Procurement with Unforeseen Contingencies[†]

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ABSTRACT: The procurement of complex projects is often plagued by large cost overruns. An important reason for these additional costs are flaws in the initial design. If the project is procured with a price-only auction, sellers who spotted some of these flaws have no incentive to reveal them early. Each seller prefers to conceal his information until he received the contract and then renegotiate when he is in a bilateral monopoly position with the buyer. We show that this gives rise to three inefficiencies: inefficient renegotiation, inefficient production and inefficient design. We derive the informationally robust direct mechanism that implements the efficient allocation at the lowest possible cost to the buyer. However, the direct mechanism requires that the buyer knows the set of possible design flaws and their payoff consequences beforehand. We show that this problem can be solved by an indirect mechanism implementing the same allocation at the same cost that does not require any prior knowledge of possible flaws.

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1 Introduction

The procurement of complex projects is often plagued by large cost overruns. One important reason for unexpected additional costs are flaws in the initial design of the project. When these flaws are revealed after production has started, the design of the project needs to be changed and contracts have to be renegotiated. This process involves physical and psychological adjustment costs that can be substantial. To minimize design flaws the early collaboration with potential contractors is of crucial importance. However, if the project is procured by a standard price-only auction, potential contractors have little incentive to contribute their expertise. For each contractor who spotted a design flaw it is a dominant strategy to conceal this information, bid more aggressively in the auction in order to get the contract, and then renegotiate with the buyer in order to fix the design flaw later.

In this paper we propose two informationally robust mechanisms that allocate the contract to the seller with the lowest cost and that induce all potential sellers to reveal any information that they may have about possible design flaws early, i.e. before the contract is assigned. First, we look for a direct mechanism that implements the efficient allocation. We derive a direct mechanism that is informationally robust in the sense that it does not depend on the priors (and higher order beliefs) of the involved parties about the likelihood of possible flaws and of the probabilities that these flaws have been spotted by each of the potential sellers. In fact, the mechanism is ex post incentive compatible, i.e. for any realization of the state of the world it is optimal for the involved sellers to announce their information truthfully. The proposed mechanism is optimal in the sense that there does not exist any other informationally robust direct mechanism that implement the efficient allocation at a cost to the buyer that is less than the cost of our proposed mechanism for any possible distribution of design flaws.

A crucial drawback of our proposed direct mechanism is that it requires the buyer to know the set of potential design flaws and their payoff consequences. In the procurement context this is a very strong assumption. Buyers are often aware that the initial design may be flawed, but they have no idea how possible flaws may look like and what their payoff implications are. After all, if they had this information, it would be easy for them to look for and detect the design flaws themselves. To deal with this problem we propose a second, indirect mechanism that implements the efficient allocation at the same cost to the buyer as the direct mechanism, but that does not require any knowledge about the set of possible flaws ex ante. This indirect mechanism is based on the assumption that pointing out a design flaw is an "eye-opener". Once the flaw has been pointed out, every industry expert understands the flaw and knows how to fix it. He also knows the payoff consequences if the flaw is fixed early rather than late. This assumption is strong but seems reasonable in the procurement context. Given this assumption our indirect mechanism can make use of an independent arbitrator. Sellers are asked to reveal all design flaws that they spotted to the arbitrator who rewards them according to the payoff consequences these flaws would have had if they had not been disclosed early. Thereafter the contract is allocated by a standard second price auction to the seller with the lowest cost.

An important feature of both proposed mechanisms is that they separate the assignment of the contract and the elicitation of the sellers' information about design flaws. Efficiency requires that the contract is assigned to the seller with the lowest cost who need not be the seller who spotted most design flaws. If the buyer is a welfare maximizing government with the objective to achieve an efficient allocation subject to the constraint that the informational rent to sellers is kept to a minimum, then this separation is optimal. However, if the buyer is a private party that is not interested in efficiency but in private profits, then the buyer can increase her profits by tying the assignment of the contract to the revelation of flaws, e.g. by offering "bonus points" in the auction in exchange for design improvements. In fact, this is what is sometimes observed in private procurement contexts.

After discussing the relation of our paper to the literature in the next section, we set up a model in Section 3 in which a buyer who wants to procure a project that may be plagued by one or several design flaws. There are two potential sellers with private information about their production costs. Each seller privately observes with some positive probability some subset of the actual design flaws. He may reveal this information to the buyer or keep it to himself. The buyer wants to set up a procurement mechanism that implements the efficient allocation subject to the constraint that the information rents to the sellers are minimized. Note that this is a multi-dimensional mechanism design problem.

In Section 4 we show that a standard price-only auction offers no incentives to sellers to reveal private information about possible design flaws early. The reason is simple: If a seller reveals the information before the auction takes place he gains nothing because once the flaw has been pointed out every seller can fix it. If he waits until he has been assigned the contract, he is in a bilateral monopoly situation with the buyer. Thus, if he now reveals the flaw, the contract has to be renegotiated and the seller can grasp some of the surplus from renegotiation. However, this gives rise to three inefficiencies. First, fixing the flaw via renegotiation is more costly than fixing it early (Inefficient Renegotiation). Second, it may happen that the flaw is spotted only by the seller with higher production cost. This seller will bid more aggressively in the auction (anticipating the renegotiation profit). Thus, if he wins the auction, production is carried out inefficiently by the more costly seller (Inefficient Production). Third, if the inferior seller is the only one who detected the flaw and if this seller does not win the auction, the flaw will not be pointed out and the buyer suffers from the flawed design (Inefficient Design).

In Section 5 we focus on the first inefficiency (Inefficient Renegotiation) by assuming that there are no cost differences between sellers and that costs are common knowledge. We also restrict attention to the case of only one possible flaw. We derive the optimal direct mechanism and show that this mechanism is informationally robust. In order to minimize the information rent that has to be paid to sellers this mechanism assigns the contract randomly if both sellers revealed the same information. Then we show that there exists an equivalent indirect mechanism that implements the same allocation and does not require any prior knowledge about the set of possible flaws and their payoff consequences.

In Section 6 we generalize this result to the case where sellers have different costs (which is their private information) and in which there may be multiple flaws. This problem is more intricate because efficiency requires that the seller with the lowest cost gets the contract. Thus, the contract cannot be assigned randomly. This implies that a higher information rent has to be paid to the sellers. We derive the informationally robust mechanism that implements the efficient allocation at the lowest possible cost to the buyer. Then we show that there exists an indirect, extended arbitration mechanism that implements the same allocation at the same cost and does not require prior knowledge about the underlying parameters. An important characteristic of this mechanism is that it separates the two problems of eliciting information about design flaws and assigning the contract to the seller with the lowest cost. This is necessary to achieve efficiency.

So far we assumed that each seller observes some subset of the actual flaws with some exogenously given probability. In Section 7 we generalize this model and allow for search costs. Each seller has to actively search for possible design flaws which is costly. The optimal mechanisms of Section 6 do not offer efficient incentives to search for design flaws. We derive the optimal mechanism that induces sellers not just to reveal their information about costs and flaws truthfully, but also to search efficiently for possible flaws. This mechanism has to pay a higher information rent to the seller, but it is also somewhat easier to specify because it does not depend on the bargaining power of the parties in the renegotiation game. Section 8 concludes and discusses some possible directions of future research.

2 Relation to the Literature

Our paper contributes to three strands of the literature. First, there is a large literature on optimal procurement auctions (McAfee and McMillan (1986), Laffont and Tirole (1993)). The novel feature in our set-up is that sellers may have superior information about possible design flaws that the buyer would like to elicit. This is closely related to the literature on scoring auctions (Asker and Cantillon (2010), Che (1993), Che, Iossa, and Rey (2016)) that also try to induce sellers to make design proposals. A scoring auction assigns the contract to the seller who comes up with the best proposal (the highest total score). In contrast, our mechanism combines the suggestions of several sellers to improve the design and assigns the contract for the improved design to the seller with lowest cost.

Second, our paper is related to the literature on robust mechanism design. Bayesian mechanism design theory has often been criticized because the optimal mechanism crucially depends on the precise information that the agents and the mechanism designer have (including their prior beliefs and higher order believes that are not observable). Wilson (1987) has pointed out that if the agents or the designer are mistaken in their beliefs, then the outcome of the supposedly optimal mechanism may be very different from the intended outcome. Bergemann and Morris (2005) require that "robust" implementation is independent of beliefs and higher order beliefs and depends only on payoff relevant types. They have shown that implementation is robust if and only if the mechanism satisfies ex post incentive compatibility, i.e. if the strategy of each agent is optimal against the strategies of all other agents for every possible realization of types.[1] Our optimal mechanism satisfies ex post incentive compatibility and is therefore informationally robust.

Ex post implementation is weaker than dominant-strategy implementation because it assumes that other agents follow their equilibrium strategy. In our set-up we assume that the outcome of the renegotiation game is given by the Generalized Nash Bargaining Solution. Thus, our results hinge on the assumption that all parties choose their optimal strategies that gives rise to the outcome of the GNBS. However, given this assumption it is a weakly dominant strategy for each seller to announce his cost type and the flaws that he observed truthfully. The mechanism we propose differs from the celebrated Vickrey-Clarke-Groves mechanism in that each seller is not paid his marginal contribution to the social surplus, but rather the increase of his outside option. However, the mechanism derived in Section 7, that induces all sellers to search efficiently for possible design flaws, is essentially a Groves mechanism.

