# Hazardous Facility Siting When Cost Information Is Private: An Application of Multidimensional Mechanism Design

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## Abstract

The siting of hazardous facilities often involves externalities that extend beyond the border of the community selected as a site. Thus, the private information of each community is potentially a vector of costs comprising a cost for each of the possible sites. I characterize the conditions for the existence of a direct mechanism that is incentive compatible, individually rational, and budget balancing. Incentive compatibility implies a pattern of compensation payments that often conflicts with compensation policy goals. When nonparticipating communities cannot block the siting of the facility, it will often be possible to implement siting policies with a balanced budget.

## 1. Introduction

A group of communities faces the problem of selecting a site for a hazardous facility. Suppose that some of the costs associated with each site are the private information of the individual communities. If the communities as a group would like to use that information in deciding where to site the facility (e.g., to efficiently site the facility), then the group must implement an incentive mechanism that is able to elicit truthful reports of the private information. However, the requirement that communities have an incentive to truthfully report their costs places certain limitations on the outcomes and

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I am grateful to Larry Ausubel, Peter Cramton, Phil Haile, Rich McLean, Marshall Reinsdorf, and Arijit Sen for their helpful comments and suggestions. I am also grateful for the comments I received from the participants of the Microeconomics Workshops at the University of Maryland and Rutgers University. Any views expressed are not purported to reflect those of the United States Department of Justice.

Received June 1999; Accepted April 2001.



*Journal of Public Economic Theory*, 5 (4), 2003, pp. 605–622.

compensation that can be achieved. For instance, incentive compatibility implies that certain increases in reported cost lead to a decrease in a community's expected compensation.

The nature of the problem of siting hazardous facilities makes it a natural application for multidimensional mechanism design techniques. Suppose that there are five potential sites for a hazardous facility. For each community there could be five different cost levels associated with the hazardous facility, one for each of the potential sites. If that cost information is private, then the community's private information is vector valued and multidimensional mechanism design techniques are required. While the discussion in this paper reflects the hazardous facility application, this model applies equally well to the problem of siting facilities in general or other allocation problems where each agent's preferences are not easily summarized by a single scalar value.

I characterize the conditions under which a siting policy can be implemented as an incentive compatible, individually rational, and budget balancing mechanism. Besides applying a more general participation constraint, this result generalizes others in the literature by considering siting policies other than efficient policies. Using this characterization, I prove a number of results showing when it is possible and not possible to implement particular siting policies. Implementation is often possible when nonparticipation by a community does not allow that community to block construction of the facility at any of the potential sites. In addition, it is impossible to achieve efficiency when it is feasible for at least one community to announce costs that imply the facility should not be built.

A number of researchers have modeled the siting problem as one of inducing communities to reveal hidden cost information,[1] but these papers model each community's private information as a scalar value rather than a vector. The private information possessed by a community is the cost associated with a site within its boundaries. The costs associated with sites outside the boundaries of a community are assumed to be public information. Ingberman (1995) is critical of most of these papers for not considering the negative effects of a site on neighboring communities as well as the host community. Ingberman argues that a host community has an incentive to shift as much of the cost as possible onto its neighbors by locating the facility near its border.[2] However, a community need not be adjacent to a site to experience the negative effects of a hazardous facility. Cross-border effects

[1]Kunreuther and Kleindorfer (1986), Kunreuther et al. (1987), O'Sullivan (1993), and Richardson and Kunreuther (1993) consider mechanisms for the siting of hazardous facilities. Cramton, Gibbons, and Klemperer's (1987) results on dissolving partnerships can be applied to the problem of selecting a site for hazardous facilities.

[2]Of the literature on siting facilities Richardson and Kunreuther (1993) is the only paper that explicitly considered cross-boundary effects.

can arise from being downwind or downstream from a site or from being along the transportation routes for hazardous materials en route to the site. These circumstances imply a model where each site could have a different effect on a community even if the site is not within the boundaries of the community.

An efficient mechanism must be able to select the site with the lowest costs while still eliciting truthful reports from the communities. Cramton, Gibbons, and Klemperer (1987) and O'Sullivan (1993) show that when cost information is scalar, then auction-like mechanisms can consistently achieve efficiency. Despite the increased complication due to the multidimensional aspect of the problem, I show that for sufficiently valuable projects, efficient siting policies can be implemented with a balanced budget.

The model I present is closely related to those presented by Jehiel and Moldovanu (1996), Jehiel, Moldovanu, and Stacchetti (1996, 1999), Krishna and Perry (1998), and Williams (1999).[3] While some of the results presented here are known from the theoretical literature on multidimensional mechanism design, I show how the application of these results to the siting of hazardous facilities answers a serious criticism by Ingberman (1995). I derive a number of previously unknown properties of the transfer or payment function that are necessary for incentive compatibility. The expected transfer payment received by a community exhibits an entropy-like property where a community's expected compensation decreases as its costs move away from the origin. While the goal of transfer payments in the mechanism may be to compensate communities for costs, incentive compatibility requires the payments to induce truthful announcements. Thus, the pattern of expected payments is not necessarily consistent with the goal of environmental justice.

The paper also contains a previously unknown characterization of allocations, both efficient and nonefficient, that are implementable with a balanced budget. The application of siting hazardous facilities implies a more complicated individual rationality constraint than previously considered in the theoretical literature. I show how different policies following nonparticipation by a community affect whether or not an efficient mechanism can be implemented with a balanced budget. When the facility is sufficiently valuable or the mechanism designer is free to choose a siting policy in the event that one community does not participate, a balanced budget mechanism can be implemented. However, implementing an efficient siting policy with a balanced budget is impossible if construction of the facility requires participation by everyone and at least one community, while participating, can effectively

[3]Other mechanism design problems where types are multidimensional include Armstrong (1996), Bernheim and Whinston (1986), McAfee and McMillan (1988), McAfee, McMillan, and Whinston (1989), Rochet (1985), and Rochet and Choné (1998).

prevent construction by announcing a cost high enough so that the net social benefit of the project is nonpositive.

