Nash equilibrium. Backward induction, which is also known as 'rollback', is a widely used technique in game theory. In this technique players begin by thinking about what will happen at the last stage of the game, and then roll back through the game tree to the initial stage. As such, this reasoning by players involves working backward one step at a time (for additional reading on the techniques please see, for example, [24]).

In this study, given P, G, and W, the players set e and q. Consequently, the equilibrium strategies are a function of these parameters and, thus, given the equilibrium strategies in the second stage, the company sets P, G, and W in the initial stage such that the ensuing e and q will maximize the company's expected utility.

We assume that both players are risk neutral and maximize their expected net payoffs. The expected payoff for the company, U, is defined as follows:

$$U=\pi[H-P]+[1-\pi][L-G]-W-S(e) \tag{1}$$

Thus, the expected payoff for the company, U, is composed of the expected payoff from success, $\pi[H-P]$, plus the expected payoff from failure, $[1-\pi][L-G]$, less the constant fee, W, and less the cost of effort for the company, $S(e)$.

The expected payoff for the vendor, V, is defined as follows:

$$V=\pi P+[1-\pi]G+W-C(q) \tag{2}$$

Thus, the expected payoff for the vendor, V, is composed of the expected payment for success, πP, plus the expected payment for failure, $[1-\pi]G$, plus the fixed fee, W, and less the cost of quality, $C(q)$.

Another assumption that we make is known in the game theory literature as the 'Individual Rationality' assumption. Under this assumption, players will not play unless their expected payoff exceeds a certain reservation payoff, or at the very least zero. If the minimum reservation payoff is defined as V_0 then this assumption may be formalized in the following manner:

$$V \geq V_0$$

The value of V_0 is dictated by the market for the service supplied by the vendor and represents the minimum amount of profits the vendor can expect in this project.[6]

Next, we explore the properties of optimal payments for outsourcing in a setting with no moral hazard (leading to a first-best solution) and a then in a setting with double moral hazard (leading to a second-best solution).

5. Solution

5.1. The first-best solution

We start from the setting without any moral hazard that leads to the first-best solution. Under this setting the company can monitor perfectly the quality of the information system and, thus, would pay only $C(q)$ to the vendor. This is quite intuitive because if the vendor is an internal department of the company there is no need to pay a profit margin over and above the cost of the system. In the first-best case there is no outside payment and thus the first-best solution will have the aggregate payoff as follows:

$$R=U+V=\pi H+(1-\pi)L-S(e)-C(q) \tag{3}$$

Under the first-best solution, the company maximizes R with respect to e and q, which leads to the following first-order condition with respect to e (we use subscript for derivative, i.e. $(\partial R/\partial e)=R_e$)

$$R_e=\pi_e[H-L]-S_e(e)=0 \tag{4}$$

Similarly, the first-order condition with respect to q will be

$$R_q=\pi_q[H-L]-C_q(q)=0 \tag{5}$$

Eqs. (4) and (5) imply the following conditions:

$$\frac{\pi_e}{\pi_q}=\frac{S_e(e)}{C_q(q)} \tag{6}$$

Condition (4) above states that if there were no moral hazard the company would set its effort at the level where its benefit

[4] Payment for failure is included for the sake of generality. We show later that the optimal payment for failure is zero. Thus, we show it endogenously rather than assume it.

[5] It is worth observing that, even in the case of internal development, quality may not be observable or easily determined by the users of the system. We do not address this complication in this paper, however.

[6] For the sake of simplicity, we can assume with out limit of generality that $V_0=0$. This assumption does not change the analysis or the results.

from the marginal unit of effort, $\pi_e[H-L]$, is equal to the marginal cost of effort, $S_e(e)$. Similarly, condition (5) above implies that the vendor (which in this case is an internal department with no moral hazard) will choose the level of quality at the point where its marginal benefit from quality, $\pi_q[H-L]$, is equal to the marginal cost of quality, $C_q(q)$. Furthermore, observe that condition (6) implies that e and q should be at the point where the ratio of marginal probabilities of success, π_e/π_q, is equal to the ratio of marginal costs, $S_e(e)/C_q(q)$.