The indirect arbitration mechanism that we propose is even more robust than dominant-strategy implementation because it does not require any knowledge about the possible type spaces of the sellers. We are not aware of any other papers on robust mechanism design with this feature. This result is based on the assumption that an arbitrator can evaluate the payoff consequences of detected flaws and that he can complete the mechanism ex post. This is a novel assumption in the mechanism design literature that is plausible in the procurement context and deserves further attention.

Finally, there is a small but growing literature on the inefficiencies of renegotiating. Several empirical studies emphasize that renegotiation is often costly and inefficient, including Crocker and Reynolds (1993), Chakravarty and MacLeod (2009), and Bajari, Houghton, and Tadelis (2014). Bajari et al. (2014, p. 1317) consider highway procure-

[1]See Bergemann (2012) for a survey of the literature on robust implementation.

ment contracts in California. They report that renegotiation costs are substantial and estimate that they "range from 55 cents to araound two dollars for every dollar in change". Herweg and Schmidt (2015) develop a behavioral model of inefficient renegotiation that is based on loss aversion. Bajari and Tadelis (2001) assume that renegotiation is costly and compare fixed price and cost plus contracts. They show that standardized goods should be procured by fixed-price contracts that give strong cost-saving incentives to sellers, while complex goods should be procured by cost-plus contracts in order to avoid costly renegotiation. Herweg and Schmidt (2016) compare price-only auctions to bilateral negotiations. They show that negotiation with one selected seller may outperform an auction because the auction induces sellers to conceal private information about design improvements which gives rise to inefficient renegotiation. While these papers compare standard contracts and procurement procedures, the current paper solves for the optimal procurement mechanism and proposes a new procedure.

3 The Model

A buyer (B), female, wants to procure a complex good from one of two sellers (male), denoted by $i \in \{1, 2\}$.[2] At date 0 the buyer has a design proposal D_0 for the good. Each seller i can produce design D_0 at cost $c^i \in [\underline{c}, \bar{c}]$, $0 < \underline{c} \leq \bar{c}$. These costs c^1 and c^2 are private information and drawn independently from some cdf $H(c^i)$. If design D_0 is optimal it generates utility v for the buyer. However, with some probability the design is plagued by one or multiple flaws which reduce the buyer's utility if he gets design D_0. In order to restore the buyer's utility to v, the flaws have to be fixed by changing the design.

We model the possibility of design flaws as follows. Let $\hat{F} = \{f_1, \ldots, f_n\}$ denote the set of possible design flaws and let $\mathcal{P}(\hat{F})$ denote the power set of $\hat{F}$, i.e. the set of all possible subsets of $\hat{F}$ including $\emptyset$.[3] A typical element of $\mathcal{P}(\hat{F})$ is denoted by F. If $F = \emptyset$, there is no design flaw. If $\emptyset \neq F \subseteq \hat{F}$, a subset of the set of possible flaws has materialized. Thus, $F \in \mathcal{P}(\hat{F})$ is the realization of the state of the world which is drawn from $\mathcal{P}(\hat{F})$ according to some probability distribution $G(F)$.

[2] We restrict attention to the case of two sellers for notational simplicity only. It is straightforward to extend the analysis to the case of N sellers.

[3] If $\mid \hat{F} \mid$ is the cardinality of $\hat{F}$, then $\mid \mathcal{P}(\hat{F}) \mid = 2^{\mid \hat{F} \mid}$.

Design flaw $f_k \in F$ can be fixed at cost $\Delta c_k \geq 0$ if the design is adjusted early, i.e. before the contract is assigned to one seller and production starts. If f_k is not fixed, the buyer's utility is reduced to $v - \Delta v_k$. We assume that $\Delta v_k > \Delta c_k$ for all $k \in \{1, \ldots, n\}$, so fixing a flaw is always efficient.

Sellers are better able to detect design flaws than the buyer. Each seller may privately observe a subset of the realized flaws with some probability. Let $\mathcal{P}(F)$ denote the power set of F. Each seller observes a private signal $F^i \in \mathcal{P}(F)$. If $F^i = \emptyset$, seller i observes nothing. If $\emptyset \neq F^i \subseteq F$, seller i observes some subset of the set of realized flaws. The joint probability distribution over (F^1, F^2) given the set of flaws F is denoted by Q_F.

At date 1 each seller can report some or all of the flaws that he observed. $\mathcal{P}(F^i)$ denotes the power set of F^i with typical element $\tilde{F}^i$. If $\tilde{F}^i = \emptyset$, seller i reports nothing. If $\emptyset \neq \tilde{F}^i \subseteq F^i$, seller i reports some (or all) of the flaws that he observed. Note that a seller can report only flaws that he observed.

Pointing out the flaw is an "eye-opener". A flaw may be very difficult to find, in particular if it is not even clear what possible flaws may exist. But once a flaw has been pointed out it becomes obvious to any industry expert what the flaw is and how to fix it. Thus, we assume that if flaw f_k is known, all sellers face the same additional cost Δc_k to fix it. Let $D(\tilde{F})$ denote the optimal design that fixes all flaws $f_k \in \tilde{F}$ (but not flaws $f_k \in \tilde{F} \setminus F$).

Only flaws that are reported at date 1 can be fixed at date 1. If the set of actual flaws is F and the sellers reported flaws $\tilde{F}^1$ and $\tilde{F}^2$, then the buyer can adjust the design in order to fix all flaws $f_k \in \tilde{F} = \tilde{F}^1 \cup F^2$. If she does so, her utility derived from the good is given by[4]

$$V(D(\tilde{F}) \mid F) = v - \sum_{\{k \mid f_k \in F \setminus \tilde{F}\}} \Delta v_k$$

while the cost of seller i to produce $D(\tilde{F})$ is

$$C^i(D(\tilde{F}) \mid F)) = c^i + \sum_{\{k \mid f_k \in \tilde{F}\}} \Delta c_k \ .$$

The fact that a flaw is obvious once it has been pointed out makes it difficult for a

[4]Note that this formulation implicitly assumes that costs and benefits of fixing flaws are additive, i.e. flaws are independent of each other.

seller who observed it to "sell" this information to the buyer at date 1. Anybody can claim that there is a flaw. To prove this claim a seller has to point out what the flaw is, but once he does so, he gives his information away and the buyer no longer needs to pay for it (see Arrow (1962) for the seminal discussion of this problem). The situation changes radically at date 2; i.e., after seller i has been assigned the contract to the good.[5] If he reveals a flaw to the buyer now, the buyer cannot simply switch to the new design that fixes this flaw but has to renegotiate the initial contract with seller i. Now the parties are in a bilateral monopoly position.

The problem with renegotiation is that it is often costly and inefficient. At date 2 the buyer has made several other commitments already (contracts with other suppliers, customers, etc.) that are based on the design of the initial contract. Furthermore, the parties may disagree on who is responsible for the design flaw and should bear the cost of fixing it which may lead to haggling, aggrievement, and further delays. We model this by assuming that the parties have to incur additional physical and/or psychological adjustment costs $\Delta x_k > 0$ to adjust design flaw f_k at date 2. We assume that $\Delta x_k < \Delta v_k - \Delta c_k$ for all $k \in \{1, \ldots, n\}$, so it is still optimal to fix a flaw at date 2. However, the surplus from fixing it shrinks from $S_k = \Delta v_k - \Delta c_k$ if f_k is fixed at date 1 to $S_k^R = \Delta v_k - \Delta c_k - \Delta x_k$ if f_k is fixed after renegotiation at date 2. The renegotiation game is modeled in reduced form by applying the Generalized Nash Bargaining Solution (GNBS). The threatpoint of the renegotiation game is that renegotiation fails and that the inital contract is carried out. Let $\alpha \in (0, 1)$ denote the bargaining power of the buyer. Then the seller's payoff from renegotiating flaw f_k at date 2 is given by $(1 - \alpha)S_k^R$.

If a flaw f_k, $k \in \{1, \ldots, n\}$ exists but is not reported (either because no seller observed it or because a seller who observed it did not report it), then the flaw becomes apparent at date 3 when the project is (to a large degree) completed. If the buyer wants to change the design now, she has to write a new contract with a (potentially) new seller. At this stage all sellers are equally good at fixing the problem and the initial contract no longer binds the buyer to seller i. We do not model this stage explicitly but assume that if this stage is reached, flaw f_k reduces net utility of the buyer by Δv_k.

Finally, we posit that sellers are protected by limited liability, i.e. they can always

[5] This is what Williamson (1985, p. 61-63), has termed the "fundamental transformation".

declare bankruptcy to avoid making negative profits.

The time structure of the model can be summarized as follows.

Date 0: Nature determines the state of the world, i.e., the set of actual flaws F drawn from $\mathcal{P}(\hat{F})$ according to cdf $G(F)$ and each seller's cost type drawn from $[\underline{c}, \bar{c}]$ according to cdf $H(c^i)$.

Date 1: Procurement mechanism:

(a) The buyer announces that she wants to procure the good with design D_0.

(b) Seller $i \in \{1, 2\}$ privately observes his cost type and a set of flaws $F^i \in \mathcal{P}(F)$ according to cdf Q_F.