## 2. The Model

Suppose that a group of communities faces a decision problem of where to site a hazardous facility. In addition, the communities may need to decide whether to build the facility at all. It is presumed that the group would like the decision to be based on the costs (and benefits) associated with each of the potential sites. For instance, an efficient siting arrangement would be the one that imposes the lowest total cost on the communities as a whole. Alternatively, the group may wish to use the cost information to compensate communities who suffer the largest environmental damage as a result of the siting. However, if the environmental cost information is known only to the individual communities, then a siting policy that is cost based will require the use of an incentive mechanism to induce the communities to truthfully reveal their costs either indirectly through their actions or directly by announcing them.

Let $M_0 = \{0, \dots, m\}$ index the set of potential siting outcomes. That is, $M_0$ is the union of the set of potential sites for the hazardous facility (outcomes $M = \{1, \dots m\}$) and the outcome corresponding to not building the facility (allocation $\{0\}$).

Let $N = \{1, \dots, n\} (n > 1)$ index the set of communities that could be affected by the siting of the hazardous facility.[4] Let $c$ denote an $m \times n$ matrix of costs where the element $c_{ji}$ is community $i$'s cost associated with site $j$. I normalize to zero the cost to each community of not building the facility. Assuming that community $i$ participates in the siting and construction of the facility, $c_{ji}$ is interpreted as the net negative effect on community $i$ from site $j$. Each community's net cost can be decomposed into three parts: $c_{ji} = c^e_{ji} + c^n_{ji} - b_{ji}$ where $c^e_{ji} \geq 0$ and $c^n_{ji} \geq 0$ are community $i$'s environmental cost and share of the construction cost for site $j$ and $b_{ji} \geq 0$ is $i$'s benefit from being able to use site $j$. I assume that the benefit $b_{ji}$ and construction cost $c^n_{ji}$ are common knowledge, and the environmental cost $c^e_{ji}$ is the private information of community $i$. Net costs can be negative so that a particular site may provide net benefits to a community. While $c_i$ is known to community $i$, it is considered a random vector by the other communities. I assume that the communities have a common belief regarding the distribution of $(c_1, \dots, c_n)$ where each community's cost vector is believed to be independent of the other communities' cost vectors. While the independence assumption may

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[4]I focus on the preferences of communities and not the individuals within the communities. Thus, the model ignores the possibility (discussed in Sullivan 1990) that individuals may move between communities either to avoid costs associated with a site or to receive compensation. Sullivan (1992) proposes a lottery siting mechanism that reduces the distortions associated with these effects.

limit the applications for the model, it is an assumption that greatly simplifies the analysis.[5] I assume that for each $i \in N$, the support of $c_i$, denoted $\Omega_i \subseteq \mathbb{R}^m$, is compact and convex and has a nonempty interior. Let $\Omega = \times_{i \in N} \Omega_i$, $\Omega_{-i} = \times_{j \in N \setminus \{i\}} \Omega_j$, and $c_{-i}$ denote all of the columns of $c$ except the $i$th. The set of all possible probability distributions over the sites is $\Xi = \{(x_1, \ldots, x_m) \in [0, 1]^m \mid \sum_{j \in M} x_j \leqslant 1\}$. The sum of the probabilities over the sites can be less than one to allow for the possibility that the facility is not built.

A mechanism for allocating hazardous facilities selects a site for the hazardous facility and the payments to be made to the participants based on reports from the communities. Nonparticipating communities do not receive any transfers. I assume that the mechanism is committed to prior to the communities' reports and that the participation decision and cost announcement are made simultaneously by all of the communities. Appealing to the Revelation Principal, I consider only direct mechanisms.

DEFINITION 1: *A direct siting mechanism is a triple* $\langle \mathbf{T}, \Phi, Q \rangle$, $\mathbf{T} : \Omega \to \mathbb{R}^n$, $\Phi : \Omega \to \Xi$, *and* $Q = (Q^1, \ldots, Q^n)$ *such that* $Q^i : \Omega_{-i} \to \Xi$.

In a mechanism $\mathbf{T} = (T_1, \ldots, T_n)$ defines the transfer payments where $T_i(c)$ is the payment made to community $i$ when the cost matrix $\mathbf{c}$ is announced. $\Phi = (\Phi_1, \ldots, \Phi_m)$ defines the rule for selecting the site when everyone participates in the mechanism, and $Q^i = (Q^i_1, \ldots, Q^i_m)$ defines the rule for selecting the site when community $i$ does not participate.[6] Together $\Phi$ and $Q$ are a siting policy.

The function $\Phi_j(c)$ indicates the probability that site $j$ will result when the cost matrix $\mathbf{c}$ is announced. The probability that no facility is built is $\Phi_0(c)$. Let $\phi^i_j(c_i)$ denote the probability that site $j$ is chosen conditional on community $i$ announcing cost vector $c_i$ and the other communities truthfully announcing their costs. Since the columns of $c$ are independent, $\phi^i_j(c_i) = E_{-i}[\Phi_j(c)]$, where $E_{-i}[\cdot]$ denotes the expectation with respect to all of the

[5]Allowing the private information to be correlated would make it possible for the mechanism designer to costlessly extract the communities' cost information and implement an efficient outcome as in Crémer and McLean (1988).

It would be simple but notationally cumbersome to generalize the present model and results to allow for uncertainties that are common across communities. The results would not significantly change as long as each community had common beliefs regarding the common uncertainties.

[6]I only consider equilibria where everyone participates. Therefore, to check that participation is indeed part of the Bayesian Nash equilibrium I need only check that every individual is not worse off participating under the Nash conjecture that all of the other communities are participating. A complete description of the game should include the definition of payoffs under any combination of actions (e.g., when two or more communities do not participate). However, those payoffs are unreached in equilibrium or in Nash deviations from equilibria where everyone participates. Hence, I leave those outcomes undefined except for the assumption that nonparticipation never lowers the net social cost associated with any given outcome.

costs except $i$'s. Let $\phi^i = (\phi^i_1, \ldots, \phi^i_m)$. I restrict attention to distributions of $c$ and the siting policies $\Phi$ such that the conditional assignment probabilities $\phi^i$ are continuous vector-valued functions in order to guarantee that the equilibrium interim expected payoff functions are differentiable at points in the interior of $\Omega_i$. Let $t^i(c_i) = E_{-i}[T_i(c)]$. Thus, $t^i(c_i)$ is community $i$'s expected transfer payment when it announces cost vector $c_i$ and the other communities announce their true cost.

