Sharing of Endogenous Risk in Construction[*]

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This version July, 2003

Abstract

In risk management of complex procurement projects in construction, the buyer has two principal instruments at his disposal: 1) the choice of time and resources put into engineering and design (project specification), thus affecting *the level of risk* in the project, 2) *the sharing of risk*, as specified by the incentive contract for the contractor. Each of the instruments implies costs for the buyer. Detailed project specification involves direct planning costs, but the major specification cost is often a time cost, i.e., the reduction in net present value due to the postponement of the project. Risk sharing by the buyer is costly even if the buyer is risk neutral, since lower risk exposure for the contractor implies weaker incentives and therby higher construction costs. Hence, risk management of procurement projects can for the buyer be perceived as a trade-off between the time costs of project specification and planning and the budget implications of weaker incentives. We model this trade-off in a risk sharing model with endogenous risk.

1   Introduction

Large and complex construction projects are often very risky; the total completion costs may be influenced by a range of unforeseen factors. The risk can be reduced, however, by careful planning and specification of the project's various components. But such planning

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takes time, and due to time costs it may be tempting to start a project with a limited amount of specification ex ante. Some risk will then remain, and it must be borne (or shared) by the buyer and the contractor. In order to motivate the contractor to control and possibly reduce construction costs, he must bear some risk. A fixed-price contract provides strong incentives for cost control, but leaves all risk with the contractor. A cost-plus contract removes all risk from the contractor, but yields low (none) incentives to reduce costs.

Trading off risk bearing and incentives, the buyer will offer more incentive based compensation (less cost sharing), the lower is the remaining project risk. Since this risk is to some degree endogenous (it is influenced by planning and specification activities), the design of incentive contracts must be considered in conjunction with the amount of project planning that is to be undertaken. It is important to note that there are two ways in which the buyer can affect the risk faced by the contractor: (a) project design, and (b) contract design. As for the former, a high level of technical specification at the time of contract award reduces the contractor's estimation risk when tendering for a contract. On the other hand, by reducing the design time income may come earlier, and thus enhance the potential net present value of the project. Usually, however, this is only achieved at the cost of increased risk. Starting construction before detailed engineering is undertaken introduces a possibility of cost overruns due to estimation failures, redesign, and reconstruction. Thus, the attempt to reduce lead times typically increases the volatility of costs. Below we present a simple model to study the combined project and contract design problem.

An interesting finding is that there may be a non-monotone relationship between the optimal amount of planning and the incentive-intensity of the associated optimal construction contract. Little planning (and hence high endogenous project risk) may occur together with either low-powered or high-powered incentive contracts, while much planning occurs together with medium-powered contracts. (An inverse-U relationship between optimal planning and contract power, i.e. a U-relationship between endogenous risk and contract power.) The reason for the non-monotonicity is a conflict between two tensions affecting contract design. First, taking project risk as given, it is the case that the more risk averse a contractor is, the less powerful (more of a cost-plus type) will the construction contract be. But second, given more risk aversion, it also pays to invest in planning to reduce the overall risk. Such a lower risk will in isolation call for a more powerful (more of

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a fixed-price type) construction contract. The two tensions produce the non-monotonicity. Across a sample of observations (where the underlying variation stems from contractors' varying degrees of risk aversion), we may then observe a non-monotone relationship betwen project risk and the power of incentive contracts, as indicated in the figures presented below.

2   Case: Norwegian offshore development projects

To illustrate the implications of endogenous risk in construction, we will address the case of contract design and risk sharing in Norwegian offshore development projects. Due to optimal division of labour, the involvement of the construction companies is limited to engineering, procurement and construction. The risk exposure for these firms is in the contracts limited to the key figures that they can affect, i.e., fabrication costs and delivery times. The following exposition is thus confined to construction risk, and not the overall risk of the petroleum project. In addition to sharing the risk in fabrication costs, oil companies also fully bear production risk and petroleum price risk.

Optimal risk sharing between oil companies and contractors can be perceived as a trade-off between the provision of incentives and optimal sharing of risk.[1] Absent incentive problems, optimal risk sharing would simply entail letting the party with the lowest risk aversion carry most of the risk. In most cases this would mean the oil company. These companies specialise in carrying risk, they often have high financial capacity, and are able to eliminate parts of the risk by holding a diversified portfolio of projects. On the Norwegian continental shelf they also form partnerships, reducing their risk exposure to the equity share they hold in each individual licence. Suppliers, the offshore construction industry, on the other hand, are less able to carry risk. One individual offshore development contract, that may amount to as much as one billion dollars, and last for several years, comprises a major part of the portfolio of a construction company.

The need to provide incentives to the contractor, however, calls for much risk to be borne by the agent: the agent is provided incentives by making his compensation contingent on timely delivery and low costs. Optimal risk sharing is highly context specific, depending on the relative risk aversions of the contracting parties and on the extent to

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[1] See e.g. Grossman and Hart (1983). For a discussion of optimal sharing of risk among oil companies and the government (fiscal design), see Osmundsen (1999a).

which provision of incentives is important for the realisation of the project objectives. The contractor's capability to carry risk may, however, effectively limit the incentive intensity. Norwegian offshore construction companies have over the last ten years experienced low returns, and financial reserves are low.