5.2. The double moral hazard setting

In this section we derive the equilibrium to the game where the two parties are independent entities and act in their own best interest. Since actions (i.e., e and q) are costly for both players and are unobservable, the game that takes place has an inherent double moral hazard problem. This setting also recognizes the fact that the success of the information system hinges not only on the quality of the system delivered by the vendor but also on the effort invested by the company providing requirements, interacting with the vendor and so forth.

Using the backward induction method, we first solve the competition stage (the last stage) when P, G, and W are known and then, given the equilibrium, we solve for the optimal P, G, and W in the previous stage (the contracting stage). However, we can show immediately that the flat wage, W, has no influence on the level of quality chosen by the vendor.

Lemma 1. *The fixed payment, W, does not affect information systems quality, q nor level of effort e.*

Proof. Differentiating the vendor's expected utility with respect to q shows that q is independent of W. Similarly, differentiating the company's expected utility with respect to e shows that e is independent of W. □

Lemma 1 indicates that whether the contract specifies a very small or a very large fixed outsourcing fee does not influence at all the inherent choices by both parties and, consequently, will not have effect on the likelihood of success. Thus, the only possible reason to have a set W is to guarantee the vendor his minimum level of payoff. As such, we can assume that $W=0$ in our subsequent analysis to get more elegant solution without changing the result.

Next, we derive the response function for both players given P and G. Subsequently we determine the optimal values of P and G.[7] The company finds for each possible level of q the e that maximizes its payoff and the vendor finds for each possible of e the q that maximizes his payoff. This procedure generates two best response functions where the intersection of them yields the level of effort and quality in equilibrium e^* and q^*. In equilibrium the best level of effort by the company given q^* is e^* and vice versa. Thus, given q the company maximizes its expected payoff, U, with respect to e. Hence, the first-order condition for the company is given by

$$U_e = \pi_e[H-L-P+G]-S_e(e) = 0 \tag{7}$$

Similarly, the vendor maximizes his expected payoff, V, with respect to q and given e:

$$V_q = \pi_q[P-G]-C_q(q) = 0. \tag{8}$$

Generating a solution to Eqs. (7) and (8) yields the best response functions for both players, namely, a function, $e=e(q)$, and another function, $q=q(e)$. In essence, the best response function for the company represents the amounts of effort that are required to maximize the payoff to the company for different levels of quality delivered by the vendor. Similarly, the best response function of the vendor represents the levels of quality required to maximize his payoff for different levels of effort exerted by the company. The point where the two response functions intersect represents Nash equilibrium for the game concerned.

It is appropriate to note at this stage of the paper that this is the first time that any analysis of outsourcing arrangements has considered explicitly and analytically the potential interaction between the effort of the developer and the effort of the user.

Proposition 1. *The response functions of the players $e(q)$ and $q(e)$ are monotonically increasing.*

Proof. See the Appendix.

Proposition 1 indicates that the response functions will be upward sloping. In other words, a choice of the effort by the company increases in response to an increase in the quality provided by the vendor and vice versa. This result provides an interesting and unexpected insight on the dynamics of the game between the company and the vendor. This relationship is depicted in Fig. 1:

e^* and q^* in Fig. 1 correspond to the Nash equilibrium values for e and q since they represent the combination of e and q at the intersection of the response functions of both players that maximize the payoffs for both parties.

The response function may change due to technological changes. For example, there may be a technological improvement such that the cost of producing quality is reduced (in the sense that every additional unit the marginal cost is lower than previously). In this case we have a new cost function $\hat{C}(q)$ such that $\hat{C}_q < C_q$ for every q. As we can see from (8) this will increase q for any given e. Thus, the response function in Fig. 1, $q(e)$, will shift to the right and the new equilibrium levels of e and q will be higher (see Fig. 2). Similarly, for the cost of effort $S(e)$, an improvement in the organization's ability to absorb new technology or provide accurate and actionable requirements to the vendor will lead to a shift in the response function $e(q)$ upward ending with a higher level effort in equilibrium (see Fig. 3). Thus, we have shown that improvements in technology or improvements in the ability of organizations to absorb new technologies or generate accurate and appropriate requirements with less effort lead to both increases in q and also increases in e. Thus, as each party's effort becomes more productive so does the other parties. This would seem to be a reasonably common situation in the information systems domain but would warrant further investigation.