Let $\pi^i(c'_i, c_i)$ denote community $i$'s expected payoff when it announces cost vector $c'_i$ but actually has cost vector $c_i$ and the other communities announce their true cost. That is, $\pi^i(c'_i, c_i) = t^i(c'_i) - c_i \cdot \phi^i(c'_i)$. Furthermore, define the function $v^i(c_i) = t^i(c_i) - c_i \cdot \phi^i(c_i)$.

DEFINITION 2: *The siting mechanism $\langle \mathbf{T}, \Phi, Q\rangle$ is incentive compatible (IC) if and only if for all $i \in N$ and $c_i, c'_i \in \Omega_i$, $v^i(c_i) \geq \pi^i(c'_i, c_i)$ (or equivalently $v^i(c_i) - v^i(c'_i) \geq -\phi^i(c'_i) \cdot [c_i - c'_i]$).*[7]

At the interim stage community $i$'s beliefs regarding the siting of the facility when it does not participate is given by $\rho^i = E_{-i}[Q^i(c_{-i})]$ where $\rho^i = (\rho^i_1, \ldots, \rho^i_m)$. That is, community $i$ expects site $j$ to be chosen with probability $\rho^i_j$ when $i$ chooses not to participate. Since they are part of the mechanism, at the interim stage of the game $\rho^1, \ldots, \rho^n$ are known to the communities.[8]

When a community does not participate, I assume that it is able to avoid construction costs and is excluded from the benefits of a facility. I assume that nonparticipating communities only suffer environmental costs. Hence, community $i$'s net cost from site $j$ when it does not participate is $c^e_{ji} = c_{ji} - s_{ji}$, where $s_{ji} = c^n_{ji} - b_{ji}$. Therefore, $s_{ji}$ is the difference in community $i$'s net cost for site $j$ when participating and its cost when not participating. I also assume that given a particular site will be chosen, the total net cost to society is not reduced by having one or more communities fail to participate in the mechanism. Let $s_i = (s_{1i}, \ldots, s_{mi})$. Therefore, community $i$'s interim expected payoff when it does not participate and the other communities truthfully announce their cost is $-(c_i - s_i) \cdot \rho^i$.

DEFINITION 3: *The siting mechanism $\langle \mathbf{T}, \Phi, Q\rangle$ is interim individually rational (IR) if and only if for all $i \in N$ and for all $c_i \in \Omega_i$, $v^i(c_i) \geqslant -(c_i - s_i) \cdot \rho^i$.*

DEFINITION 4: *The siting mechanism $\langle \mathbf{T}, \Phi, Q\rangle$ exhibits an ex post balanced budget (BB) if and only if for all $c \in \Omega$, $\sum_{i \in N} T_i(c) = 0$.*

[7]When $\phi^i$ is continuous, incentive compatibility implies that $\nabla v^i = -\phi^i$.

[8]Notice that in the out-of-equilibrium event that community $i$ decides not to participate, $Q^i$ need not induce truthful revelation from the other communities. I assume that the participation and cost announcements are made simultaneously. Hence, the other communities will announce their costs assuming equilibrium behavior by community $i$ and, hence, assuming that the siting decision will be governed by $\Phi$.

I say that siting policy $\Phi$ is *implementable with a balanced budget* if there exists a $\mathbf{T}$ and $Q$ such that $\langle \mathbf{T}, \Phi, Q\rangle$ satisfies (IC), (IR), and (BB). In the present context an efficient siting policy is one where no matter what the profile of costs are in $\Omega$, the policy selects the site with the lowest total net cost as long as that cost is less than zero.

DEFINITION 5: *A siting policy $\Phi$ is ex post efficient (E) if and only if for any other siting policy $\hat{\Phi}$ and for all $c \in \Omega$, $\sum_{i\in N} c_i \cdot \Phi(c) \leqslant \sum_{i\in N} c_i \cdot \hat{\Phi}(c)$.*

## 3. Characterization of Implementable Siting Policies

In characterizing implementable siting policies, it is necessary to show that for a particular policy there exists a transfer function such that when paired with that siting policy, the resulting mechanism is incentive compatible. The following condition on siting policies, cyclical monotonicity, is both necessary and sufficient for the existence of such a transfer function (see Rochet 1987). The vector-valued function $-\phi^i$ is *cyclically monotone* if and only if

$$-\phi^i\left(c_i^1\right)\cdot\left(c_i^2-c_i^1\right)-\phi^i\left(c_i^2\right)\cdot\left(c_i^3-c_i^2\right)-\cdots-\phi^i\left(c_i^k\right)\cdot\left(c_i^1-c_i^k\right)\leqslant 0,$$

for any finite set of cost vectors $\{c_i^1,\ldots,c_i^k\}\subset\Omega_i$.[9] If the condition above holds for $k=2$, then $-\phi^i$ is said to be monotone. Clearly cyclical monotonicity implies monotonicity.

The following lemma presents necessary and sufficient conditions for incentive compatibility which I use in the proofs of other results.[10]

LEMMA 1: *The siting mechanism $\langle \mathbf{T}, \Phi, Q\rangle$ is incentive compatible if and only if for all $i \in N$ and $c_i, c_i' \in \Omega_i$,*

$$v^i(c_i)-v^i(c_i') = -\int_0^1 \phi^i(\alpha c_i+(1-\alpha)c_i')\cdot(c_i-c_i')\,d\alpha. \tag{1}$$

*and $-\phi^i$ is monotone.*

Lemma 1 implies that any interim expected payoff function $v^i$ that is consistent with an incentive compatible siting mechanism is nonincreasing in a community's costs. Except in the trivial case where the probabilities of all of the sites are zero, in expectation, a community is always worse off when it has strictly higher costs. Therefore, even if the primary goal is to design a mechanism that compensates communities for higher costs, the only siting policy that holds communities harmless when they have higher costs is the policy of never siting the facility.

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[9]The use of cyclical monotonicity in this analysis can be seen in the proof of Theorem 1. (See footnote 15 in that proof.)

[10]Similar characterization results and proofs are presented by Jehiel, Moldovanu, and Stacchetti (1999), Krishna and Perry (1998), McAfee and McMillan (1988), and Rochet (1985).