In the beginning of the 1990s, the Norwegian petroleum industry experienced a cost level that did not justify new offshore development projects. To reduce development time and costs drastically on the Norwegian shelf, economic and technical task forces were appointed, with members from oil companies, suppliers and government. This process, known as NORSOK, was inspired by the cost reduction initiative CRINE on the UK continental shelf. A consensus was reached in the Norwegian petroleum industry to implement a number of organisational and contractual changes.

Much attention has been devoted to reducing lead times. Deep water offshore development projects are extremely capital intensive, and getting the field on stream at an early stage may be decisive for a positive project appraisal (net present value analyses). By reducing the lead time by one year, ceteris paribus, the expected net present value may increase as much as 25 per cent. To reduce lead times, oil companies may thus be willing to accept somewhat higher expected development costs and somewhat higher capex uncertainty.

To reduce development times, contract awards (and to some extent fabrication) has started before detailed engineering was completed. This has led to a considerable increase in estimation risk[2]. For a number of extraction facilities there has been considerable amounts of reengineering and refabrication, causing delays and cost overruns. In some cases this has been due to updated information about reservoir characteristics and a wish to implement new technology. In other cases initial engineering and planning were simply inadequate.

Previously, oil companies (the licence groups, represented by the operators) coordinated deliveries from contractors that were specialised within, respectively, project management, engineering, module fabrication, at-shore/inshore hook-up or marine operations. Today, the Norwegian offshore development market is dominated by 3 to 4 major entities marketing themselves as capable of carrying out total enterprise contracts and/or projects from concept development to offshore installation and start up. Hence, the project management tasks which previously had to be carried out by a project team managed by the

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[2]For a discussion of cost estimation in offshore development projects, see Emhjellen et al. (2001a).

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client, have after 1994 been carried out by the major offshore contractors, regulated by EPCI-contracts (Engineering, Procurement, Construction, Installation). The large size of the contracts, and the new coordination tasks that were to be performed, implied a considerable increase of risk for the turnkey suppliers. In the previous fabrication contracts, founded on cost-plus principles, most of the risk was borne by the oil companies. In the EPCI-contracts, however, an even split of cost overruns and savings, relative to a target sum was introduced. There was an upper limit to the cost overruns to be borne by the contractor, but this cap was substantial compared to the contractor's financial strength. Thus, in a situation of a considerable increase in risk, a higher fraction of the risk is now borne by the contractors.

The performance of the new contractual and organisational solutions in Norwegian offshore development projects was evaluated by a government study (Government Report NOU 1999:11).[3] For the new type of development projects, implemented after 1994, the study reports aggregate cost overruns exceeding 4 billion dollars. Still, development costs are estimated to have fallen; but not to the extent of the over-optimistic expectations. As a result, the main contractors have experienced financial problems. Moreover, clients have been forced to pay in excess of their contractual obligations in order to secure delivery of the contract object when contractor's financial stability is jeopardised. A poor technical definition and a resulting under-estimation of scope has also caused schedule delays and subsequent losses to the oil companies that they were unable to recover through liquidated damages paid by contractors.

Experience gained by the Norwegian oil industry indicates that there should be more focus on developing better technical specifications prior to the award of EPCI contracts; planning time has been suboptimal. Furthermore, incentive contracts need to be curtailed to the financial capacity of the supplier. The simple model below illustrates these points by showing that the choice of design time - which influences the amount of risk - must be seen in conjunction with the choice of risk sharing arrangements.

3   The Model

The general trade-off between incentive provision and optimal risk sharing is developed by, among others Holmstrom (1979), Grossman and Hart (1983) and Milgrom and Roberts

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[3] The particular contractual solutions are analysed in Osmundsen (1999b).

(1992). In these models the focus is on incentive schemes. Planning time is not an issue and project risk is exogenous. We extend this model framework by including a decision on planning time and thereby endogenising the project risk. The simultaneous setting of incentives and planning time sheds new light on the optimal incentive structure. Bajari and Tadelis (2001) analyse procurement contracts, with a focus on design time and renegotiation of contract terms, with exogenous project risk. Our focus is complementary to that of Bajari and Tadelis, as we focus on risk sharing, instead of contract renegotiation. We do not include contract renegotiation, but instead extend the model framework to allow for endogenous project risk. We also allow for a wider set of incentive contracts, e.g., like the cost sharing contracts that have been applied in Norwegian and UK offshore development projects. Bajari and Tadelis confine the set of feasible contracts to fixed price or cost-plus contracts, and derive the optimal choice between the two types of contracts as a trade-off between incentives to reduce costs (calling for a fixed price contract) and the ability to deliver on time (calling for cost plus contracting, leaving no room for time-consuming renegotiations). Interesting discussions on contractor compensation schemes are also provided by Howard and Bell (1998) and by Business Roundtable Report A-7 (1982), but not in terms of formal models.

The particular features of our model are as follows. We consider a construction project where a complete and successful installation has gross expected value v for the buyer. The project may be more or less specified ex ante, let $\tau > 0$ denote the degree of specification. The more specified the project is, the less risk remains regarding construction costs.