(c) A procurement mechanism is executed. This mechanism may induce the sellers to reveal (some of) their private information c^i and $\tilde{F}^i \subseteq F^i$. This determines the design $D(\tilde{F}^1 \cup \tilde{F}^2)$ of the good, it determines which seller is assigned the contract, and which payments are made.

Date 2: The buyer and the contractor may engage in contract renegotiation if the contractor observed a flaw that has not been revealed at stage 1(c).

Date 3: The state of the world becomes publicly observable and payoffs are realized.

4 Three Inefficiencies

In this section we discuss a simple example to point out the inefficiencies that arise if the buyer naïvely uses a standard price-only auction to allocate the procurement contract. In this example we assume that there is only one possible flaw denoted by f that exists with probability p. If the flaw exists, each seller observes it with probability q in which case $F^i = \{f\}$, with probability $1 - q$ he observes nothing, so $F^i = \emptyset$. We also assume that $\Delta c = 0$. Thus, if there is a design flaw and if the flaw is reported at date 1, then the problem can be solved at no additional cost. However, if the flaw is reported only at date 2 and the parties have to renegotiate, then there is an inefficiency Δx, with $\Delta v > \Delta x > 0$.

Suppose that the buyer uses a sealed-bid second-price auction. This auction implements the efficient allocation if the probability of a design flaw is 0. It is also revenue maximizing for the buyer if her valuation for the good is sufficiently high so that she wants to procure it with probability one.

Before the auction is conducted, the buyer asks the sellers whether they have detected a flaw in design D_0. If none of the suppliers reports a flaw, the buyer auctions off the procurement order for design D_0. If at least one of the suppliers reports the flaw f, the buyer understands the flaw, knows how to fix it, and puts the improved design $D(f)$ up for auction.

Observation 1. *Suppose the buyer uses a sealed-bid, second-price auction to allocate the procurement contract. Then, any seller who detected flaw f has a strict incentive to conceal this information. There is a unique symmetric Nash equilibrium in which each seller bids*

$$b(c^i, F^i) = \begin{cases} c^i - (1-\alpha)S^R & \textit{if } D = D_0 \textit{ and } F^i = \{f\} \\ c^i & \textit{otherwise} \end{cases}.$$

Proof. The proof focuses on the incentives of a seller to reveal the flaw. The bidding strategies in the second-price auction can be shown to be optimal by applying standard arguments.

Consider the case where there is a design flaw and seller 1 observed it. If the flaw was reported at date 1, there is no scope for renegotiation at date 2. In this case it is a weakly dominant strategy for each seller i to bid $b(c^i, \{f\}) = c^i$. Thus, seller 1's expected profit if he reveals the flaw (REV) is given by

$$\Pi^1(REV) = Prob[c^1 \leq c^2] \cdot E[c^2 - c^1 \mid c^1 \leq c^2]. \quad (1)$$

Alternatively, seller 1 could conceal the information, hope that he wins the auction, then report the flaw at date 2 and renegotiate. If he manages to get the contract and to renegotiate it, his payoff from renegotiation is given by $(1-\alpha)[\Delta v - \Delta x] = (1-\alpha)S^R$. Thus, if he conceals the flaw, it is a weakly dominant strategy for seller 1 to bid $b(c^1, f_1) =$

$c^1 - (1-\alpha)S^R$ in the auction at date 1.[6] Let q' denote the probability that seller 2 also observed the flaw given that seller 2 did not inform the buyer about it. Clearly, $q' \leq q$. With probability q' seller 2 bids $b(c^2, \{f\}) = c^2 - (1-\alpha)S^R$, with probability $1-q'$ he bids $b(c^2, \emptyset) = c^2$.[7] Thus, the expected payoff of seller 1 if he conceals the flaw (CON) is given by

$$\begin{aligned}
\Pi^1(CON) &= q' Prob\left[c^1 - (1-\alpha)S^R \leq c^2 - (1-\alpha)S^R\right] \\
&\quad \times E\left[c^2 - (1-\alpha)S^R - c^1 + (1-\alpha)S^R \mid c^1 - (1-\alpha)S^R \leq c^2 - (1-\alpha)S^R\right] \\
&\quad + (1-q')Prob\left[c^1 - (1-\alpha)S^R \leq c^2\right] \times E\left[c^2 - c^1 + (1-\alpha)S^R \mid c^1 - (1-\alpha)S^R \leq c^2\right] \\
&= q' Prob\left[c^1 \leq c^2\right] \times E\left[c^2 - c^1 \mid c^1 \leq c^2\right] + (1-q')Prob\left[c^1 - (1-\alpha)S^R \leq c^2\right] \\
&\quad \times E\left[c^2 - c^1 + (1-\alpha)S^R \mid c^1 - (1-\alpha)S^R \leq c^2\right] \; > \; \Pi^1(REV) \qquad (2)
\end{aligned}$$

The strict inequality follows from $q' \leq q < 1$, $Prob[c^1 - (1-\alpha)S^R \leq c^2] > Prob[c_1 \leq c^2]$ and $E\left[c^2 - c^1 + (1-\alpha)S^R \mid c^1 - (1-\alpha)S^R \leq c^2\right] > E[c^2 - c^1 \mid c^1 \leq c^2]$. This is very intuitive. With probability q' seller 2 also observed the design flaw. In this case competition in the auction induces both sellers to reduce their bids by exactly $(1-\alpha)S^R$ – the amount each of them would gain if he wins the contract. Thus, in this case payoffs are the same as in the case with no renegotiation. With probability $(1-q')$, however, seller 1 is the only one who observed the flaw. In this case he gets an additional rent of $(1-\alpha)S^R$ if he manages to win the contract which happens with strictly positive probability.

□

It is strictly optimal for a seller not to report the flaw at date 1, but to keep this information to himself, bid more aggressively in the auction, and if he wins the auction to benefit from renegotiating the contract. The finding that a seller has an incentive to conceal his information because it gives him an advantage in the auction may trigger three inefficiencies if a price-only auction is used. First, because the flaw is only revealed at date

[6]Note that this strategy is weakly dominant given the reduced form outcome of the renegotiation game.

[7]If seller 2 did not observe any flaw, he may still expect that there is a flaw with positive probability. However, as long as he does not know the flaw, this is of no relevance to him. The flaw will become apparent at date 3 only, when the initial contract expires and the contractor has no advantage over other sellers anymore.

1 the parties have to renegotiate with positive probability and incur the renegotiation cost $\Delta x > 0$. Second, if $c^i > c^j$ and i observes the flaw while j does not, it may happen that $c^i - (1-\alpha)S^R < c^j$. In this case the seller with the higher cost gets the contract which is inefficient – i.e., the auction does not achieve efficient production. Finally, if $c^i > c^j$ and i observes the flaw while j does not, it may happen that $c^i - (1-\alpha)S^R > c^j$. In this case the lower cost seller gets the contract, but the flaw is not fixed and $S^R = \Delta v - \Delta x$ cannot be realized.

Proposition 1 (Three Inefficiencies)**.** *Suppose the buyer uses a sealed-bid, second-price auction to allocate the procurement contract. Then, three inefficiencies arise.*

1. *Inefficient Renegotiation:*
   With probability $pq\left[q + 2(1-q) \times Prob(c^i - (1-\alpha)S^R < c^j)\right]$ *there is a design flaw that is detected by at least one seller who wins the auction. In this case the design flaw is fixed via renegotiation which is inefficient because the parties have to incur* $\Delta x > 0$.

2. *Inefficient Production:*
   With probability $2pq(1-q) \times Prob(c^j < c^i < c^j + (1-\alpha)S^R)$ *there is a design flaw that is detected by one seller, this seller has higher production costs but wins the auction because of his expected profit in the renegotiation game. In this case production is carried out inefficiently by the seller with the higher cost.*

3. *Inefficient Design:*
   With probability $2pq(1-q) \times Prob(c^j < c^i - (1-\alpha)S^R)$ *there is a design flaw that is detected by one seller, but this seller does not win the auction. In this case the design flaw is not reported to the buyer and it cannot be fixed, so the buyer has to incur the loss of* Δv *which is inefficient.*

The question arises whether there is a mechanism that induces sellers to report a design flaw at date 1 and that allocates the contract to the seller with the lowest cost. In the next section we focus on the first problem assuming that there are no cost differences between sellers, so that *Inefficient Renegotiation* is the only issue. Furthermore, we restrict attention to the case of just one possible design flaw for notational simplicity. In Section 5 we allow for cost differences between sellers in order to address the problems of *Inefficient Production* and *Inefficient Design*, and we allow for multiple design flaws. We discuss how these problems interact and show that there exists an efficient and informationally robust mechanism that solves all three problems.

5 Inducing Sellers to Report a Design Flaw Early

In this section we focus on how to optimally induce sellers to report a design flaw early. We abstract from cost differences between firms and assume that $c^1 = c^2 = c$ is commom knowledge. Furthermore, we restrict attention to only one design flaw. We proceed in two steps. First, we assume that the mechanism designer knows all the parameters of the model. We derive a direct mechanism that induces both sellers to reveal their private information at date 1 and that implements the efficient allocation at the lowest cost for the buyer. In the second step we show that there exists an indirect mechanism that implements the same allocation but that is informationally robust. It does not require the mechanism designer to know any of the parameters of the model when she sets up the mechanism.