In most scalar mechanism problems, individual rationality is shown to hold everywhere if and only if the "worst type" (i.e., highest cost) is guaranteed at least its reservation utility. In this multidimensional environment the participation constraint is complicated by the fact that a community's so-called reservation utility also depends on its type. Thus, the worst type/cost in terms of satisfying individual rationality is not necessarily the cost associated with the lowest interim expected payoff. Define $c_i^*$ such that

$$(\forall c_i \in \Omega_i) \quad \int_0^1 \left[\rho^i - \phi^i\left(\alpha c_i + (1-\alpha) c_i^*\right)\right] \cdot \left(c_i - c_i^*\right) d\alpha \geq 0. \tag{2}$$

Notice that $c_i^*$ does not depend on the transfer function.[11] When incentive compatibility is satisfied, $c_i^*$ is the "worst cost" in the sense that if individual rationality holds for $c_i^*$, then individual rationality holds for all types. To see this, notice

$$\begin{aligned} & v^i(c_i) + (c_i - s_i) \cdot \rho^i - \left[v^i\left(c_i^*\right) + \left(c_i^* - s_i\right) \cdot \rho^i\right] \\ & = \int_0^1 \left[\rho^i - \phi^i\left(\alpha c_i + (1-\alpha) c_i^*\right)\right] \cdot \left(c_i - c_i^*\right) d\alpha \geq 0, \end{aligned}$$

where the equality follows from Lemma 1 and the inequality follows from the definition of $c_i^*$. Therefore, if incentive compatibility is satisfied and $v^i(c_i^*) + (c_i^* - s_i) \cdot \rho^i \geq 0$, then individual rationality is satisfied.[12] With this simplification of the participation constraint I characterize siting policies that can be implemented with a balanced budget.

THEOREM 1: *The siting policy $\langle \Phi, Q \rangle$ is implementable with a balanced budget, if and only if for all $i \in N$, $-\phi^i$ is cyclically monotone and*

$$\sum_{i \in N} \left\{E\left[\Upsilon^i\left(c_i, c_i^*\right)\right] + c_i^* \cdot \left[\phi^i\left(c_i^*\right) - \rho^i\right] + s_i \cdot \rho^i\right\} \leqslant 0, \tag{3}$$

*where* $\Upsilon^i(c_i, c_i') = c_i \cdot \phi^i(c_i) - c_i' \cdot \phi^i(c_i') - \int_0^1 \phi^i(\alpha c_i + (1-\alpha) c_i') \cdot (c_i - c_i')\, d\alpha.$

A similar result that applies only for efficient mechanisms is presented by Makowski and Mezzetti (1994) and Williams (1999). The preceding theorem provides a characterization of all policies that can be implemented with a balanced budget, not just efficient policies. Hence, it allows for the consideration of a broader range of policy goals. For cases where an efficient siting policy cannot be implemented with a balanced budget, Theorem 1

[11]When $-\phi^i$ is cyclically monotone, $c_i^*$ is well defined. Using Theorem 24.8 in Rockafellar (1970), cyclical monotonicity implies that there exists a convex function $w^i$ so that the Inequality (2) can be written as $w^i(c_i) - w^i(c_i^*) + (c_i - c_i^*) \cdot \rho^i \geq 0$. Hence, $c_i^*$ exists since $\arg\min_{c_i \in \Omega_i} \{w^i(c_i) + c_i \cdot \rho^i\}$ is nonempty.

[12]Given $\rho^i$ finding $c_i^*$ is straightforward because assuming incentive compatibility $v^i(c_i) + (c_i - s_i) \cdot \rho^i$ is convex in $c_i$ with gradient equal to $\rho^i - \phi^i(c_i)$. Therefore, if $c_i^* \in \mathrm{int}\Omega_i$, then $\rho^i = \phi^i(c_i^*)$, and if there exists $c_i' \in \Omega_i$ such that $\rho^i = \phi^i(c_i')$, then $\phi^i(c_i') = \phi^i(c_i^*)$. If there is no $c_i \in \Omega_i$ such that $\rho^i = \phi^i(c_i)$, then $c_i^*$ is an element of the boundary of $\Omega_i$.

provides the constraint on the optimization problem to implement a policy that minimizes the overall cost of the project.

## 4. Properties of Implementable Mechanisms

As described by Rochet (1985) in the multidimensional case and Myerson (1981) for the scalar case, Lemma 1 implies that the effect of different costs on a community's interim expected payoff is completely determined by the siting policy. If two mechanisms implement the same siting policy and imply interim expected payoffs of $v^i$ and $\hat{v}^i$ such that for at least one $c_i \in \Omega_i$, $v^i(c_i) = \hat{v}^i(c_i)$, then $v^i(c_i) = \hat{v}^i(c_i)$ for all $c_i \in \Omega_i$. Clearly, the same property must hold for the expected transfer function $t^i$ since (1) if and only if

$$t^i(c_i) - t^i(c_i') = c_i \cdot \phi^i(c_i) - c_i' \cdot \phi^i(c_i') - \int_0^1 \phi^i(\alpha c_i + (1-\alpha)c_i') \cdot (c_i - c_i')\, d\alpha.$$

Therefore, once a siting policy has been decided upon, the mechanism designer has no leeway regarding the design of interim expected compensation payments except to add or subtract a constant.

As described in the previous section, incentive compatibility implies that it is not possible to fully compensate communities for their environmental costs. If compensation is one of the goals of the siting mechanism, then the designer may at least wish to implement a mechanism that makes higher transfers to communities with higher costs even if the payments are not fully compensating. However, the following theorem implies such a goal is impossible to achieve.

THEOREM 2: *Suppose* $\langle \mathbf{T}, \Phi, Q\rangle$ *is incentive compatible. Then for* $c_i, c_i' \in \Omega_i$,

(a) $t^i(c_i) = t^i(c_i')$, *if* $\phi^i(c_i) = \phi^i(c_i')$,

(b) $t^i(c_i) \geqslant t^i(c_i')$, *if* $c_i' = \alpha c_i$, *for* $\alpha > 1$.