The contractor can exert cost-reducing effort e, which is unverifiable. Effort costs are $g(e)$. His total costs are

$$c(e,\tau) + \varepsilon + g(e), \qquad \text{where} \qquad c_e < 0 \ \text{ and } \ c_\tau \leq 0,$$

and ε is stochastic element whose variance decreases with more ex ante specification

$$\varepsilon \sim N(0, \sigma^2(\tau)), \qquad \text{where} \qquad \frac{d\sigma^2}{d\tau} < 0$$

Realized project costs

$$C = c + \varepsilon$$

are verifiable. The contractor is paid according to the payment schedule

$$p(C) = \alpha + \beta C$$

Here β is a cost sharing parameter; $\beta = 0$ corresponds to a fixed-price (FP) contract, and $\beta = 1$ to a cost-plus (CP) contract. The power of the contract can be measured by $1 - \beta$.

The contractor's profit is now

$$\pi = p(C) - C - g(e) = \alpha + (\beta - 1)c(e, \tau) - g(e) + (\beta - 1)\varepsilon$$

He is risk averse, and has utility (certainty equivalent)

$$E\pi - \frac{r}{2}var(\pi) = \alpha + (\beta - 1)c(e, \tau) - g(e) - \frac{r}{2}(\beta - 1)^2\sigma^2(\tau)$$

This certainty equivalent follows from a utility function of the form $e^{-r\pi}$. There may be several reasons why the contractor is risk averse. Contractors are often vulnerable due to lack of diversification, their construction portfolio typically only consist of a few large projects. Even if the owners may be diversified, holding stocks in many firms, the managers of construction firms may act in a risk averse manner since their human capital are linked to the persistence of the firm (principal-agent problem between owners and managers). Bankruptcy costs, financial stress and liquidity constraints may also generate behaviour that mimics risk aversion.

The contractor's choice of effort will in general depend on incentives β and on design τ; so $e = e(\beta, \tau)$. His optimal effort is given by (the IC constraints)

$$\begin{aligned}(\beta - 1)c_e(e, \tau) &= g'(e) \quad &for \quad \beta < 1 \quad &\text{(incentive contract)} \\ e &= 0 \quad &for \quad \beta = 1 \quad &\text{(cost-plus contract)}\end{aligned}$$

The buyer has payoff

$$\Pi = \tilde{v} - p(C) - d(\tau) = \tilde{v} - \alpha - \beta(c(e, \tau) + \varepsilon) - d(\tau)$$

He is (possibly) risk averse, with certainty equivalent

$$E\Pi - \frac{R}{2}var(\Pi) = \nu^S - \alpha - \beta c(e, \tau) - d(\tau) - \frac{R}{2}\beta^2\sigma^2(\tau)$$

where $\nu^S = E\tilde{v} - \frac{R}{2}var(\tilde{v})$ (the certainty equivalent corresponding to gross benefits) is assumed independent of project specification τ. Specification costs are captured by $d(\tau)$. These can be perceived as covering direct costs of engineering and planning, as well as the loss in net present value of delaying the project (time costs).

The buyer maximizes his payoff, given participation (IR) and IC constraints for the contractor. The participation constraint is

$$\alpha + (\beta - 1)c(e, \tau) - g(e) - \frac{r}{2}(\beta - 1)^2\sigma^2(\tau) \geq 0$$

Taking this into account, the buyer's payoff is

$$B = v^S - c(e,\tau) - g(e) - \frac{r}{2}(\beta-1)^2\sigma^2(\tau) - \frac{R}{2}\beta^2\sigma^2(\tau) - d(\tau)$$

Assumption. In the following we assume $\frac{\partial^2 c}{\partial \tau \partial e} = 0$; so effort e and design τ are independent cost factors. Design costs can then be redefined so that without loss of generality $c()$ is a function of e only; $c(e)$.

As a reference case we first consider **the first best solution,** which is obtained when effort is verifiable. Optimal effort is then given by $-c'(e) = g'(e)$; i.e. effort is provided to the point where the marginal gain in terms of reduced project costs is equal to the marginal effort cost for the contractor. Optimal β (optimal risk sharing) is given by

$$r(\beta - 1) - R\beta = 0 \qquad i.e. \qquad \beta = \frac{r}{r+R}$$

The buyer's share of the cost is thus higher, the more risk averse is the contractor, and the less risk averse is the buyer. We see that if the buyer is risk neutral ($R = 0$) we get $\beta = 1$, i.e. a cost-plus contract, so the contractor then bears no risk. These are well known properties of first-best optimal risk sharing arrangements.

The optimal design specification is obtained by equating the marginal costs and benefits associated with this activity, which yields

$$d'(\tau) = -\left(\frac{r}{2}\left(\frac{R}{r+R}\right)^2 + \frac{R}{2}\left(\frac{r}{r+R}\right)^2\right)\frac{d\sigma^2}{d\tau} = -\frac{d\sigma^2}{d\tau}\frac{1}{2}\frac{rR}{r+R}$$

The last expression in this equation captures the marginal benefit, which consists of the marginal reduction in risk times the marginal effect of reduced risk on the parties' risk costs. The latter increases with more risk aversion, hence it follows that more risk aversion (larger r or R) will unambigously increase the level of project specification ex ante.