We leave a more extensive analysis of the behavior of response functions to subsequent research. Suffice it to say that we feel

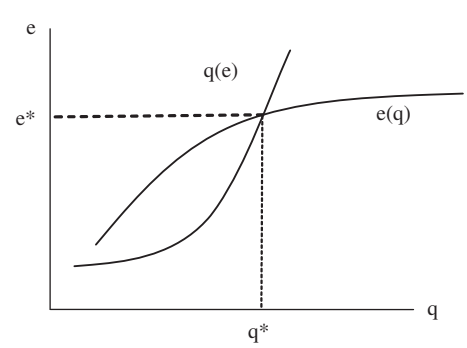

Fig. 1. The Nash equilibrium of the game between the vendor and the company as an intersection between the players' best response curves.

[7] Note that the equilibrium in this simultaneous stage is equivalent to the solution of Cournot competition.

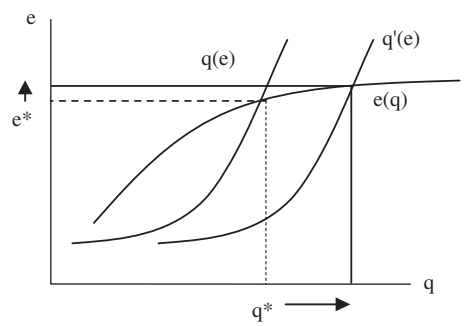

Fig. 2. The effects of technology's cost reduction on the game's equilibrium.

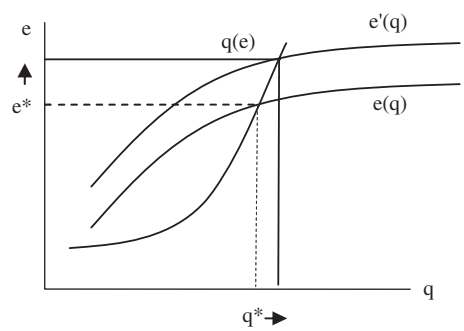

Fig. 3. The effects of improvement in the company's ability to absorb new technologies on the game's equilibrium.

they provide a tool for investigating some of the important interdependencies that obtain in information systems outsourcing and are worthy of further study.

Returning to the main theme of the paper—from (7) and (8) we find that the equilibrium levels of quality and effort are functions of $(P-G)$ and $(H-L)$.

Proposition 2. *Under the optimal contract for the company there should be no payment for failure, i.e.,* $G=0$.

Proof. See the Appendix.

The intuition behind Proposition 2 is that payment for failure results in a decrease in the quality of the information system provided by the vendor and, in turn, this payment decreases the company's payoff (since both response functions are monotonically increasing, as shown in Proposition 1 above). Proposition 2 shows that there will be no advantage in providing compensation by the company to the vendor for failure. This is an interesting insight since many outsourcing contracts actually result in failure or only partial success particularly those involving complex requirements and/or involving multiple service providers or customers. To reiterate, no outsourcing contract of this type should include the provision of any payment should the implementation of the information system fail. Consequently, Proposition 2 indicates that the outsourcing fee should essentially be solely performance based. This may also be problematic in the case of large, complex outsourcing arrangements where there may be a need for interim payments however, as noted in our analysis; such payments will lead to the development of lower quality systems. We note that this result differs from the result obtained by Bhattachrayya and Laforntaine [16] but is broadly consistent the hypotheses investigated by Homburg and Stabel [18].

If the equilibrium effort and quality (the intersection between the response function given by (7) and (8)) as functions of P, the payment to the vendor, are denoted as $e^*=e^*(P)$ and $q^*=q^*(P)$. We can now characterize the value of P.

Proposition 3. *The optimal payment to the vendor, P, satisfies the following property*:

$$P=H-L-\frac{\pi}{\pi_q q_P^*} \tag{9}$$

Proof. See the Appendix.