The results of Theorem 2 help to provide some intuition regarding the implications of incentive compatibility for the interim expected transfer functions $t^i$. Part (a) of Theorem 2 states that if two cost vectors imply the same distribution of outcomes to community $i$, then any incentive compatible mechanism must provide community $i$ with the same expected payment for the two cost vectors. To understand the implication of this result consider the case of an efficient siting policy where $c_i$ and $c_i'$ are low enough to rule out not siting the facility and suppose $c_{ji} - c_{ji}' = \alpha > 0$ for all $j \in M$. (Thus, $c_i$ can be derived from $c_i'$ simply by adding $\alpha$ to each element of $c_i'$.) It is straightforward to see that efficiency and the assumption that $\phi_0^i(c_i) = \phi_0^i(c_i') = 0$ imply that $\phi^i(c_i) = \phi^i(c_i')$ and thus, $t^i(c_i) = t^i(c_i')$ by part (a) of Theorem 2. Community $i$ can expect no additional compensation when it has cost vector $c_i$ over what it receives for costs of $c_i'$ even though $c_i$ is unambiguously higher than $c_i'$.

Describing part (b) in words, the transfer function falls when announced costs "move away" in a straight line in any direction from the origin. A net cost vector of all zeros implies that a community is indifferent among the alternatives: the different sites and not building the facility at all. The further a community's net cost vector is from the origin, the stronger its preference for particular outcomes over others. Hence, the expected transfer function decreases as a community's preferences become stronger. Recall that by the revelation principle, this result also applies to the Bayesian Nash equilibria of any indirect mechanism (e.g., a bidding mechanism).

The intuition for part (b) of the theorem follows from the association between equal costs and indifference among outcomes. In incentive mechanisms, transfer payments are designed to induce truthful announcements. When a community is indifferent between all outcomes, it does not care how its announced costs affect the choice of outcome. Thus, it would maximize its payoff by announcing the cost vector associated with the highest expected transfer. Therefore, in order to induce such a community to truthfully announce its costs, the highest expected payment must be associated with being indifferent between all of the outcomes. Similarly, the more equal the costs, the more compensation must be paid to induce truthful reporting.

The pattern of transfer payments implied by part (b) of Theorem 2 makes little sense in terms of compensating communities for their announced costs. Notice that according to this result if $c_i \in \mathbb{R}^m_{++}$ and $c_i,\ c'_i \in \Omega_i$ where $c'_i = \alpha c_i$ for some $\alpha > 1$, then $t^i(c_i) \geq t^i(c'_i)$. Even though $c'_i > c_i$, the expected transfer associated with an announcement of $c'_i$ can never be larger than that received when $c_i$ is announced. Thus, announcing higher costs will at times result in a decrease in the expected transfer.

Using a well-known characterization of efficient mechanisms (for example, see D'Aspremont and Gerard-Varet 1979, Krishna and Perry 1998, and Williams 1999), a characterization of the conditions under which efficient policies are implementable with a balanced budget are straightforwardly obtainable from Theorem 1. I provide a short proof in the Appendix to demonstrate the lemma's relation to the conditions of Theorem 1.[13]

LEMMA 2: *An efficient siting policy $\langle \Phi, Q \rangle$ is implementable with a balanced budget if and only if*

$$\sum_{i\in N} E\left[\sum_{j\in N\setminus\{i\}} c_j \cdot \left[\Phi\left(c_i^*, c_{-i}\right) - \Phi(c_i, c_{-i})\right] + c_i^* \cdot \left[\phi^i\left(c_i^*\right) - \rho^i\right] + s_i \cdot \rho^i\right] \leqslant 0. \tag{4}$$

For a given siting policy, whether or not (3) is satisfied depends on $s_1, \ldots, s_n$ and the $c_1^*, \ldots, c_n^*$ resulting from $Q$ (the siting policies when one community chooses not to participate). In the remainder of this section I

[13] Similar results to the following corollary have been derived by Krishna and Perry (1998), Makowski and Mezzetti (1994), and Williams (1999). Any differences between the corollary presented here and those presented in these other papers are for the most part a result of differences in the generality of the individual rationality constraints.

present a series of results that help to indicate when it is possible and when it is impossible to implement particular siting policies including the efficient policy.

Whether or not a siting policy can be implemented with a balanced budget in many cases depends on the implications of nonparticipation. If the mechanism designer can select any site for the facility even when some communities refuse to participate, then, as demonstrated by the following proposition, sufficient conditions for the implementation of a siting policy with a balanced budget are relatively easy to satisfy. Suppose that $Q$ is defined as if the mechanism designer tries her best to implement the policy $\Phi$ even when one community refuses to participate. That is, if community $i$ does not participate, then let the siting rule be $Q^i(c_{-i}) = E_i[\Phi(c)]$. Importantly, if $\Phi$ is an efficient policy, then $E_i[\Phi(c)]$ is the constrained efficient policy when community $i$'s cost information is unavailable.

PROPOSITION 1: *Consider any siting policy $\langle \Phi, Q \rangle$ such that for all $i \in N$, $-\phi^i$ is cyclically monotone and $Q^i(c_{-i}) = E_i[\Phi(c)]$. Then $\langle \Phi, Q \rangle$ is implementable with a balanced budget if $\sum_{i\in N} E[c_i \cdot \Phi(c)] \leqslant 0$.*

*Proof:* Note that $0 \geqslant \sum_{i\in N} E[c_i \cdot \Phi(c)] = \sum_{i\in N} E[(c_i^e + s_i) \cdot \Phi(c)] \geqslant \sum_{i\in N} s_i \cdot E[\Phi(c)]$ since environmental costs are always nonnegative and $s_1, \ldots, s_n$ are nonrandom. Also note that for each $i \in N, \rho^i = E_{-i}[Q^i(c_{-i})] = E[\Phi(c)]$. With these facts in mind, the conclusion of the proposition follows from the fact that cyclical monotonicity and $\sum_{i\in N}\{c_i^* \cdot E[\Phi(c)] + [s_i - c_i^*] \cdot \rho^i\} \leqslant 0$ are sufficient for implementability with a balanced budget. ■

Notice that to implement a siting policy with a balanced budget it is not necessary to set the default assignment probabilities to place all of the probability weight on a community's least preferred site, and thus, use the siting of the facility as a threat to induce participation. In the event of nonparticipation, if the designer selects the site based on ex ante information and the policy $\Phi$, then the policy is implementable with a balanced budget.