The **second-best solution** is obtained when—more realistically—effort is not verifiable. Effort is then $e = e(\beta)$ as given by the IC constraint $(\beta - 1)c'(e) = g'(e)$ (for $\beta < 1$). The buyer chooses the contract parameter β and the design parameter τ to maximize his payoff (certainty equivalent)

$$B(\beta,\tau) = v^S - c(e(\beta)) - g(e(\beta)) - \frac{r}{2}(\beta-1)^2\sigma^2(\tau) - \frac{R}{2}\beta^2\sigma^2(\tau) - d(\tau)$$

The first-order conditions for this problem are

$$\begin{aligned} 0 &= -(c'(e) + g'(e))\frac{de}{d\beta} - (r(\beta-1) + R\beta)\sigma^2(\tau) \\ &= -\beta c'(e)\frac{de}{d\beta} - (r(\beta-1) + R\beta)\sigma^2(\tau) \end{aligned} \qquad (1)$$

$$0 = -(\frac{r}{2}(\beta - 1)^2 + \frac{R}{2}\beta^2)\frac{d\sigma^2}{d\tau} - d'(\tau) \tag{2}$$

The essential insights in this paper can be most easily conveyed by means of a *parametric case*, where explicit functional forms are assumed. In the main text we therefore assume the following simple functional forms:

$$c(e) = c_0 - e$$
$$g(e) = \frac{\gamma}{2}e^2$$
$$d(\tau) = d_0\tau + d_1$$
$$\sigma^2(\tau) = \frac{s}{s_0 + s_1\tau}$$

In an appendix we show that our results are robust and hold more generally.

Given the functional forms above, effort $e(\beta)$ is from the IC-constraint given by

$$e(\beta) = \frac{1}{\gamma}(1 - \beta)$$

and the condition (1) for optimal β takes the form

$$0 = -\beta\frac{1}{\gamma} - (r(\beta - 1) + R\beta)\sigma^2(\tau) = -[\frac{1}{\gamma} + (r + R)\sigma^2(\tau)]\beta + r\sigma^2(\tau)$$

Hence we obtain

$$\beta = \frac{r}{\frac{1}{\gamma\sigma^2(\tau)} + r + R} \equiv \frac{r}{\mu + r + R} \qquad \text{where} \qquad \mu = \frac{1}{\gamma\sigma^2(\tau)} \tag{3}$$

The variable μ captures the combined effects of risk and effort sensitivity on optimal incentives β. Other things equal, the more risk (higher variance), or the harder it is to induce effort (higher γ), the higher is the cost sharing parameter β, i.e. the closer is the contract to a cost-plus contract. The more risk averse is the contractor (higher r), the closer is also the contract to a cost-plus arrangement. The more risk averse is the buyer (higher R), the smaller is β, i.e. the closer is the contract then to a fixed-price type, implying that the contractor bears more risk. We also see that the second-best β is smaller than the first-best one; risk bearing is distorted so that the contractor bears more risk than what is first-best optimal. All this is well known, given that the variance is exogenous. Here the variance is endogenous (a function of γ, r, R among other parameters), and the comparative statics will, as shown below, be different.

An interesting result in this setting is that the endogenous variance can vary non-monotoneously with the seller's risk aversion. The reason why this is so can be grasped from the expression in (2) for the marginal value of increased design specification (reduced project variance). Consider the case of a risk-neutral buyer ($R = 0$). Substituting for the

optimal bonus from (3), the marginal value of better design is

$$\frac{\partial B}{\partial \tau} = -\frac{r}{2}(\beta - 1)^2 \frac{d\sigma^2}{d\tau} - d'(\tau) = -\frac{r}{2}\left(\frac{1}{1 + r\gamma\sigma^2(\tau)}\right)^2 \frac{d\sigma^2}{d\tau} - d'(\tau)$$

The gain stemming from reduced project variance is proportional to $r(1-\beta)^2$, and the formula shows that this gain is very small both when the constructor's risk aversion r is very small and when it is very large. When the constructor is close to risk neutral ($r \approx 0$) risk reduction is of little value, and hence little design will optimally be undertaken. On the other hand, when the constructor is very risk averse it is optimal, for a given project risk, to let the incentive contract be close to a cost-plus contract ($1 - \beta \approx 0$). This means that the buyer bears most of the risk, and when the buyer is risk neutral, risk reduction is again of little value. This indicates that it will be optimal to invest little in project design both when the constructor's risk aversion r is small and when it is large.

To derive (the second-best) optimal design τ explicitly, note that for $\sigma^2(\tau) = \frac{s}{s_0 + s_1\tau}$ we have

$$-\frac{d\sigma^2}{d\tau} = \frac{ss_1}{(s_0 + s_1\tau)^2} = (\sigma^2(\tau))^2 \frac{s_1}{s} = \left(\frac{1}{\gamma\mu}\right)^2 \frac{s_1}{s}$$

From the expression for β in (3) we have further

$$\frac{r}{2}(\beta - 1)^2 + \frac{R}{2}\beta^2 = \frac{1}{2}r\frac{(\mu + R)^2 + Rr}{(\mu + r + R)^2}$$

The first-order condition for optimal design τ is then, from (2)

$$d_0 = -\frac{d\sigma^2}{d\tau}\frac{r}{2}\frac{(\mu + R)^2 + Rr}{(\mu + R + r)^2} = \left(\frac{1}{\gamma\mu}\right)^2 \frac{s_1}{s}\frac{r}{2}\frac{(\mu + R)^2 + Rr}{(\mu + R + r)^2} \tag{4}$$

From this relation we get the following comparative statics results.