Proposition 3 leads to an intuitive profit sharing rule (or, as it is sometimes referred to, benefit sharing), $H-L=P+(\pi/\pi_q q_P^*)$. This sharing rule states that the difference in payoffs between success and failure, $H-L$, is shared by the vendor, who gets P, and the company, which gets, $\pi/\pi_q q_P^*$. The company's share of the success premium, $H-L$, is the probability of success, π, divided by the marginal effect on π due to a change in P, $\pi_q q_P^*$. As such, if, for example, the impact of an increased P on the probability of success, $\pi_q q_P^*$, is miniscule then the firm's share of the success premium will be large and the vendor's share will be relatively small. If, on the other hand, the influence of an increased P on the probability of success, $\pi_q q_P^*$, is substantial then the firm's share of the success premium will be relatively small and the vendor's share will be relatively large. The practical implication of this sharing rule is that the more mission critical the outsourced information system, i.e., having a large π_q, leading to a large $\pi_q q_P^*$, the company will take a smaller share and the vendor a larger share of the success premium, $H-L$. We may further interpret this result as indicating that the more critical a system is to the survival of the company then the greater proportional incentive the vendor is provided with.

We would note that the above result is significantly different from that obtained by Bhattacharyya and Lafontaine [16]. Their result is based, among other assumptions, on the assumption of the outsourcing vendor and company's production functions being in the form Cobb–Douglas production functions. Our model makes no explicit assumption as to the nature of production functions and allows for the more nuanced investigation of the interaction between the productive effort entered into by the outsourcing vendor and by the outsourcing company.

6. A comparison between the first-best and second-best solutions

In this section we compare the first- and second-best solutions. It is well known that the second-best solutions generate lower level of efforts by the players. We provide a formal proof of this.

Proposition 4. *The equilibrium level of effort and quality in the second-best solution is lower than in the first-best solution.*

Proof. See the Appendix.

In Eqs. (4) and (5) above (repeated below), the first-order conditions, under a first-best solution, for both players are:

$$\pi_e[H-L]=S_e(e) \text{ and } \pi_q[H-L]=C_q(q) \tag{10}$$

On the other hand, the first-order conditions, under the second-best solution (Eqs. (7) and (8) which are repeated below) are as follows:

$$U_e=\pi_e[H-L-P]-S_e(e)=0 \text{ and } V_q=\pi_q P-C_q(q)=0 \tag{11}$$

From (9) it follows that in the second-best solution the following occurs:

$$P<H-L \tag{12}$$

Using (12), we can represent Eqs. (10) and (11) in graphical form. Fig. 4 below depicts the choice of optimal e by the company

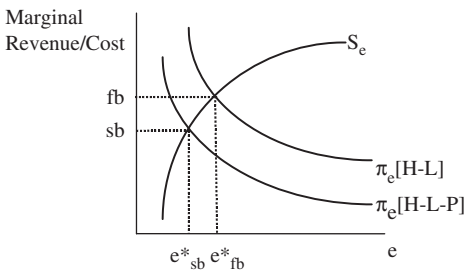

Fig. 4. Comparison of equilibrium effort e^* under first-best and second-best solutions.

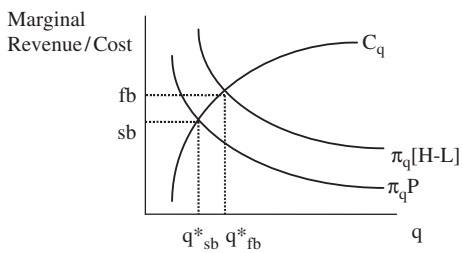

Fig. 5. Comparison of equilibrium effort q^* under first-best and second-best solutions.

under the first-best (fb) compared with the second-best (sb) solution. The graph shows clearly that the optimal e is lower under the second-best solution than under the first-best. Further, the payoff is also lower under sb than fb.

Fig. 5 below depicts the choice of optimal q by the vendor under the first-best (fb) compared with the second-best (sb) solution. The graph clearly shows that the optimal q is lower under the second-best solution than under the first-best. Again the payoff is lower under sb than fb.

7. Information systems outsourcing vs. internal sourcing

If, as shown above, internal sourcing of information systems leads to a first-best solution and outsourcing to a second-best solution why would a company ever outsource its information systems? The answer, as shown below, stems from the fact that the ensuing first-best solution in the case of internal sourcing will not be the same as the first-best solution under outsourcing if the cost of quality $C(q)$ is different under internal sourcing compared to outsourcing.