In Proposition 1 I consider situations where a community's decision not to participate has no effect on the set of sites that are available to the participating communities. Now consider a situation where any nonparticipating community can block the construction of the facility on any site. Given that they suffer the environmental costs of a facility and none of the benefits, nonparticipating communities that have the right to block construction would do so and thus, $\rho^i = 0$ for all $i \in N$.

When nonparticipation implies the facility is not built, implementing siting policies with a balanced budget becomes more difficult. The following proposition is related to a well-known result by Myerson and Satterthwaite (1983) for the scalar case.

PROPOSITION 2: *Consider an efficient siting policy $\langle \Phi, Q \rangle$ such that for each $i \in N$, $\rho^i = 0$. Furthermore, suppose $E[\sum_{i\in N} c_i \cdot \Phi(c)] < 0$ and for at least one $k \in$*

*N, there exists a* $\hat{c}_k \in \Omega_k$ *such that* $\Phi(\hat{c}_k, c_{-k}) = 0$, *for all* $c_{-k} \in \Omega_{-k}$. *Then this efficient siting policy cannot be implementable with a balanced budget.*

## 5. Conclusion

I have described the siting mechanism as a means of solving an informational problem. The siting mechanism elicits cost information from communities that would otherwise not be available when selecting a site. In this paper I demonstrate that in many cases it is possible to construct efficient mechanisms for siting hazardous facilities that are also budget balancing. However, the incentive compatibility implies that announced costs cannot be compensated for in any meaningful way. In some cases, expected transfer payments will decline when announced costs increase. Two problems face any authority wishing to use such mechanisms as the basis for their siting decision: (1) it is not yet clear what simple mechanism can achieve the efficient outcome described here, and (2) recent research seems to indicate that the general public may resist attempts to treat the siting decision as a commodity. While the sufficiency part of the proof of Theorem 1 is completed by construction and, hence, presents a direct mechanism that achieves efficiency with a balanced budget, the mechanism is hardly simple.

Compensation has been discussed as a means of gaining the support for a siting choice from injured communities. However, as indicated by Theorem 2, the expected compensation associated with incentive-compatible mechanisms may be considered unfair since even communities who benefit from a selected site in some cases will be paid compensation. However, as discussed by Frey and Oberholzer-Gee (1996), Frey, Oberholzer-Gee, and Eichenberger (1996), and Kunreuther and Easterling (1996), compensating communities as a means of gaining their acquiescence for a particular siting plan can backfire if the compensation is viewed as a bribe. The fairness of the decision-making process seems to be key to the acceptance of the final siting decision. Decentralized mechanisms such as the cost mechanisms described here might provide some legitimacy to the decision.[14] However, the results of Frey and Oberholzer-Gee (1996), Frey, Oberholzer-Gee, and Eichenberger (1996), and Kunreuther and Easterling (1996) may indicate that the general public does not believe that siting decisions should be tradeable commodities.

## Appendix

*Proof of Lemma 1:* The proof is standard. It is included for completeness.

[14]When a decision is made according to a decentralized mechanism, it acquires a legitimacy that might not be present if the decision were made by a corruptible individual or an individual with a personal stake in the outcome. Smith (1989) discusses this and other "noneconomic" aspects of auctions.

(If): (IC) is satisfied if for all $i \in N$ and $c_i, c_i' \in \Omega_i$, $v^i(c_i) - v^i(c_i') \geqslant -\phi^i(c_i') \cdot (c_i - c_i')$. Using (1), this inequality can be written as $\int_0^1 [\phi^i(c_i') - \phi^i(\alpha c_i + (1-\alpha)c_i')] \cdot (c_i - c_i')\, d\alpha \geq 0$. The inequality follows from monotonicity. To see this, notice that monotonicity implies $-\phi^i(\alpha c_i + (1-\alpha)c_i') \cdot [c_i' - \alpha c_i - (1-\alpha)c_i'] - \phi^i(c_i') \cdot [\alpha c_i + (1-\alpha)c_i' - c_i'] \leqslant 0$ which implies $[\phi^i(c_i') - \phi^i(\alpha c_i + (1-\alpha)c_i')] \cdot (c_i - c_i') \geq 0$, for $\alpha > 0$.

(Only if): Monotonicity follows from the fact that incentive compatibility implies that for all $i \in N$ and $c_i, c_i' \in \Omega_i$, $-\phi^i(c_i) \cdot (c_i - c_i') \geq v^i(c_i) - v^i(c_i') \geq -\phi^i(c_i') \cdot (c_i - c_i')$.

Pick any $i \in N$ and $c_i, c_i' \in \mathcal{C}_i$. For $\alpha \in [0, 1]$, let $z(\alpha) = \alpha c_i + (1-\alpha)c_i'$, $w(\alpha) = v^i(z(\alpha))$, and $\sigma(\alpha) = \phi^i(z(\alpha)) \cdot (c_i - c_i')$. Note that the monotonicity and boundedness of $-\phi^i$ implies the monotonicity and boundedness of $-\sigma$. Incentive compatibility implies that for all $\alpha, \alpha' \in [0, 1]$, $-(\alpha - \alpha')\sigma(\alpha) \geqslant w(\alpha) - w(\alpha') \geqslant -(\alpha - \alpha')\sigma(\alpha')$, and hence, $dw(\alpha)/d\alpha = -\sigma(\alpha)$ for almost every $\alpha \in (0, 1)$. The function $w$ is continuous since $\sigma$ is bounded. Thus, by the fundamental theorem of calculus, for all $\alpha, \alpha' \in [0, 1]$, $w(\alpha) - w(\alpha') = -\int_{\alpha'}^{\alpha} \sigma(\xi)\, d\xi$. Therefore, the conclusion follows from

$$\begin{aligned} v^i(c_i) - v^i(c_i') &= w(1) - w(0) \\ &= -\int_0^1 \sigma(\xi)\, d\xi \\ &= -\int_0^1 \phi^i(\xi c_i + (1-\xi)c_i') \cdot (c_i - c_i')\, d\xi. \quad \blacksquare \end{aligned}$$