Proposition 1 *Higher risk aversion R for the buyer leads to more ex ante design (higher τ) and thus a lower variance $\sigma^2(\tau)$ in equilibrium. The lower variance and the higher risk aversion R leads in turn to a lower cost sharing parameter β in equilibrium.*

Thus, in accordance with economic intuition, higher risk aversion on the part of the buyer is accommodated in two ways: (1) overall project risk is reduced (by an increase in specification activities τ), and (2) the contractor bears more of the (remaining) risk, and is thus provided with stronger incentives for cost reduction.

The proposition can be verified formally by noting that the expression on the RHS of (4) is increasing in R and decreasing in μ, and that μ as defined in (3) is increasing in τ.

Varying the contractor's risk tolerance (r), we can verify (from the expression in (4)) that a higher risk aversion r for the contractor gives higher μ, and thus lower σ^2, if and only if $(\mu + R)^2 > (\mu - R)r$. The equilibrium variance may thus be non-monotone in the contractor's risk parameter. To look into this more closely, we consider the special case of **a risk neutral buyer:** $R = 0$.

In this case we can solve the condition (4) for the optimal design parameter τ explicitly (by first solving for μ, and then using $\mu = \frac{1}{\gamma\sigma^2(\tau)}$) This procedure shows that the second-best optimal design entails a construction project with variance given by

$$\sigma^2(\tau) = \frac{1}{\gamma\mu} = \frac{1}{\sqrt{\frac{s_1}{sd_0}\frac{r}{2} - \gamma r}} \qquad (\text{provided} \qquad r < \frac{s_1}{\gamma^2 2 sd_0})$$

The following graph depicts the equilibrium project variance $\sigma^2(\tau)$ as a function of the contractor's risk aversion r (for parameters $s_1 = 2, \gamma = 1, s = d_0 = 1$)
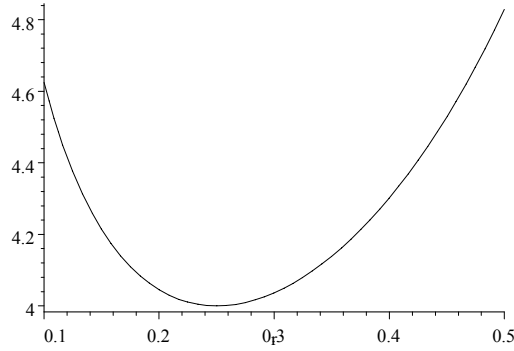

Figure 1 Equilibrium project variance ($\sigma^2(\tau)$; vertical axis) and risk aversion (r).

(The non-monotonicity can be verified analytically by noting that $\sigma^2(\tau)$ is increasing in r if and only if $r > \frac{s_1}{\gamma^2 8 sd_0}$.) These relations show that when the buyer is risk neutral ($R = 0$), the optimal solution for the project variance $\sigma^2(\tau)$ is first decreasing and then increasing in r (for $r < \frac{s_1}{\gamma^2 2 sd_0}$). The model is continuous in its parameters, and a similar relationship between the contractor's risk aversion and the project variance will therefore hold also when the buyer has a positive but 'small' risk aversion parameter ($R > 0$). Hence we get the following result:

Proposition 2 *When the buyer is sufficiently risk tolerant (when R is small), the optimal solution for the project variance $\sigma^2(\tau)$ is non-monotone in the contractor's risk aversion r: the variance $\sigma^2(\tau)$ is first decreasing and then increasing in r.*

We get the somewhat surprising result that - over some range - it is the case that as the contractor gets more risk averse, the buyer puts less resources into design specification aimed at reducing project uncertainty. In the following, the intuition behind this result is provided.

In risk management of complex procurement projects in construction, the buyer has two principal instruments at his disposal: 1) the choice of time and resources put into engineering and design (project specification), τ, thus affecting *the level of risk* in the project, 2) *the sharing of risk*, β, as specified by the incentive contract for the contractor. Each of the instruments implies costs for the buyer. Detailed project specification involves direct planning costs, but the major specification cost is often a time cost, such as the reduction in net present value due to a postponement of the project. Risk sharing by the buyer is costly even if the buyer is risk neutral, since lower risk exposure for the contractor implies weaker incentives and thereby higher construction costs. Hence, risk management of procurement projects can for the buyer be perceived as a trade-off between time costs and the budget implications of weaker incentives.

The explanation of the diagram in Figure 1 (where the buyer is assumed risk neutral) follows from this trade-off, when the contractor is risk averse. In the event that the contractor is risk neutral - the point where the diagram intersects the $y-axis$, there is no trade-off. In this event the contractor does not require a risk premium. Thus, maximum incentives $(1-\beta = 1)$ can be achieved at no cost for the buyer. There is therefore no need for the buyer to reduce the project risk; focus is on a short lead time for the project. When we increase the contractor's risk aversion slightly, the buyer is optimally responding by both reducing project risk (increasing τ and reducing $\sigma^2(\tau)$) and by bearing a larger fraction of the risk (increasing β). This is the case in the part of the diagram where risk is decreasing.