5.1 The Optimal Mechanism Design Problem

Consider the problem of a mechanism designer who knows that there is one potential flaw f and who knows the values of v, c, Δv, Δc, and Δx, and the probabilities p and q. Each seller i, $i \in \{1, 2\}$, is one of two possible types. If he did not observe a design flaw, he is (with a slight abuse of notion) of type $\emptyset$. This is the case if either there is no flaw (in state $F = \emptyset$) or if there is a flaw (in state $F = \{f\}$) but the seller did not observe it. If the seller observed the flaw, he is of type f which happens with probability pq.

A direct mechanism asks each seller i to send a message $\tilde{F}^i \in \{\emptyset, f\}$. In words, a seller either claims that he did not observe anything, $\tilde{F}^i = \emptyset$, or he reports that he observed the flaw, $\tilde{F}^i = f$. While message $\tilde{F}^i = \emptyset$ can always be sent, message $\tilde{F}^i = f$ is feasible only if supplier i indeed observed the flaw f (is of type f). The mechanism specifies a transfer t^i, paid by the buyer and received by seller i, a design $D \in \{D_0, D_f\}$ that has to be delivered, and a probability ω^i with which seller i has to deliver the good that depend on both messages. Because the problem is symmetric we restrict attention to symmetric mechanisms, i.e.

$$\omega^i = \omega(\tilde{F}^i, \tilde{F}^j) \in [0,1], \quad \text{and} \quad t^i = t(\tilde{F}^i, \tilde{F}^j) \in \mathbb{R}$$

with $j \neq i$. The design is the same for both sellers, so $D = D(\tilde{F}^1, \tilde{F}^2)$.

The mechanism designer wants to implement an efficient outcome. This requires:

(i) The specified design is optimal given the available information (efficient design, ED)

$$D(\tilde{F}^1, \tilde{F}^2) = \begin{cases} D_0 & \text{if } \tilde{F}^1 = \tilde{F}^2 = \emptyset \\ D_f & \text{otherwise} \end{cases} \tag{ED}$$

(ii) Production always takes place (efficient production, EP, because the good is sufficiently valuable to the buyer)

$$\omega(\tilde{F}^1, \tilde{F}^2) + \omega(\tilde{F}^2, \tilde{F}^1) = 1 \quad \forall\, \tilde{F}^1, \tilde{F}^2 \in F \tag{EP}$$

(iii) It is optimal for an informed seller to reveal the state truthfully (incentive compatibility, IC)

$$\begin{aligned} &q[t(f,f) - \omega(f,f)(c+\Delta c)] + (1-q)[t(f,\emptyset) - \omega(f,\emptyset)(c+\Delta c)] \\ &\quad \geq q[t(\emptyset,f) - \omega(\emptyset,f)(c+\Delta c)] + (1-q)[t(\emptyset,\emptyset) - \omega(\emptyset,\emptyset)(c-(1-\alpha)S^R)] \end{aligned} \tag{IC}$$

(iv) Sellers make non-negative profits because they are protected by limited liability, i.e. they can walk away (declare bankruptcy) if the mechanism imposes a negative payoff

$$t(\tilde{F}^i, \tilde{F}^j) - \omega(\tilde{F}^i, \tilde{F}^j)\; C^i(D(\tilde{F}^1, \tilde{F}^2)) \geq 0 \quad \forall\, \tilde{F}^i, \tilde{F}^j \in F \tag{LL}$$

Note that (LL) implies that all sellers voluntarily participate in the mechanism (individual rationality).

We want to find a mechanism that implements the efficient allocation at the lowest possible cost to the buyer.[8] Thus, the mechanism design problem can be stated as follows:

$$\min_{t(\cdot,\cdot)} 2t(\emptyset,\emptyset)[p+(1-p)(1-q)^2] \\ + 2t(f,f)(1-p)q^2 + 2[t(f,\emptyset)+t(\emptyset,f)](1-p)(1-q)q$$

subject to (ED), (EP), (IC) and (LL).

Let $u(\tilde{F}^i,\tilde{F}^j)$ denote the expected payoff that supplier i obtains from participating in the mechanism at date 1 (not including any additional payoffs from renegotiation at date 2), i.e.

$$u(\tilde{F}^i,\tilde{F}^j) \equiv t(\tilde{F}^i,\tilde{F}^j) - \omega(\tilde{F}^i,\tilde{F}^j)C^i(D(\tilde{F}^i,\tilde{F}^j)). \tag{3}$$

Limited liability is satisfied if and only if for all $\tilde{F}^i,\tilde{F}^j \in \{\emptyset, f\}$ it holds that $u(\tilde{F}^i,\tilde{F}^j) \geq 0$. With this notation the incentive constraint can be written as

$$qu(f,f) + (1-q)u(f,\emptyset) \geq qu(\emptyset,f) + (1-q)u(\emptyset,\emptyset) + (1-q)\omega(\emptyset,\emptyset)(1-\alpha)S^R \tag{IC}$$

Notice that symmetry together with (EP) implies that $\omega(\emptyset,\emptyset) = 1/2$. Obviously the buyer has an incentive to choose $u(\emptyset,\tilde{F}^j) = 0$ for all $\tilde{F}^j \in \{\emptyset, f\}$: Doing so relaxes the (IC) constraint and reduces the expected transfer. Hence, the mechanism design problem simplifies to

$$\min_{u(f,f),\, u(f,\emptyset)} \quad 2qu(f,f) + 2(1-q)u(f,\emptyset)$$

subject to:

$$u(f,f) \geq 0, \qquad u(f,\emptyset) \geq 0 \tag{LL}$$

$$qu(f,f) + (1-q)u(f,\emptyset) \geq (1-q)(1-\alpha)S^R/2 \tag{IC}$$

Note that (IC) must hold with equality in the optimal solution and that the buyer is indifferent between all utility vectors that achieve this. Thus, the following pair of payoffs is a solution to the problem:

$$u^*(f,f) = 0, \qquad u^*(f,\emptyset) = (1-\alpha)S^R/2.$$

[8] Note that this allocation is efficient but not necessarily profit maximizing. The buyer may achieve higher expected profits if she is willing to accept that design flaws are not always reported at date 1.

Proposition 2 (Optimal Direct Mechanism)**.** *The following efficient direct mechanism induces each seller of type f to report his type truthfully at the lowest possible cost to the buyer:*

$$\begin{aligned}
&D^*(\emptyset,\emptyset) = D_0, \qquad && \omega^*(\emptyset,\emptyset) = \frac{1}{2}, \qquad && t^*(\emptyset,\emptyset) = \frac{c}{2} \\
&D^*(\emptyset,f) = D_f, && \omega^*(\emptyset,f) = 0, && t^*(\emptyset,f) = 0 \\
&D^*(f,\emptyset) = D_f, && \omega^*(f,\emptyset) = 1, && t^*(f,\emptyset) = c + \Delta c + \frac{(1-\alpha)S^R}{2} \\
&D^*(f,f) = D_f, && \omega^*(f,f) = \frac{1}{2}, && t^*(f,f) = \frac{c+\Delta c}{2}
\end{aligned}$$

Proof. The result is proven in the text above. □

Note that $t^*(\emptyset,\emptyset)$ and $t^*(f,f)$ are the expected transfers. If both sellers make the same announcement, each seller gets the contract with probability 0.5. In order to satisfy ex post limited liability, the seller who produces the good is reimbursed his cost, while the other seller receives nothing.

The mechanism of Proposition 2 is very intuitive. If one seller reports the flaw while the other one does not, then the former produces the good with the adjusted design D_f and gets a strictly positive rent, while the latter gets a utility of zero. This rent is necessary to induce the seller to reveal his information ex ante rather than to wait and renegotiate after having received the contract. Note that if the seller claims $\emptyset$, then – given that the other seller also claims $\emptyset$ – he gets the contract only with probability 1/2. Thus, the rent that has to be paid is only $\frac{1}{2}(1-\alpha)S^R$. With N sellers this rent can be reduced to $\frac{1}{N}(1-\alpha)S^R$ because the probability of getting the contract if all sellers report $\emptyset$ is only $1/N$. If two sellers (or more) report f, there is no need to pay a rent to these sellers because each of them would receive the contract with probability zero if he claimed to be of type $\emptyset$.

5.2 The Arbitration Mechanism

So far we assumed that the mechanism designer knows all the parameters of the problem when he sets up the mechanism. However, a typical buyer does not have this information. She is not aware of the design flaw, she does not know the probability that there is a flaw nor the likelihood that any of the sellers is going to find it, and she does not know how the flaw looks like and how costly it is to fix it. However, the buyer is aware that she is unaware. She knows that mistakes happen and that they can be very costly if they are not fixed early. Thus, she would like to prepare for this possibility and to give incentives to the sellers to reveal their information at date 1 already.

One possibility to achieve this is the use of a knowledgeable independent arbitrator. If a seller reveals a design flaw, the flaw becomes obvious to any expert in the industry. Thus, a knowledgeable arbitrator understands the flaw, she knows how it can be fixed and she knows the payoff consequences if the flaw is fixed early rather than late. The buyer can commit ex ante to using such an independent arbitrator and to follow her verdict. In particular, she can set up the following indirect mechanism that will be called the *Arbitration Mechanism* in the following:

1) The buyer publicizes her design proposal D_0 and invites all potential sellers to evaluate the proposal and to report possible design flaws in sealed envelopes to an independent arbitrator.