*Proof of Theorem 1:*

(Only if): The cyclical monotonicity of $-\phi^i(c)$ is necessary for (IC) (see Rochet 1987). Notice that (BB) implies $0 = \sum_{i \in N} E[T_i(c)] = \sum_{i \in N} E[t^i(c_i)]$. Therefore,

$$\begin{aligned} 0 &= \sum_{i \in N} E\big[t^i(c_i)\big] \\ &= \sum_{i \in N} E\big[c_i \cdot \phi^i(c_i) + v^i(c_i)\big] \\ &= \sum_{i \in N} E\big[c_i \cdot \phi^i(c_i) + v^i(c_i) - v^i\big(c_i^*\big) + v^i\big(c_i^*\big) \\ &\qquad - c_i^* \cdot \phi^i\big(c_i^*\big) + c_i^* \cdot \phi^i\big(c_i^*\big)\big] \\ &\geqslant \sum_{i \in N} E\big[c_i \cdot \phi^i(c_i) + v^i(c_i) - v^i\big(c_i^*\big) - c_i^* \cdot \phi^i\big(c_i^*\big) \\ &\qquad + c_i^* \cdot \big[\phi^i\big(c_i^*\big) - \rho^i\big] + s_i \cdot \rho^i\big] \\ &= \sum_{i \in N} E\big[\Upsilon^i\big(c_i, c_i^*\big) + c_i^* \cdot \big[\phi^i\big(c_i^*\big) - \rho^i\big] + s_i \cdot \rho^i\big] \end{aligned}$$

where the inequality follows from the fact that (IR) implies for all $i \in N$, $v^i(c_i^*) \geqslant -(c_i^* - s_i) \cdot \rho^i$ and the last equality follows from (IC) by Lemma 1.

(If): For each $i \in N$, consider the transfer function

$$T_i(c) = \Psi_i(c) - \left(c_i^* - s_i\right) \cdot \rho^i + a_i$$
$$-\frac{1}{n}\sum_{j \in N}\{\Psi_j(c) - E_{-i}[\Psi_j(c)] + E_{-(i+1)}[\Psi_j(c)] - E[\Psi_j(c)]\}$$

where $\Psi_i(c) = c_i \cdot \Phi(c) - \int_0^1 \Phi(z_i(\alpha), c_{-i}) \cdot (c_i - c_i^*)\, d\alpha$, $z_i(\alpha) = \alpha c_i + (1-\alpha) c_i^*$ and $E_{-i}[\cdot]$ denotes the expectation with respect to all of the cost vectors except $i$, $E_{-(n+1)}[\cdot] = E_{-1}[\cdot]$, and $a_i$ is a constant with respect to $c$. Note that

$$\begin{aligned} t^i(c_i) &= E_{-i}[T_i(c)] \\ &= E_{-i}[\Psi_i(c)] - \left(c_i^* - s_i\right) \cdot \rho^i + a_i \\ &= c_i \cdot \phi^i(c_i) - \int_0^1 \phi^i(z_i) \cdot \left(c_i - c_i^*\right) d\alpha - \left(c_i^* - s_i\right) \cdot \rho^i + a_i. \end{aligned}$$

The expression for $t^i$ can be rearranged to yield

$$v^i(c_i) = -\int_0^1 \phi^i(z_i) \cdot \left(c_i - c_i^*\right) d\alpha - \left(c_i^* - s_i\right) \cdot \rho^i + a_i$$

and, hence, for all $c_i \in \Omega_i$,

$$v^i(c_i) - v^i\left(c_i^*\right) = -\int_0^1 \phi^i(z_i) \cdot \left(c_i - c_i^*\right) d\alpha. \tag{5}$$

Cyclical monotonicity implies there exists a transfer function $\hat{\mathbf{T}}$ such that $\langle \hat{\mathbf{T}}, \Phi, Q \rangle$ is incentive compatible (see Rochet 1987).[15] For each $i \in N$, let $w^i(c_i) = E_{-i}[\hat{T}_i(c) - c_i \cdot \Phi(c)]$. Therefore, for all $c_i, c_i' \in \Omega_i$,

$$\begin{aligned} v^i(c_i) - v^i(c_i') &= \left[v^i(c_i) - v^i\left(c_i^*\right)\right] - \left[v^i(c_i') - v^i\left(c_i^*\right)\right] \\ &= \left[w^i(c_i) - w^i\left(c_i^*\right)\right] - \left[w^i(c_i') - w^i\left(c_i^*\right)\right] \\ &= w^i(c_i) - w^i(c_i') \\ &= -\int_0^1 \phi^i(\alpha c_i + (1-\alpha) c_i') \cdot (c_i - c_i')\, d\alpha. \end{aligned}$$

The second and fourth equalities follow from Lemma 1. Hence, by Lemma 1, the equality established above and cyclical monotonicity imply that the mechanism $\langle \mathbf{T}, \Phi, Q \rangle$ is incentive compatible.

[15] The role of the cyclical monotonicity assumption can be seen at this point in the proof. Note that (5) is slightly different from the equality in Lemma 1 which is sufficient to show incentive compatibility. What remains to establish is the path independence of this integral. Using the cyclical monotonicity assumption I establish path independence by the argument that follows this footnote.

Interim individual rationality is satisfied if $a_i \geqslant 0$. To see this, notice that the transfer function defined above implies $v^i(c_i^*) = -(c_i^* - s_i) \cdot \rho^i + a_i$. If $a_i \geqslant 0$, then $v^i(c_i^*) + (c_i^* - s_i) \cdot \rho^i \geqslant 0$ and (IR) is satisfied.

It remains to show that there exists $(a_1, \dots, a_n) \in \mathbb{R}_+^n$ that are consistent with an ex post balanced budget. Let $a_i = \frac{1}{n}\sum_{j\in N}\{(c_j^* - s_j) \cdot \rho^j - E[\Psi_j(c)]\}$. The fact that $a_i \geqslant 0$ follows from (3), and the mechanism has an ex post balanced budget since for any $c \in \Omega$,

$$\sum_{i\in N} T_i(c) = \sum_{i\in N}\left\{E[\Psi_i(c)] - \left(c_i^* - s_i\right) \cdot \rho^i + a_i\right\} = 0. \quad \blacksquare$$

*Proof of Theorem 2:*

Part (a): Incentive compatibility implies

$$t^i(c_i) - t^i(c_i') \geq \left[\phi^i(c_i) - \phi^i(c_i')\right] \cdot c_i \qquad \text{and}$$
$$t^i(c_i') - t^i(c_i) \geq \left[\phi^i(c_i') - \phi^i(c_i)\right] \cdot c_i'.$$

Combining these two inequalities yields

$$\left[\phi^i(c_i) - \phi^i(c_i')\right] \cdot c_i' \geq t^i(c_i) - t^i(c_i') \geq \left[\phi^i(c_i) - \phi^i(c_i')\right] \cdot c_i.$$

Notice that $\phi^i(c_i) = \phi^i(c_i')$ implies $t^i(c_i) = t^i(c_i')$.