At some point, further increases in project planning is very costly to the firm. Also, providing incentives to the contractor becomes very costly when the contractor's risk aversion exceeds a certain level. Thus, the contract is moving more towards a cost-plus regime, such that the contractor's risk exposure is reduced overall. Due to this reduced risk exposure for the contractor (higher β), it is not necessary to put more resources into activities aimed at reducing project risk (increase τ). Actually, at some point it becomes optimal to let the risk sharing of the project be the main vehicle for risk management, and again reduce the time spent on planning, thus explaining the increasing section of the

diagram. At the extreme point on the right hand side of the diagram, the contractor's risk aversion is so high that a cost plus contract is called for. Risk aversion is then so high that the risk premium would have exceeded any benefits of enhanced incentives. Thus, risk sharing is in this instance the only adequate risk management instrument, and project planning time is low - and risk is high - in order to save time costs.

Turning to the optimal contract, we have (for $R = 0$, according to (3)) $\beta = \frac{r}{\mu + r}$. Substituting for $\mu + r$ from (4) we then get

$$\beta = \frac{r}{\mu + r} = \frac{r}{\frac{1}{\gamma} \sqrt{\frac{s_1}{sd_0} \frac{r}{2}}} = \gamma \sqrt{\frac{2rsd_0}{s_1}}$$

This yields the conventional result that β is unambiguously increasing in the contractor's risk parameter r; the more risk averse is the contractor, the closer is the equilibrium contract to a cost-plus contract.

The graph below depicts the co-variation of (endogenously optimal) incentives $(1 - \beta)$ and project variance $\sigma^2(\tau)$ as the contractor's risk aversion r varies for parameters $s_1 = 2, \gamma = 1, s = d_0 = 1$; for these parameters we have $\beta = \sqrt{r}$ and $\sigma^2(\tau) = \frac{1}{\sqrt{r} - r}$, hence $\sigma^2(\tau) = \frac{1}{\beta - \beta^2}$. The last formula shows that there is a non-monotone co-variation between optimal variance and optimal incentives.
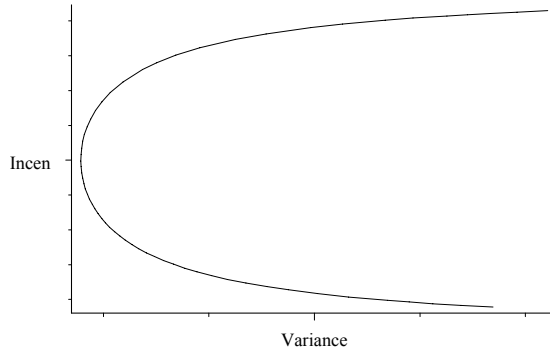

Figure 2. Optimal incentives $(1 - \beta$; vertical axis) and variance $(\sigma^2(\tau))$.

We may thus state:

Corollary 3 *Suppose buyers are risk neutral (or slightly risk averse). In a sample of contracts (from a population of contractors with varying degrees of risk aversion) we may observe a non-monotone relationship between optimal incentives for the contractor $(1 - \beta)$ and the project risk, measured by the variance $\sigma^2(\tau)$.*

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The lower part of the graph in Figure 2 resembles the negative relationship found between risk (variance) and incentives in conventional models where risk is exogenous. Here it is endogenous, and the variation stems from an underlying variation in the agents' (contractors') aversion to risk. This aversion to risk is increasing along the lower part of the graph, and the increase results in lower incentives (less cost sharing) and higher project risk. Highly risk averse contractors are given low incentives–and thus a high degree of insurance against cost overruns–and little resources are spent on planning and specification to reduce project risk.

The upper part of the graph in Figure 2 illustrates that the conventional negative relationship between observed incentives and risk can be reversed when those entities are both endogenously determined. Along this part of the graph the underlying risk aversion for the contractor (r) is decreasing from left to right in the diagram. Contractors with very low aversion to risk are given very powerful incentives (close to fixed-price contracts)–and thus little or no insurance against cost overruns–and the buyer optimally spends little to reduce risk. This explains the right end of the upper graph in Figure 2. The left end is explained by the fact that contractors with higher (more precisely; intermediate) aversion to risk are given less powerful (intermediate) incentives, and in such cases it becomes very profitable for the buyer to spend resources on planning and specificaton to reduce the inherent riskiness of the project.

Figure 2 can be related to our case of Norwegian offshore development projects, where there over time has been a movement along the diagram. Starting at the top of the diagram in the 1970's, the construction contracts exhibited strong incentives. Fixed price incentive schemes were put out for tender, based on fairly detailed engineering of the job to be undertaken. Some projects with large cost overruns caused the cost uncertainty to be higher than expected. With updated information on cost distribution, the risk aversion of the contractors increased somewhat, moving leftwards in the diagram. Elements of risk sharing were introduced in the offshore development contracts. In the 1990s target sum contracts, with an even split of cost savings and overruns (subject to caps) were introduced. This represents the far left of Figure 2. Large cost overruns took place in this time period. One of the main reasons of the increase in cost risk was the inreased emphasis on reduced lead times of the projects, achieved by a reduction of detailed engineering before the start up of the fabrication phase. The major constractors came into financial strains, and risk aversion rose. As a consequence, we saw a movement towards cost plus contracts, i.e.

towards the lower right part of the diagram.