Define $C^{is}(q)$, $C^{os}(q)$ as the total cost of quality under internal sourcing and outsourcing, respectively. Also, define q_{is} as the q associated with internal sourcing (the related first-best solution), q_{os} as the outsourcing first-best q, and q_{sb} as the outsourcing second-best q. If the marginal costs of q, $C^{os}_q(q)$ is substantially lower than $C^{is}_q(q)$ then the ensuing q_{is} will be as follows:

Fig. 6 above demonstrates that if the marginal cost of producing q is greater under internal sourcing than under outsourcing then, even though we have a second-best outsourcing solution, the company is better off than the first-best internal sourcing solution (q_{is} is below q_{sb}). This is an important result, which has not been demonstrated analytically previously in the information systems outsourcing literature. As we have noted, outsourcing under double moral hazard leads to a second-best solution, which is inferior to a first-best solution. However, if the marginal costs of the vendor are less than the marginal costs of the company the resulting second-best solution is potentially better than the first-best solution.

What is particularly interesting is that this analysis provides a link between the game-theoretic analysis and transaction-cost

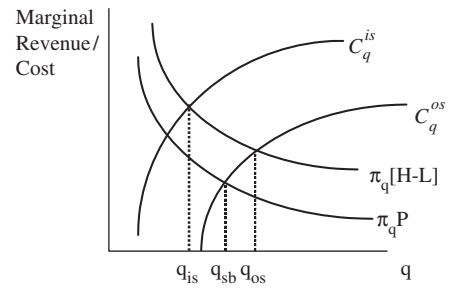

Fig. 6. Comparison between outsourcing and internal sourcing.

analysis in the context of outsourcing information systems. The practical implication is that there are clearly situations in which the production efficiencies of the outsourcing vendor (for example, due to economies of scale) outweigh the disadvantages associated with managing outsourcing relationships. This finding is also consistent with Lacity et al. [1] who state:

> For nearly 20 years of ITO [Information Technology Outsourcing] research, client firms have primarily pursued outsourcing as a way to reduce ITO costs. Cost reduction drove domestic ITO decisions in the 1990s and continues to drive both domestic and offshore outsourcing in the 2000s. (p. 134)

It is also worth noting that in recent years a variety of companies that had previously outsourced some or all of their information services have brought some or all of these services back in-house. This may, of course, be a result of poor levels of service provided by the outsourcing vendor but it may also reflect the presence of a variety of transaction costs that had not been taken into account in the initial negotiations of the outsourcing contract such as those associated with co-ordinating the provision of information services with other processes and activities within the company engaging in outsourcing.

8. Reprise of prior work and review of contribution

Table 1 provides a summary of the nature of previous research contributions (as discussed in the review at the beginning of the paper) and an indication as to how the research presented in this paper develops and enhances prior research contributions. The current paper uses a formal game-theoretic approach assuming risk-neutrality of both parties. We have taken into information asymmetries by adopting a model incorporating double moral hazard. The quality of the resulting system is represented through the consideration that the resulting system may have a high or low value to the user.

Reviewing Table 1 the conclusions that we reach are distinct from previous research in this area. First we establish that the optimal contract will only involve a sharing rule—there is no fixed payment, no payment for failure. The sharing rule is a function of the contribution of each party's effort to the probability of success of the resulting system; an interestingly different result than that indicated in the previous research. Further, consistent with Wang et al. [10] we establish that there can be situations where the second-best solution achievable through outsourcing may dominate the first-best solution represented by in-sourcing. Finally, we provide a nuanced approach to considering all types of interaction between the effort of both parties on the matching productivity of the other party. The nature of this interaction is considered qualitatively by Sharma [15] but our analysis represented the first time that an attempt has been made to explicitly model this relationship in the context of information systems outsourcing.