2) If there is a design flaw that is reported by at least one seller, the arbitrator evaluates the flaw and its consequences, i.e. she estimates Δv, Δc and Δx.

3) The contract is allocated as follows:

   – If none of the sellers reports a design flaw, one of them is selected randomly and gets the contract to produce D_0 and receives payment c.

   – If only one seller reports the design flaw he gets the contract to produce D_f and the payment $c + \Delta c + (1 - \alpha)S^R/2$.

   – If both sellers report the design flaw, each of them gets the contract to produce D_f and the payment $c + \Delta c$ with probability $1/2$ while the other one gets nothing.

4) If no flaw was reported but the seller who got the contract observed a flaw, he may renegotiate the contract with the buyer.

Proposition 3 (Arbitration Mechanism). *The Arbitration Mechanism is an efficient mechanism that is cost minimizing for the buyer. It implements the same allocation as the optimal direct mechanism of Proposition 2. Furthermore, the arbitration mechanism is informationally robust, i.e. it does not require the ex ante knowledge of* p, q, v, Δv, Δc *and* Δx.

Proof. The Arbitration Mechanism gives rise to the same monetary outcomes and the same incentives for each seller as the mechanism of Proposition 2. Thus, given that it is an equilibrium in the direct mechanism for each seller to reveal the design flaw early, it is also an equilibrium in the Arbitration Mechanism. The mechanism is informationally robust because it is independent of the probabilities p and q and because the reward for reporting a design flaw is determined ex post by the independent arbitrator. □

Informational robustness is a highly desirable property of the Arbitration Mechanism. The buyer must be aware that there could be a design flaw, but she does not have to know how this flaw looks like, what payoff consequences it implies, and what the probabilities p and q are. However, the buyer has to be able to assess her bargaining power α if the initial contract has to be renegotiated. Furthermore, the independent arbitrator must be able to assess Δv, Δc and Δx after the flaw has been pointed out to her. The existence of such an independent industry expert seems plausible when a design flaw has to be evaluated. It may be less plausible if the seller comes up with ideas for new features of the product that may be valuable for the buyer. In this case it is more difficult for an outsider to assess exactly how valuable the idea of the seller is for the buyer. [Discuss this in more detail, preferably in the introduction.]

6 Multiple Design Flaws and Seller Heterogeneity

In this section we generalize the optimal mechanism derived in Section 5 in two directions. First, sellers may have different costs which are private information. Second, we allow for multiple design flaws. With some probability each seller observes some subset F^i of the set of actual flaws F. Efficiency requires that the seller with the lowest cost produces the good and that both sellers are induced to reveal all flaws that they observed at date 1.

The mechanism design problem is now more intricate. The optimal mechanism in Section 5 allocates the contract by a coin flip if both producers claim not to have observed any flaw. This minimizes the information rent that has to be paid to a seller. If both sellers have the same cost, a random allocation is efficient, but if sellers have different costs, efficiency requires that the seller with the lower cost gets the contract with probability 1. We show in this section that this increases the information rent that has to be paid to the seller.

Note that we are now dealing with a multi-dimensional mechanism design problem. Sellers have to be induced to report both the observed design flaws and their cost parameter truthfully. In subsection 6.1 we derive a mechanism that implements the efficient allocation. In subsection 6.2 we show that this mechanism is informationally robust and that it implements the efficient allocation at the lowest possible cost to the buyer in the sense that there does not exist any other informationally robust mechanism that implements the efficient outcome at a lower cost for all possible parameter distributions. In subsection 6.3 we derive an informationally robust indirect mechanism that replicates the optimal direct mechanism without requiring any ex ante knowledge of the underlying parameters and probability distributions.

6.1 The Mechanism Design Problem

We return to the general model described in Section 3. As in Section 5 we start out assuming that the mechanism designer knows all parameters of the model, i.e. the set of possible cost types $[\underline{c}, \bar{c}]$, the set of possible flaws $\hat{F} = \{f_1, \ldots, f_n\}$, the costs Δv_k, Δc_k and Δx_k associated with each potential flaw $k \in \{1, \ldots, n\}$, and the (conditional) probability distributions $G(F)$, $H(c)$, and Q_F. In the next subsection we will relax this assumption. Note that the type of seller i is now multi-dimensional: it consists of a cost type c^i and an information type F^i (the set of flaws that seller i observed). Thus, the type of seller i is $(c^i, F^i) \in [\underline{c}, \bar{c}] \times \mathcal{P}(F)$.

We focus on direct mechanisms that ask each seller i to send a message $(\tilde{c}^i, \tilde{F}^i) \in [\underline{c}, \bar{c}] \times \mathcal{P}(F)$. Put verbally, each seller i reports a cost $\tilde{c}^i$ and a set of observed flaws $\tilde{F}^i$. Supplier i is free to report any cost $\tilde{c}^i \in [\underline{c}, \bar{c}]$ but is restricted to report only flaws that he observed. Of course, he can always decide to conceal some or all of the detected flaws, i.e. $\tilde{F}^i \subseteq F^i$ or $\tilde{F}^i = \emptyset$.

The (symmetric) direct mechanism specifies for any announced types $((\tilde{c}^1, \tilde{F}^1), (\tilde{c}^2, \tilde{F}^2))$ a design $D = D((\tilde{c}^1, \tilde{F}^1), (\tilde{c}^2, \tilde{F}^2))$, a transfer $t^i = t((\tilde{c}^i, \tilde{F}^i), (\tilde{c}^j, \tilde{F}^j))$ paid by the buyer and received by seller i, and a probability $\omega^i = \omega((\tilde{c}^i, \tilde{F}^i), (\tilde{c}^j, \tilde{F}^j))$ with which seller i gets the contract – i.e., with probability ω^i seller i has to produce the good, for $i, j \in \{1, 2\}$ and $i \neq j$.

The mechanism designer seeks to induce an efficient outcome. Therefore, the mechanism has to satisfy four constraints. Efficient design (ED); (ii) efficient production (EP); (iii) incentive compatibility (IC); and (iv) limited liability (LL).

(i) The specified design is optimal given the available information (efficient design, ED)

$$D((c^1, F^1), (c^2, F^2)) = D(F^1 \cup F^2) \tag{ED}$$

(ii) The good is produced by the seller with the lowest cost (efficient production, EP)

$$\omega((c^i, F^i), (c^j, F^j)) = \begin{cases} 1 & \text{if } c^i < c^j \\ 1/2 & \text{if } c^i = c^j \\ 0 & \text{if } c^i > c^j \end{cases} \tag{EP}$$

(iii) It is optimal for each seller to reveal his type truthfully (incentive compatibility, IC)

$$\begin{aligned} &\forall\ i \in \{1, 2\},\ F^i, F^j \subseteq F,\ c^i, c^j \in [\underline{c}, \bar{c}]\ : \\ &\mathbb{E}_{(c^j, F^j)} \left\{ t((c^i, F^i), (c^j, F^j)) - \omega((c^i, F^i), (c^j, F^j)) \left[c^i + \sum_{\{k | f_k \in F^i \cup F^j\}} \Delta c_k \right] \right\} \geq \\ &\max_{\tilde{F}^i \subseteq F^i, \tilde{c}^i \in [\underline{c}, \bar{c}]} \mathbb{E}_{(c^j, F^j)} \left\{ t((\tilde{c}^i, \tilde{F}^i), (c^j, F^j)) - \omega((\tilde{c}^i, \tilde{F}^i), (c^j, F^j)) \left[c^i + \sum_{\{k | f_k \in \tilde{F}^i \cup F^j\}} \Delta c_k \right] \right. \\ &\qquad \left. + \, \omega((\tilde{c}^i, \tilde{F}^i), (c^j, F^j))(1 - \alpha) S^R(F^i, D(\tilde{F}^i \cup F^j)) \right\}. \end{aligned} \tag{IC}$$

(iv) Sellers make non-negative profits (limited liability, LL)

$$\forall\ i \in \{1,2\}, F^i, F^j \subseteq F,\ c^i, c^j \in [\underline{c}, \bar{c}]\ :$$
$$t((c^i,F^i),(c^j,F^j)) - \omega((c^i,F^i),(c^j,F^j))\left[c^i + \sum_{\{k|f_k \in F^i \cup F^j\}} \Delta c_k\right] \geq 0. \quad \text{(LL)}$$

Note that (LL) implies that all sellers voluntarily participate in the mechanism (individual rationality).