Turning finally to variations in the cost for the contractor of providing effort, we see from the expression of $\sigma^2(\tau)$ and β above that we have $d\sigma^2(\tau)/d\gamma < 0$ and $d\beta/d\gamma > 0$.

Proposition 4 *When the cost of inducing effort from the contractor (γ) increases, the equilibrium project risk ($\sigma^2(\tau)$) is reduced and contractor's incentives ($1 - \beta$) are reduced.*

When it gets more costly to induce extra effort from the contractor, incentive schemes become less effective. Thus, optimal incentives are reduced, and the buyer is now carrying more of the project risk. Project risk is then less costly, in terms of the contractor's risk premium, and equilibrium risk is increased.

4   Discussion

By careful planning and engineering activities, the buyer can reduce the risk of construction projects. Thus, there are two ways in which the buyer can affect the risk faced by the contractor: (a) by project design, and (b) by contract design. Detailed engineering and project planning involves time costs, e.g., a petroleum development project is delayed and the postponement of time when the field comes on stream involves a reduction in net present value. A higher fraction of the risk borne by the buyer in the construction contract, on the other hand, implies lower incentives and lower effort of the contractor. Thus, procurement risk management can be perceived as a trade-off between time costs and incentive costs. We develop a procurement model with endogenous project risk that allows us to simultaneously address these interlinked issues.

We find that there is a non-monotonic relationship among project risk and contractor incentives (risk sharing). Increasing risk aversion of the contractor will - for the lower range of risk aversion - be met by the buyer by a combination of enhanced project planning to reduce project risk and by a reduction of contract incentives to reduce the fraction of risk borne by the contractor. For a range of high risk aversion among the contractors, it is optimal to let risk sharing of the project be the main vehicle for risk management, and then reduce the time spent on detailed design. When risk aversion on the part of the contractor is high, the risk premium exceeds the benefits of enhanced incentives. We then approach fixed price contracts, and it is not optimal to bear substantial time costs for engineering and planning.

There will be some projects where the buyer is restricted as to the choice of design time, due to external commitments, such as contracted gas sales that make it necessary to reduce the execution time to such an extent that the contract has to be awarded based on a suboptimal technical definition. As shown by our model, the high level of specification risk limits the extent of risk that can be borne by the contractor, and thereby the contractor's incentives. Under such circumstances the project also has to take into account the possibility for additional expenses due to substantial amount of design refinement and changes during the phases of detailed engineering and construction. Typically, a certain amount of refabrication is also necessary. This would have to be reflected in the choice of compensation format, contract strategy and distribution of contractual risk. Refabrication costs may be substantial and call for more time and resources to be spent on project specification.

Appendix

In this appendix we show that the non-monotone relationship identified in Proposition 2 between the contractor's risk aversion r and the project equilibrium variance $\sigma^2(\tau)$ holds for more general functional forms than those considered in the main text. The essential feature of this result is that the equilibrium variance *increases* with more risk aversion r when the latter is above some threshold. We therefore focus on 'large' values of r, and show that the equilibrium variance is increasing in r for such values.

To simplify notation we take here the project variance $V = \sigma^2(\tau)$ as independent variable, and hence let $\tau(V)$ denote the design effort necessary to yield project variance V. Let $D(V)$ denote the associated cost $(D(V) = d(\tau(V)))$. This cost is now decreasing in V; $D'(V) < 0$. The buyer's objective is then to choose incentives β and variance V to maximize

$$B(\beta, V) = v^S - c(e(\beta)) - g(e(\beta)) - \frac{r}{2}(\beta - 1)^2 V - \frac{R}{2}\beta^2 V - D(V)$$

where effort $e(\beta)$ is given by the agent's IC-condition $(\beta - 1)c'(e) = g'(e)$. Taking account of this relation, the first-order conditions for an interior optimum in the buyer's problem are

$$0 = B_\beta(\beta, V) = -\beta c'(e)e'(\beta) - (r(\beta - 1) + R\beta)V \qquad (5)$$

$$0 = B_V(\beta, V) = -(\frac{r}{2}(\beta - 1)^2 + \frac{R}{2}\beta^2) - D'(V) \qquad (6)$$

and the second-order conditions include $B_{\beta\beta} < 0$ and $\Delta = B_{\beta\beta}B_{VV} - (B_{\beta V})^2 > 0$, (with $B_{VV} = -D'' < 0$). To justify interior solutions we further assume $D'(V^0) = 0$, where $V^0 = \sigma^2(0)$ is the initial project variance. Some design effort to reduce variance will then always be profitable, so $V < V^0$ will be optimal for $r > 0$.

Proposition A

Suppose that $c' < 0, c'' \geq 0, g' > 0, g'' > 0$ with $g'(0) = 0$, and that $\Gamma(e) = \frac{c'(e)^3}{c'(e)g''(e) - g'(e)c''(e)}$ as well as $\frac{\Gamma'(e)}{c'(e)}$ are bounded. Suppose further that the design cost $D(V)$ to achieve project variance V satisfies $-D'(V) > 0, -D''(V) < 0$ for $V < V^0$, and $D'(V^0) = 0$. Let $V_l(R)$ be defined by $-D'(V_l(R)) = \frac{R}{2}$. Then we have

$$\lim_{r \to \infty} \frac{dV}{dr} > 0 \qquad \text{if and only if} \qquad RV_l(R) < \Gamma(0) \tag{7}$$

(where $\Gamma(0) = \frac{c'(0)^2}{g''(0)}$ if $g''(0) > 0$). In particular, for $R = 0$ we have $\lim_{r \to \infty} \frac{dV}{dr} > 0$.