Table 1

Paper	Domain	Modeling approach	Major conclusions
Richmond et al. [9]	Systems development—enhancements	One stage—asymmetries concerning value of enhancements. Simulation approach investigating in six different scenarios relating to different values of enhancement surplus they investigate the impact of a sharing parameter α. Does not model moral hazard.	No overarching conclusion—in some cases in-sourcing dominates in others outsourcing dominates. Internal development is always preferred if the developer has an incentive to conceal the actual development cost.
Whang [12]	Systems development	Multi-stage model. Does not take into potential changes in design/requirements but does allow for information asymmetries.	Optional contract involves payment for first stage and payment for delivery or penalty for non-delivery. Indicated that a contract can be developed that will yield outcome equivalent to first-best outcome of internal sourcing.
Bhattacharyya and Lafontaine [16]	Share contracts	Game-theoretic taking into account double moral hazard and empirical component	Linear contracts can implement second-best solutions. Provides an analysis of the optimal share parameter incorporating production functions and disutility of efforts.
Sharma [15]	Professional services	Qualitative recognizing double moral hazard	Establishes how reputation and other characteristics of the professional service relationship may mitigate opportunism by either party. Provides some initial analysis of the potential interactions between interaction between the effort of both parties on productivity.
Wang et al. [10]	Custom software development	Game-theoretic—presence of information asymmetries.	Indicate how first-best solution can be achieved internally but second-best is only possible with external provider. External provider must have significant cost advantage over internal provider to dominate internal provider.
Kim and Wang [17]	Wage contracts	Game-theoretic analysis with double moral hazard	When agent is risk averse optimal contract is non-linear.
Elitzur and Wensley [11]	Information systems outsourcing	Game-theoretic model taking into account single moral hazard—closed-form solution	Primarily indicates that one-sided moral hazard leads to second-best solution and that optimal contract is a combination of fixed and variable components
Agarwal [13]	Sharecropping	Two-stage game-theoretic closed-form solution	Variety of types of optimal contract though typically of the type involving both fixed and variable components.
Homburg and Stebel [18]	Professional service contracts	Empirical and conceptual taking into account double moral hazard.	As behavior becomes more difficult to verify fixed price contracts will be preferred and a variety of other qualitative hypotheses.
Jiang et al. [8]	Outsourcing contracts	Option-based numerical modeling	When there is considerable uncertainty provides some guidance concerning the bottom line for bidding and also the decision between waiting and acting in situations where costs change over time.

9. Summary and conclusions

This paper examines outsourcing as a non-cooperative game with two players: an outsourcing company and an outsourcing vendor. The game between the two players has an inherent double moral hazard problem since the success of the information systems outsourcing project depends on the actions of both players, and these actions are costly for the player that takes them and unobservable to the other player. Both parties make their decisions in consideration of the effect these decisions have on the other player's actions. We compare the solution obtained without a moral hazard problem (the first-best solution) to the one obtained under the double moral hazard setting (the second-best solution). Our results include the characterization of response functions and the ensuing Nash solution, including the optimal outsourcing fee.

We have provided insights as to how incentive contracts may be structured in response to the double moral hazard problem. We demonstrate that optimal contracts should not include any payment for failure. We further indicate the nature of a rule for sharing the expected value of the information system being outsourced between the vendor and the company. In particular we note that the more critical the system being developed the greater the proportional share of the value added by the system is provided to the vendor. This result has not been provided in the research literature addressing information systems to date and is interesting in the context of recent statements in the literature that companies should not shy away from outsourcing their core processes and services.

We also demonstrate analytically that in situations where the marginal costs of the vendor are lower than the marginal costs of the company then the second-best solution may well be superior to the first-best solution. This situation may also be considered to represent a game-theoretic equivalent modeling of the transactions costs analysis of outsourcing.

Future directions for research include modeling the outsourcing of information systems as a multi-period game. Interesting issues may involve the dynamic setting of technology and effort by the players, 'low balling' by the vendor and other multi-period aspects of the relationship. We have not investigated any learning effects in the current paper—these present another avenue for further study.

Another interesting direction is the analysis of the reasons companies choose to outsource their information systems. This direction may be better suited for the transaction cost economics model (TCE).[8] However, it is interesting to speculate both how the company would infer that the outsourcing vendor had lower marginal costs and also how the outsourcing vendor would signal such a situation. It would also certainly be appropriate to extend

[8] See Williamson [7], for a discussion of transaction cost economics and Lacity and Poppo [25] for a recent discussion of TCE and outsourcing.

the game-theoretic analysis to account for warranties as Cooper and Ross [14] did in their earlier work.

Another fertile area for further investigation is to explore the situation where outsourcing contracts effectively provide payment for failure, which we have demonstrated is sub-optimal and leads to the development of systems of lower quality than those that would be created if there were no payment for failure. One explanation for this behavior may be as a signal to the outsourcing company that the company contracting for the outsourcing service will exert appropriate effort. However, this particular behavior would benefit from a more detailed analysis both formally and empirically.