Proposition 4 (Efficient Direct Mechanism)**.** *The following direct mechanism implements the efficient allocation; i.e., it satisfies (ED), (EP), (IC), and (LL):*

$$D^*((c^1,F^1),(c^2,F^2)) = D^*(F^1,F^2) = D(F^1 \cup F^2)$$

$$\omega^*((c^i,F^i),(c^j,F^j)) = \omega^*(c^i,c^j) = \begin{cases} 1 & \textit{if}\ \ c^i < c^j \\ 1/2 & \textit{if}\ \ c^i = c^j \\ 0 & \textit{if}\ \ c^i > c^j \end{cases}$$

$$t^*((c^i,F^i),(c^j,F^j)) = \omega^*(c^i,c^j)\left[c^j + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k\right] + (1-\alpha)S^R(F^i, D(F^j))$$

With this mechanism no seller has an incentive to revise his announcement after learning the announcement of the other seller, i.e., the mechanism is ex post incentive compatible.[9]

Proof. The above mechanism obviously satisfies (ED), (EP), and (LL). It remains to be shown that the (IC)-constraint is also satisfied. A sufficient condition for (IC) to hold is ex post incentive compatibility – i.e., in any possible state no seller can gain by misreporting his type no matter what type was revealed by the other seller (no regret). Ex post incentive compatibility is satisfied if and only if for all $i \in \{1,2\}$, $c^i, c^j, \tilde{c}^i \in [\underline{c}, \bar{c}]$,

[9] Note again that t^* is the expected transfer payment. If $c^i = c^j$ each seller gets the contract with probability one half. To make sure that (LL) is always satisfied the actual transfer payment is given by $[c^i + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k] + (1-\alpha)S^R(F^i, D(F^j))$ if seller i gets the contract and $(1-\alpha)S^R(F^i, D(F^j))$ otherwise.

$F^i, F^j \subseteq F$ and $\tilde{F}^i \subseteq F^i$ the following inequality holds:

$$
\begin{aligned}
t((c^i, F^i), (c^j, F^j)) - \omega((c^i, F^i), (c^j, F^j)) \left[c^i + \sum_{\{k | f_k \in F^i \cup F^j\}} \Delta c_k \right] \geq \\
t((\tilde{c}^i, \tilde{F}^i), (c^j, F^j)) - \omega((\tilde{c}^i, \tilde{F}^i), (c^j, F^j)) \left[c^i + \sum_{\{k | f_k \in \tilde{F}^i \cup F^j\}} \Delta c_k \right] \\
+ \omega((\tilde{c}^i, \tilde{F}^i), (c^j, F^j))(1-\alpha) S^R(F^i, D(\tilde{F}^i \cup F^j)). \quad \text{(EPIC)}
\end{aligned}
$$

Using the expression for the transfer payments, the (EPIC) constraint can be written as

$$
\begin{aligned}
\omega^*(c^i, c^j)[c^j - c^i] + (1-\alpha) S^R(F^i, D(F^j)) \geq \\
\omega^*(\tilde{c}^i, c^j)[c^j - c^i + (1-\alpha) S^R(F^i, D(\tilde{F}^i \cup F^j))] + (1-\alpha) S^R(\tilde{F}^i, D(F^j)). \quad (4)
\end{aligned}
$$

First, note that

$$
\begin{aligned}
& S^R(\tilde{F}^i, D(F^j)) + S^R(F^i, D(\tilde{F}^i \cup F^j)) \\
&= \sum_{\{k | f_k \in \tilde{F}^i \setminus F^j\}} \Delta v_k - \Delta c_k - \Delta x_k + \sum_{\{k | f_k \in F^i \setminus F^j \cup \tilde{F}^i\}} \Delta v_k - \Delta c_k - \Delta x_k \\
&= \sum_{\{k | f_k \in F^i \setminus F^j\}} \Delta v_k - \Delta c_k - \Delta x_k = S^R(F^i, D(F^j)). \quad (5)
\end{aligned}
$$

Using (5), (4) reduces to

$$
\omega^*(c^i, c^j)[c^j - c^i] \geq \omega^*(\tilde{c}^i, c^j)[c^j - c^i] - [1 - \omega^*(\tilde{c}^i, c^j)](1-\alpha) S^R(F^i, D(\tilde{F}^i \cup F^j)). \quad (6)
$$

Thus, given that $\omega^* \leq 1$ it never pays off for a seller to misreport the observed flaws. The remaining question is whether a seller can benefit from misreporting his cost. Given that the set of observed flaws is revealed truthfully, inequality (6) simplifies to

$$
\omega^*(c^i, c^j)[c^j - c^i] \geq \omega^*(\tilde{c}^i, c^j)[c^j - c^i]. \quad (7)
$$

If $c^i < c^j$, we have $\omega^*(c^i, c^j) = 1$, so misreporting cannot be beneficial. If $c^i > c^j$, we have $\omega^*(c^i, c^j) = 0$, so misreporting can lead to seller i getting the contract but this is not in seller i's interest because $[c^j - c^i] < 0$. For the knife-edge case $c^j = c^i$, seller i is indifferent between all potential cost reports – i.e., reporting truthfully is a best response. $\square$

Each seller i has to be induced to report his information F^i and his cost c^i truthfully. The direct mechanism of Proposition 4 separates these two problems. It induces the seller to report his information F^i by paying him $(1-\alpha)S^R(\tilde{F}^i, D(F^j))$ if he reports $\tilde{F}^i$. This is exactly the rent that seller i can obtain by revealing $\tilde{F}^i$ ex post – at the renegotiation stage – rather than ex ante. Thus, the mechanism is ex post incentive compatible, i.e. no seller has an incentive to revise his decision after learning the announcement $\tilde{c}^j, \tilde{F}^j$ of the other seller.

It is useful to compare this mechanism to the mechanism of Proposition 2. Suppose that there is at most one flaw and this flaw is reported by seller i but not by seller j. Then, according to the mechanism of Proposition 4, seller i obtains a rent of $(1-\alpha)S^R$.[10] This rent is larger than the rent $\frac{1}{2}(1-\alpha)S^R$, which was paid by the direct mechanism of Proposition 2. The reason is that in Proposition 2 the contract was allocated randomly if both sellers claim to be of type $\emptyset$, while the mechanism of Proposition 4 allocates the contract to the seller with the lowest cost.

An important question is whether the buyer can reduce the information rent of a seller who observed one or more flaws? If the mechanism designer knows all the probability distributions, in particular the distribution of cost types H, then the answer is yes. For the sake of the argument, consider the scenario with at most one flaw. Suppose seller i observed the flaw and has relatively high cost. In order to obtain the contract with a high probability – and then being able to profit from renegotiation – seller i has to under-report his cost significantly. This, however, is costly to seller i. Suppose seller j reports his cost $c^j < c^i$ truthfully. Thus, the ex post utility of seller i from obtaining the contract and concealing the flaw is $(1-\alpha)S^R - (c^i - c^j)$. In other words, the higher the cost type, the lower the incentive of a seller to conceal the flaw. This suggests that the transfer a seller obtains for revealing the flaw could be reduced by making it contingent on the announced costs (c^i, c^j). However, in order to make such a mechanism incentive compatible, the buyer has to know the distribution of cost types.

[10] In this case we have $F = \{\emptyset, \{f\}\}$ and (with slight abuse of notation) can define $S^R := S^R(f, D_0)$.

6.2 Informational Robust Implementation

The buyer does not know the probability distributions G, Q_F, and H. The next proposition shows that the direct mechanism of Proposition 4 is an informationally robust efficient mechanism; i.e., it implements the efficient allocation no matter what these probability distributions are (even the support can be unknown). Furthermore, the mechanism is the informationally robust mechanism that implements the efficient allocation at the lowest possible cost to the buyer.

Proposition 5 (Informational Robustness and Optimality)**.**

(a) The mechanism of Proposition 4 is informationally robust, i.e. it implements the efficient allocation for any probability distributions G, Q_F, and H and for any higher order beliefs that the sellers may have.

(b) There does not exist any other informationally robust direct mechanism that implements the efficient outcome at a lower cost for the buyer for all possible parameter distributions.

Proof. See Appendix. □

6.3 The Extended Arbitration Mechanism

The mechanism of Proposition 4 assumes that the buyer knows all the parameters of the problem when she designs the optimal revelation mechanism. However, this assumption is not necessary. An extended version of the *Arbitration Mechanism* introduced in Section 4.2 implements the same allocation as the optimal mechanism of Proposition 4 and does not require that the buyer knows anything about the nature or the payoff consequences of possible flaws, nor does she have to know the probability distributions over the realization of these flaws and over the costs of the seller. However, the buyer has to be aware that flaws are possible and she has to be able to commit to using an independent arbitrator who understands the flaws once they have been pointed out to her and who determines payoffs ex post after flaws have been revealed. The *Extended Arbitration Mechanism* is defined as follows:

1) The buyer publicizes her initial design proposal D_0 and invites all potential sellers

to evaluate the proposal and to report possible design flaws in sealed envelopes to an independent arbitrator.

2) Let $\tilde{F}^i$ denote the set of flaws reported by seller $i \in \{1, 2\}$. The arbitrator evaluates all flaws $f_k \in \tilde{F} \equiv \tilde{F}^1 \cup \tilde{F}^2$ and their potential consequences, i.e., for any reported flaw f_k she estimates Δv_k, Δc_k and x_k. She awards the following reward to each seller i:

$$T_1^i(\tilde{F}^i, \tilde{F}^j) = (1 - \alpha) S^R(\tilde{F}^i, D(\tilde{F}^j)) \tag{8}$$

3) The buyer uses the information on the reported design flaws $\tilde{F}$ to redesign the good to $D(\tilde{F})$ and runs a sealed-bid, second-price auction. Each seller $i \in \{1, 2\}$ submits a bid b^i, the contract is allocated to the lowest bidder, and seller i receives

$$T_2^i = \begin{cases} b^j & \text{if } b^i < b_j \\ b^j/2 & \text{if } b^i = b_j \\ 0 & \text{if } b^i > b^j \end{cases} . \tag{9}$$

If both sellers place the same bid $b^1 = b^2 = b$, one seller is selected at random and obtains the contract at price b.