Proof. Differentiation of the first-order conditions (5,6) for β, V yields

$$0 = B_{\beta\beta}\frac{d\beta}{dr} + B_{\beta V}\frac{dV}{dr} - (\beta - 1)V$$
$$0 = B_{\beta V}\frac{d\beta}{dr} + B_{VV}\frac{dV}{dr} - \frac{1}{2}(\beta - 1)^2$$

This yields

$$\frac{d\beta}{dr} = \frac{1}{\Delta}\left(B_{VV}(\beta - 1)V - B_{\beta V}\frac{1}{2}(\beta - 1)^2\right) > 0$$
$$\frac{dV}{dr} = \frac{1}{\Delta}\left(B_{\beta\beta}\frac{1}{2}(\beta - 1)^2 - B_{\beta V}(\beta - 1)V\right)$$

where the inequality $\frac{d\beta}{dr} > 0$ follows from $\Delta > 0$, $B_{VV} < 0$, $\beta < 1$ and

$$B_{\beta V} = -(r(\beta - 1) + R\beta) = \frac{\beta c'(e)e'(\beta)}{V} > 0$$

(The last equality follows from the first first-order condition (5)). We have now

$$sign\left[\frac{dV}{dr}\right] = sign\left[-B_{\beta\beta}\frac{1}{2}(\beta - 1) + B_{\beta V}V\right]$$

The first term inside the bracket on the RHS is negative, the second term is positive. Consider

$$B_{\beta\beta} = \left(-c'(e)e'(\beta) - (r + R)V\right) - \beta\frac{d}{d\beta}\left(c'(e)e'(\beta)\right)$$
$$= -\frac{rV}{\beta} - \beta\frac{d}{d\beta}\left(c'(e)e'(\beta)\right)$$

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where the last equality follows from (5). So we may write

$$\left[-B_{\beta\beta}\frac{1}{2}(\beta-1)+B_{\beta V}V\right]=\left(\frac{rV}{\beta}+\beta\frac{d}{d\beta}\left(c'(e)e'(\beta)\right)\right)\frac{1}{2}(\beta-1)+\beta c'(e)e'(\beta)$$

We show below that $c'(e)e'(\beta)=\Gamma(e(\beta))$, and that $\frac{d}{d\beta}\left(c'(e)e'(\beta)\right)=\Gamma(e(\beta))\frac{\Gamma'(e(\beta))}{c'(e(\beta))}$, and hence it follows that both these expressions are bounded.

Consider now r becoming large; $r\to\infty$. Snce $c'(e)e'(\beta)$ is bounded, it follows from (5,6) that $\beta\to 1$, and therefore $e\to 0$. Then from (5,6) again we have

$$0 = -c'(0)e'(1)-\lim_{r\to\infty}rV(\beta-1)-R\lim_{r\to\infty}V$$
$$0 = -\frac{R}{2}-\lim_{r\to\infty}D'(V)$$

The last equation yields $\lim V=V_l(R)$ given by $-D'(V_l(R))=\frac{R}{2}$. Then from the first

$$\lim_{r\to\infty}rV(1-\beta)=RV_l(R)+c'(0)e'(1)$$

Given that $c'(e)e'(\beta)$ and its derivative is bounded, we then get

$$\begin{aligned}\lim_{r\to\infty}\left[-B_{\beta\beta}\frac{1}{2}(\beta-1)+B_{\beta V}V\right] &= -\lim_{r\to\infty}rV(1-\beta)\frac{1}{2}+c'(0)e'(1)\\ &= -\frac{1}{2}(RV_l(R)+c'(0)e'(1))+c'(0)e'(1)\\ &= -\frac{1}{2}RV_l(R)+\frac{1}{2}c'(0)e'(1))\end{aligned}$$

Since $\frac{dV}{dr}$ has the same sign as the square bracket, the proposition follows from $c'(0)e'(1)=\Gamma(0)$.

It remains to show that $c'(e)e'(\beta)=\Gamma(e(\beta))$ and $\frac{d}{d\beta}\left(c'(e)e'(\beta)\right)=\Gamma(e(\beta))\frac{\Gamma'(e(\beta))}{c'(e(\beta))}$. Consider $e(\beta)$ given by $(\beta-1)c'(e)=g'(e)$. We get $c'(e)+((\beta-1)c''(e)-g''(e))e'(\beta)=0$, so

$$c'(e)e'(\beta)=\frac{c'(e)^2}{g''(e)-(\beta-1)c''(e)}=\frac{c'(e)^3}{c'(e)g''(e)-g'(e)c''(e)}=\Gamma(e)$$

where the second equality follows from $(\beta-1)c'(e)=g'(e)$. Then differentiation yields $\frac{d}{d\beta}\left(c'(e)e'(\beta)\right)=\Gamma'(e)e'(\beta)=\Gamma'(e)\frac{\Gamma(e)}{c'(e)}$, which was to be shown. QED

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