In our analysis we have modeled the outsourcing situation in a variety of stylized ways. In particular we have considered that the information system being developed will be either of high quality, leading to an overall benefit of H, or low-quality, leading to an overall benefit of L. Clearly a more nuanced analysis of the situation would allow for the quality of the resulting information system to be a continuous variable. Such an extension of the model may, however, prove to be too complex to be tractable.

In addition, it would be instructive to investigate the nature of response functions in more detail as well as the impact of technological changes on the response functions. In this paper we have made an assumption about the interaction between the effort of the vendor and the effort of the company on the quality of the resulting information system. That is we have assumed that they are mutually reinforcing. To some extent this approach provides a formal specification of the characteristic associated with the provision of services referred to as integrativity by Homburg and Stabel [18]. It is an open question as to whether the positive interaction we have assumed always obtains. As Cooper and Ross [14] demonstrate interestingly different results are obtained in situations where there was a negative interaction or no interaction at all. It would be appropriate to investigate the nature and effect of this particular interaction in more detail.

We would also suggest that mission critical systems, in addition to having a very high 'success premium', that is a high value of $[H-L]$ also often allow the vendor to develop knowledge which may be valuably applied in other outsourcing contracts with similar clients. In these situations this additional value should be considered in the contracting model. Elitzur and Wensley [11] have considered this in the case of a single moral hazard model. It would be informative to investigate how this affects contracting in a double moral hazard situation.

Finally, following Bhattacharyya and Lafontaine [16] Homburg and Stabel [18] it would be appropriate to investigate the extent to which the conclusions of our model could be empirically verified.

Acknowledgments

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Appendix. Mathematical addendum

Proof of Proposition 1. To show that $q(e)$ is monotonic increasing with respect to e, we differentiate the first-order condition of the vendor (8) with respect to e and rearranging:

$$\frac{\partial q(e)}{\partial e} = -\frac{\pi_{qe}(P-G)}{\pi_{qq}(P-G)-C_{qq}} \tag{A.1}$$

Observe from (8) that $P>G$, else the vendor will set $q=0$. Furthermore, based on the assumptions that $\pi_{qq}<0$, $C_{qq}>0$, and $\pi_{eq}>0$ (obviously $\pi_{eq}=\pi_{qe}$), the numerator is positive and the dominator is negative. Consequently, $(\partial q(e)/\partial e)>0$. The same argument holds for $e(q)$. □

Proof of Proposition 2. Given that both the company and the vendor are playing according to the Nash equilibrium for every given P, G (recall that $W=0$), we can write the equilibrium effort and quality as a function of P and G, namely $e^*=e(P,G)$ and $q^*=q(P,G)$. From (1), the company's expected utility is given by[9]

$$U = \pi(e,q)[H-L-P+G]+L-G-S(e) \tag{A.2}$$

We show that $(\partial U/\partial G)<0$ for every P and G and thus $G=0$ is optimal for the company. Differentiating (A.2) with respect to G and P and rearranging yields

$$\begin{aligned}\frac{\partial U}{\partial G} &= e_G[\pi_e[H-P-L+G]-S_e]+\pi_q q_G[H-P-L+G]-(1-\pi)\\ \frac{\partial U}{\partial P} &= e_P[\pi_e[H-P-L+G]-S_e]+\pi_q q_P[H-P-L+G]-\pi\end{aligned} \tag{A.3}$$

From the first-order condition (7), the first component of both equations in (A.3) is zero. Next, we prove by contradiction that the optimal G cannot be positive.

Suppose that the optimal G is strictly positive then, both equations in (A.3) are binding which yields the system

$$\begin{aligned}\pi_q q_G[H-P-L+G] &= (1-\pi)\\ \pi_q q_P[H-P-L+G] &= \pi\end{aligned} \tag{A.4}$$

By dividing the first equation by the second one we have

$$\frac{q_G}{q_P} = \frac{1-\pi}{\pi} \tag{A.5}$$

Since $((1-\pi)/\pi)>0$, we conclude from (A.5) that q_G and q_P have the same sign.