4) If seller i got the contract and if he observed design flaws f_k that have not been revealed to the buyer at stage 1, he may renegotiate the contract with the buyer.

Proposition 6 (Extended Arbitration Mechanism)**.** *The Extended Arbitration Mechanism is an efficient and informationally robust mechanism. It implements the same allocation as the direct mechanism of Proposition 4 at the same cost, but it does not require the ex ante knowledge of F, Δv_k, Δc_k and x_k for all $k \in \{1, \ldots, n\}$.*

Proof. The Extended Arbitration Mechanism gives rise to the same monetary outcomes and the same incentives for each seller as the mechanism of Proposition 4. Thus, given that it is an equilibrium in the direct mechanism for each seller to reveal all observed design flaws early, it is also an equilibrium in the Extended Arbitration Mechanism. Furthermore, given that all observed flaws have been revealed it is optimal for each seller to bid his true cost in the sealed-bid, second-price auction. Hence, with the Extended

Arbitration Mechanism the total payment that seller i receives is given by

$$T_1^i + T_2^i = (1-\alpha) S^R(\tilde{F}^i, D(\tilde{F}^j)) + \begin{cases} c_j + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k & \text{if } c^i < c_j \\ (1/2)\left(c_j + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k\right) & \text{if } c^i = c_j \\ 0 & \text{if } c^i > c^j \end{cases}, \quad (10)$$

where $T_1^i + T_2^i$ denotes the expected total payment. The mechanism is informationally robust because it is independent of the probability distributions G, Q_F, and H, and because the reward for reporting design flaws is determined ex post by the independent arbitrator. By Proposition 5 it is ϵ-optimal. □

The Extended Arbitration Mechanism is a two-stage mechanism that separates the problems of (i) inducing sellers to reveal observed design flaws early, and (ii) allocating the contract to the seller with the lowest cost. This separation is necessary if the buyer wants to implement an efficient allocation. If the buyer ties the allocation of the contract to the revelation of design flaws (e.g. by offering bonus points that create an advantage in the auction for sellers who reveal flaws early), then the buyer may be able to reduce the rent that has to be paid to sellers, but this comes at the price that the allocation is inefficient with positive probability.

The Extended Arbitration Mechanism requires the commitment of the buyer to pay sellers for the information on design flaws that they provide. The simplest and most transparent way to do this is the use of an independent third party. However, there are also other ways how to achieve this commitment. For example, if the buyer frequently procures similar projects, i.e., if she is in a repeated relationship with the sellers, and if the allocation procedure is fully transparent, then she may be able to credibly commit to paying out $T_1^i(\tilde{F}_i, \tilde{F}_j) = (1-\alpha) S^R(\tilde{F}_i, D(\tilde{F}_j))$ herself. If parties are sufficiently patient, this commitment is sustained by the threat of the sellers not to reveal any design flaws in the future if the buyer ever reneges on her promise.

7 Incentives to Invest in Finding Design Flaws

So far, we assumed that sellers receive the signal about design flaws for free. In reality finding flaws requires effort and other costly resources. Thus, the question arises whether the Extended Arbitration Mechanism provides optimal incentives to invest into finding flaws.

We analyze the investment incentives of the two sellers for the baseline model with at most one flaw; i.e., $\hat{F} = \{\emptyset, \{f\}\}$. The flaw exists with probability $p \in (0,1)$. If the flaw exists and is detected and revealed ex ante, this creates a social surplus of $S = \Delta v - \Delta c$. If the flaw is revealed only at the renegotiation stage, the social surplus is reduced to $S^R = \Delta v - \Delta c - x > 0$.

Each seller i can invest resources in order to increase the probability of detecting the flaw if it exists. The probability of detecting the flaw if it exists is q when seller i invests the amount $\phi^i(q)$. Recall that the mechanism separates the problem of flaw revelation and production. Thus, we can focus on the profits a seller obtains from detecting and revealing the flaw. The expected profit of seller i under the Extended Arbitration Mechanism (ignoring potential profits from production) is

$$\pi^i(q^i) = pq^i(1 - \hat{q}^j)(1 - \alpha)S^R - \phi^i(q^i), \tag{11}$$

where $\hat{q}^j$ with $j \neq i$ is the investment made by the competitor.

A social planner, who can choose q^1 and q^2, maximizes

$$W(q^1, q^2) = p(q^1 + q^2 - q^1 q^2)S - \phi^1(q^1) - \phi^2(q^2). \tag{12}$$

The welfare optimal investments are

$$(q^{1*}, q^{2*}) \in arg \max_{q^1, q^2} \; W(q^1, q^2). \tag{13}$$

We assume that there exists a unique welfare maximizing tuple of investment levels (q^{1*}, q^{2*}).

With the Extended Arbitration Mechanism seller i receives less than the social value generated by his efforts. He receives only share $(1-\alpha) < 1$ of the *renegotiation* surplus, which is the social surplus reduced by the cost of renegotiation. Thus, the Extended Arbitration Mechanism induces sellers to underinvest into finding design flaws. This problem can easily be fixed by replacing T_1^i in the Extended Arbitration Mechanism by the full social surplus S; i.e., if seller i reports the flaw and seller j reports nothing, seller i obtains a payment of S and nothing otherwise. Now, the expected profit of seller i amounts to

$$\pi^i(q^i) = pq^i(1-\hat{q}^j)S - \phi^i(q^i) \tag{14}$$

Proposition 7 (Investment Incentives). *Suppose the Arbitration Mechanism specifies $\hat{T}_1^i(f,\emptyset) = S$ and $\hat{T}_1^i(f,f) = \hat{T}_1^i(\emptyset,f) = \hat{T}_1^i(\emptyset,\emptyset) = 0$. This mechanism induces both sellers to reveal their information truthfully, it allocates the contract to the seller with the lowest cost, and it induces both sellers invests efficiently; i.e., $(q^1,q^2) = (q^{1*},q^{2*})$.*

Proof. By the definition and the uniqueness of the welfare optimal investment levels, we can write

$$q^{i*} = arg\max_{q^i} W(q^i,q^{j*}) = arg\max_{q^i} \left\{p(q^i+q^{j*}-q^iq^{j*})S - \phi^i(q^i) - \phi^j(q^{j*})\right\}, \tag{15}$$

for $i,j \in \{1,2\}$ and $i \neq j$.

If seller i expects that seller j invests efficiently – i.e., $q^j = q^{j*}$, then the expected profit of i is

$$\pi^i(q^i) = pq^i(1-\hat{q}^{j*})S - \phi^i(q^i). \tag{16}$$

The above expression is maximized at the investment level given in equation (15). Hence, investing efficiently is a mutually best response, which completes the proof.

$\square$

The mechanism implements the efficient investment levels but does not require that the buyer knows the investment cost functions. Each seller, however, has to be able to anticipate the behavior of the other seller correctly, which requires knowledge of the rival's investment costs.

8 Conclusions

Procurement managers are well aware of the problems described in this paper. In private industry they often offer preferential treatment to sellers who reveal design flaws early and come up with proposals for design improvements. Sometimes this is done explicitly by offering bonus points for design improvements. These bonus points can be used in the auction to get the contract with a higher probability and at a higher price. Consider, for example, a second-price, sealed-bid auction in which seller 1 has B^1 bonus points. Then, seller 1 wins the auction if $b^1 \leq b^2 + B^1$ and gets the contract at price $b^2 + B^1$. Thus, seller 1 will bid $b^1 = c^1 - B^1$ and his expected profit is $Prob(c^1 - B^1 \leq c^2)E(c^2 - c^1 + B^1 \mid c^1 - B^1 \leq c^2)$. If B^1 is chosen appropriately, such a mechanism can be used to induce sellers to reveal observed design flaws early. However, by linking the allocation of the contract to the revelation of design flaws this mechanism necessarily involves an inefficiency. The seller who observed most design flaws is not necessarily the one with the lowest cost to produce the good, but he will be chosen with positive probability nevertheless. On the other hand, linking the allocation of the contract to the revelation of design flaws reduces the rent that has to be paid to sellers. The buyer effectively uses some of the rent that a seller receives if he gets the contract to induce him to reveal his information early.