Differentiate (7) once with respect to P and once with respect to G and sum these equations yields after rearranging

$$(\pi_{ee}(H-L-P+G)-S_{ee})(e_P+e_G)+\pi_{eq}(H-L-P+G)(q_P+q_G)=0 \tag{A.6}$$

Repeating the same procedure with (8) yields

$$\pi_{eq}(P-G)(e_P+e_G)+(\pi_{qq}(P-G)-C_{qq})(q_P+q_G)=0 \tag{A.7}$$

Consider (A.6) and (A.7) as a system of two homogenous linear equations with variables $x=e_P+e_G$ and $y=q_P+q_G$. Observe that the determinant of the coefficient is

$$\begin{aligned}\Delta &= (\pi_{ee}(H-L-P+G)-S_{ee})(\pi_{qq}(P-G)-C_{qq})\\ &\quad -\pi_{eq}(H-L-P+G)\pi_{eq}(P-G)=(\pi_{ee}\pi_{qq}-\pi_{eq}^2)(H-L-P+G)(P-G)\\ &\quad -\pi_{ee}(H-L-P+G)C_{qq}-\pi_{qq}(P-G)S_{ee}+S_{ee}C_{qq}\end{aligned}$$

By the concavity of π we have $\pi_{ee}\pi_{qq}-\pi_{eq}^2>0$; $\pi_{ee}<0$, $\pi_{qq}<0$. It thus follows that if G is positive then Δ is strictly positive and, hence, this system would have only the trivial solution $x=y=0$. Since $x=q_P+q_G=0$, the partial derivatives q_P and q_G have opposite signs, which contradicts (A.5).

[9] We omit the variables P and G and write e and q instead of $e(P,G)$ and $q(P,G)$, respectively.

We show that the optimal compensation cannot be positive for successes and failure in the same time and the only avenue left open is whether we can have $P=0$ and $G>0$. Suppose that it is indeed the case then this would lead to $P-G$ being negative. Using (8) it must follow then that q must be 0. $q=0$ would not be in the best interest of the company and, thus, it will not choose a positive payment for failure, or $G>0$. □

Proof of Proposition 3. Given $G=0$ and $W=0$ the first-order condition for optimal P is the second equation of (A.4):

$$\pi_q q_P[H-P-L]=\pi \tag{A.8}$$

Rearranging (A.8) yields the result. □

Proof of Proposition 4. The first-order conditions for both, first- and second-best solution are given by the following system:

$$\alpha\pi_e = S_e(e)$$
$$\beta\pi_q = C_q(q) \tag{A.9}$$

where in the first-best case, $\alpha=\beta=H-L$ (see Eqs. (4) and (5)) and in second-best case $\alpha=H-L-P$ and $\beta=P=H-L-(\pi/(\pi_q q_P^*))$ (see Eqs. (7) and (8) and use the result in Proposition 3 and $G=0$). It follows that in the second-best case the values of α and β are lower. To complete the proof we need to show that the values of e_α, q_α, e_β, q_β are always positive. Differentiating (A.9) with respect to α yields

$$\pi_e+\alpha(\pi_{ee}e_\alpha+\pi_{eq}q_\alpha)=S_{ee}(e)e_\alpha$$
$$\beta(\pi_{qe}e_\alpha+\pi_{qq}q_\alpha)=C_{qq}(q)q_\alpha \tag{A.10}$$

Rearranging yields

$$e_\alpha(\alpha\pi_{ee}-S_{ee}(e))+\alpha\pi_{eq}q_\alpha=-\pi_e$$
$$\beta\pi_{qe}e_\alpha+q_\alpha(\beta\pi_{qq}-C_{qq}(q))=0 \tag{A.11}$$

Substituting e_α from the second equation in (A.11) into the first one and rearranging, we have

$$q_\alpha=\frac{\beta\pi_e\pi_{eq}}{\alpha\beta[\pi_{ee}\pi_{qq}-\pi_{eq}^2]-\beta\pi_{qq}S_{ee}-\alpha\pi_{ee}C_{qq}+C_{qq}S_{ee}} \tag{A.12}$$

Given the concavity of π we may infer that $\pi_{ee}\pi_{qq}-\pi_{eq}^2>0$; $\pi_{qq}<0$, $\pi_{ee}<0$. Further given the convexity of C, S we may infer that $C_{qq}>0$ and $S_{ee}>0$. Thus, the denominator of (A.12) is positive and based on the assumption $\pi_{eq}>0$ the numerator is positive which implies that $q_\alpha>0$. Similar arguments hold for all e_α, e_β, q_β. □

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