Appendix

Proof of Proposition 5: Efficiency requires that the buyer procures the best design from the seller with the lowest cost. Thus, the mechanism has to satisfy the efficient design (ED) and efficient production (EP) constraints. Constraint (ED) determines the design and constraint (EP) determines the contractor. Sellers do not have own financial resources and thus the mechanism has to ensure that each seller's ex post profit is non-negative, constraint (LL). Finally, the buyer does not know the distribution of sellers' types nor a seller's belief about the other seller's type distribution. Therefore, in order to ensure truthful revelation, the mechanism has to satisfy the ex post incentive compatibility constraint. Formally, the buyer's problem is:

$$\min_{t(\cdot,\cdot)} \quad \mathbb{E}[t((c^1, F^1), (c^2, F^2)) + t((c^2, F^2), (c^1, F^1))] \tag{17}$$

subject to:

$$D((c^1, F^1), (c^2, F^2)) = D(F^1, F^2) = D(F^1 \cup F^2) \tag{ED}$$

$$\omega((c^1, F^1), (c^2, F^2)) = \omega(c^1, c^2) = \begin{cases} 1 & \text{if } c^1 < c^2 \\ 1/2 & \text{if } c^1 = c^2 \\ 0 & \text{if } c^1 > c^2 \end{cases} \tag{EP}$$

$$t((c^1, F^1), (c^2, F^2)) - \omega(c^1, c^2)\left[c^1 + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k\right] \geq 0 \tag{LL}$$

$$\begin{aligned} & t((c^1, F^1), (c^2, F^2)) - \omega(c^1, c^2)\left[c^1 + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k\right] \geq \\ & t((\tilde{c}^1, \tilde{F}^1), (c^2, F^2)) - \omega(\tilde{c}^1, c^2)\left[c^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k\right] + \omega(\tilde{c}^1, c^2) \sum_{\{k|f_k \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} (1-\alpha) S_k^R \end{aligned} \tag{EPIC}$$

The constraints have to hold for both sellers and for all seller types.

Solving the Buyer's Problem

First, we will analyze the implications of constraint (EPIC). We consider the incentives of seller 1 to misreport his type (the incentives of seller 2 are symmetric). Ex post incentive compatibility requires that for all $(c^1, F^1) \in \mathcal{C} \times \mathcal{P}(\hat{F})$ and for all $(c^2, F^2) \in \mathcal{C} \times \mathcal{P}(\hat{F})$ it must hold that:

$$t((c^1, F^1), (c^2, F^2)) - \omega(c^1, c^2)\left[c^1 + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k\right] \geq$$
$$t((\tilde{c}^1, \tilde{F}^1), (c^2, F^2)) - \omega(\tilde{c}^1, c^2)\left[c^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k\right] + \omega(\tilde{c}^1, c^2) \sum_{\{k|f_k \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} (1-\alpha) S_k^R \tag{EPIC}$$

In the following, we derive conditions on transfers that need to be satisfied, so that seller 1 has no incentive to misreport his type. We have to distinguish four cases.

Case (i) $c^1 < c^2$ **and** $\tilde{c}^1 < c^2$**:** Seller 1 is more efficient than seller 2. He must have no incentive to misreport his type by claiming to have cost $\tilde{c}^1 \neq c^1$ such that he is still selected as the contractor. This is the case iff

$$t(c^1, F^1, \cdot) - [c^1 + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k]$$
$$\geq t(\tilde{c}^1, \tilde{F}^1, \cdot) - [c^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k] + \sum_{\{k|f_f \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} (1-\alpha) S_k^R.$$

Rearranging yields

$$t(c^1, F^1, \cdot) - t(\tilde{c}^1, \tilde{F}^1, \cdot) \geq \sum_{\{k|f_k \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} \left[\Delta c_k + (1-\alpha) S_k^R\right] \quad \forall c^1, \tilde{c}^1 < c_2. \tag{18}$$

Case (ii) $c^1 < c^2$ **and** $\tilde{c}^1 > c^2$**:** If Seller 1 is more efficient than seller 2 he must also have no incentive to report to be less efficient than seller 2, which is the case iff

$$t(c^1, F^1, \cdot) - t(\tilde{c}^1, \tilde{F}^1, \cdot) \geq c^1 + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k \quad \forall c^1 < c^2, \tilde{c}^1 > c_2. \tag{19}$$

Case (iii) $c^1 > c^2$ **and** $\tilde{c}^1 > c^2$**:** Seller 1 is less efficient than seller 2. He must have no incentive to report $\tilde{c}^1 \neq c^1$ such that he is still less efficient. In this case (EPIC) reduces to

$$t(c^1, F^1, \cdot) - t(\tilde{c}^1, \tilde{F}^1, \cdot) \geq 0 \tag{20}$$

The reverse condition has to hold to deter type $\tilde{c}^1$ from reporting to be type c^1. Furthermore these conditions have to hold for all F^1 and $\tilde{F}^1 \subseteq F^1$, so in particular for $\tilde{F}^1 = F^1$. Thus, different types of seller 1 that report the same set of flaws and different costs so that production is executed by seller 2 must receive the same transfer: For all $c^1, \tilde{c}^1$ so that $\omega(c^1, \cdot) = \omega(\tilde{c}^1, \cdot) = 0$ we must have

$$t(c^1, F^1, \cdot) = t(\tilde{c}^1, F^1, \cdot) \quad \forall F^1, \forall c^1, \tilde{c}^1 > c_2. \tag{21}$$

Case (iv) $c^1 > c^2$ and $\tilde{c}^1 < c^2$: If seller 1 is less efficient than seller 2 he must not have an incentive to report to be more efficient. The (EPIC) constraint in this case is equivalent to

$$\begin{aligned} t(c^1, F^1, \cdot) - t(\tilde{c}^1, \tilde{F}^1, \cdot) \geq \\ -\left[c^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k\right] + \sum_{\{k|f_k \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} (1-\alpha) S_k^R \quad \forall c^1 > c^2, \tilde{c}^1 < c_2. \end{aligned} \tag{22}$$

We now turn to the limited liability constraint (LL). Clearly, the buyer would like the (LL) constraint to hold with equality. If $\tilde{c}^1 < c^2$ this is the case iff

$$t(\tilde{c}^1, \tilde{F}^1, \cdot) = \tilde{c}^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k.$$

Using this in inequality (18) yields

$$t(c^1, F^1, \cdot) \geq \tilde{c}^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k + \sum_{\{k|f_k \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} (1-\alpha) S_k^R, \tag{23}$$

which must hold for all $c^1, \tilde{c}^1 < c^2$ and $\tilde{F}^1 \subseteq F^1$. In particular, it has to hold for all $\tilde{c}^1$ arbitrarily close to c^2 and for $\tilde{F}^1 = F^1$. Thus, a necessary condition for ex post incentive compatibility to hold for a type (c^1, F^1) with $c^1 < c^2$ is:

$$t(c^1, F^1, \cdot) \geq c^2 - \epsilon + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k + \sum_{\{k|f_k \in F^1 \setminus F^2\}} (1-\alpha) S_k^R \quad \forall c^1 < c_2. \tag{24}$$

Now, consider case (iv). If $\tilde{c}^1 < c^2$ and $t(\tilde{c}^1, \tilde{F}^1, \cdot)$ satisfies (LL) with equality, then

$$t(\tilde{c}^1, \tilde{F}^1, \cdot) = \tilde{c}^1 + \sum_{\{k|f_k \in \tilde{F}^1 \cup F^2\}} \Delta c_k$$

as before. Using this in inequality (22) yields

$$t(c^1, F^1, \cdot) \geq \tilde{c}^1 - c^1 + \sum_{\{k|f_k \in F^1 \setminus (\tilde{F}^1 \cup F^2)\}} (1-\alpha) S_k^R, \tag{25}$$

which has to be satisfied for all $\tilde{c}^1 < c^2$ and $\tilde{F}^1 \subseteq F^1$. In particular, it must hold for $\tilde{F}^1 = F^1$ and any $\tilde{c}^1$ arbitrarily close to c^2 which implies

$$t(c^1, F^1, \cdot) \geq c^2 - c^1 + \sum_{\{k|f_k \in F^1 \setminus F^2\}} (1-\alpha) S_k^R \quad \forall c^1 > c_2. \tag{26}$$

By (21) it has to hold that $t(c^1, F^1, \cdot) = t(\hat{c}^1, F^1, \cdot)$ for all $c^1, \hat{c}^1 > c^2$; i.e., if the seller does not execute production, his transfer is independent of the reported cost type. Hence, a necessary condition for ex post incentive compatibility is

$$t(c^1, F^1, \cdot) \geq \sum_{\{k|f_k \in F^1 \setminus F^2\}} (1-\alpha) S_k^R \quad \forall c^1 > c_2. \tag{27}$$

The following Lemma follows immediately from equations (24) and and (27)

Lemma 1. *Consider an ex post incentive compatible mechanism that also satisfies the constraints (EP), (ED), and (LL). Then, the transfer schedule satisfies*

$$t(c^1, F^1, \cdot) \geq \begin{cases} \sum_{\{k|f_k \in F^1 \setminus F^2\}} (1-\alpha) S_k^R & \text{if } c^1 > c^2, \\ c^2 + \sum_{\{k|f_k \in F^1 \cup F^2\}} \Delta c_k + \sum_{\{k|f_k \in F^1 \setminus F^2\}} (1-\alpha) S_k^R & \text{if } c^1 < c^2. \end{cases} \tag{28}$$

Note that the ex post utility of seller 1 with cost type $c^1 = c^2$ is the same, irrespective of whether he has to produce the good and the transfer is given by the lower bound of the term for $c^1 < c^2$ or he does not obtain the contract and the transfer is given by the lower bound of the term for $c^1 > c^2$.

The proposed mechanism satisfies the conditions provided in Lemma 1 with equality. In other words, the proposed mechanism satisfies the four constraints (EPIC), (EP), (ED), and (LL) at the lowest feasible cost to the buyer.

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