Part (b): (IC) implies monotonicity and, thus, for any $c_i \in \Omega_i$ and any $\alpha > 1$ such that $\alpha c_i \in \Omega_i$, $-\phi^i(c_i) \cdot (\alpha c_i - c_i) - \phi^i(\alpha c_i) \cdot (c_i - \alpha c_i) \leq 0$. Since $\alpha > 1$ and $c_i{}' = \alpha c_i$, $0 \leq [\phi^i(c_i) - \phi^i(c_i{}')] \cdot c_i \leq t^i(c_i) - t^i(c_i{}')$. The final inequality and the conclusion of this part of the theorem follows from the fact that (IC) implies $t^i(c_i) - t^i(c_i') \geqslant [\,\phi^i(c_i) - \phi^i(c_i')] \cdot c_i$. $\blacksquare$

*Proof of Lemma 2:* Lemma 1 and a well-known result of D'Aspremont and Gerard-Varet (1979) and the fact that efficient mechanisms satisfy (IC) imply that when the siting policy is efficient, cyclical monotonicity holds and for all $c_i, c_i' \in \Omega_i$, $\Upsilon^i(c_i, c_i') = E_{-i}[\sum_{j\in N\setminus\{i\}} c_j \cdot [\Phi(c_i', c_{-i}) - \Phi(c_i, c_{-i})]]$. $\blacksquare$

*Proof of Proposition 1:* Note that $0 \geq \sum_{i\in N} E[c_i \cdot \Phi(c)] = \sum_{i\in N} E[(c_i^e + s_i) \cdot \Phi(c)] \geq \sum_{i\in N} s_i \cdot E[\Phi(c)]$ since environmental costs are always nonnegative and $s_1, \dots, s_n$ are nonrandom. Also note that for each $i \in N$, $\rho^i = E_{-i}[Q^i(c_{-i})] = E[\Phi(c)]$. The proof is complete if (3) holds. Thus,

$$\begin{aligned}
&\sum_{i\in N} E\left[\Upsilon^i\left(c_i, c_i^*\right) + c_i^* \cdot \left[\phi^i\left(c_i^*\right) - \rho^i\right] + s_i \cdot \rho^i\right] \\
&\quad = \sum_{i\in N} E\left[\int_0^1 \left[\phi^i(c_i) - \phi^i\left(\alpha c_i + (1-\alpha)c_i^*\right)\right] \cdot \left(c_i - c_i^*\right) d\alpha\right] \\
&\quad\quad + s_i \cdot E\,[\Phi(c)] \\
&\quad \leqslant \sum_{i\in N} s_i \cdot E\,[\Phi(c)] \leqslant 0.
\end{aligned}$$

The first inequality follows from monotonicity. $\blacksquare$

*Proof of Proposition 2:* Before presenting the main argument of the proof, I show a few implications of (E), (IC), and (IR). Note that (E) and (IC) imply that for all $i \in N$ and $c_i, c_i' \in \Omega_i$,

$$v^i(c_i) - v^i(c_i') = E_{-i}\left[\left(c_i' + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi(c_i', c_{-i}) - \sum_{j\in N} c_j \cdot \Phi(c_i, c_{-i})\right] \tag{6}$$

Thus, (E), (IC), and (IR) and the fact that for all $i \in N$, $\rho^i = 0$ imply that for all $i \in N$ and $c_i, \in \Omega_i$,

$$\begin{aligned} 0 &\geqslant E_{-i}\left[\left(c_i^* + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi\big(c_i^*, c_{-i}\big)\right] \\ &\geqslant E_{-i}\left[\left(c_i + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi(c_i, c_{-i})\right]. \end{aligned} \tag{7}$$

The first inequality follows from (E), and the second inequality follows from (2) and (6). Specifically, note that $E_{-k}[(c_k^* + \sum_{j\in N\setminus\{k\}} c_j) \cdot \Phi(c_k^*, c_{-k})] = 0$ since for some $\hat{c}_k \in \Omega_k$, $\Phi(\hat{c}_k, c_{-k}) = 0$.

Now I show that for all $i \in N$,

$$E_{-i}\left[\left(c_i^* + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi\big(c_i^*, c_{-i}\big)\right] > E\left[\sum_{j\in N} c_j \cdot \Phi(c)\right]. \tag{8}$$

The assumption that $E[\sum_{i\in N} c_i \cdot \Phi(c)] < 0$ implies $\Phi(c) > 0$ for all $c$ in a nonnegligible subset of $\Omega$ and, hence, implies $\phi^i(c_i) > 0$, for all $c_i$ in a nonnegligible subset of $\Omega_i$. Therefore, (IR) implies since $\nabla v^i(c_i) = -\phi^i(c_i) < 0$, for all $c_i$ in a nonnegligible subset of $\Omega_i$. Hence, making use of (6), Inequality (8) follows from the fact that $E[v^i(c_i)] > v^i(c_i^*)$.

I now complete the proof by making use of the facts established above. Assuming that for all $i \in N$, $\rho^i = 0$, by Lemma 3, an efficient siting policy is implementable with a balanced budget only if

$$\sum_{i\in N} E_{-i}\left[\left(c_i^* + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi\big(c_i^*, c_{-i}\big)\right] \leqslant (n-1)E\left[\sum_{i\in N} c_i \cdot \Phi(c)\right].$$

However, given the assumptions of the proposition this inequality cannot hold. Note that

$$\begin{aligned} &\sum_{i\in N} E_{-i}\left[\left(c_i^* + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi\big(c_i^*, c_{-i}\big)\right] \\ &\quad = \sum_{i\in N\setminus\{k\}} E_{-i}\left[\left(c_i^* + \sum_{j\in N\setminus\{i\}} c_j\right) \cdot \Phi\big(c_i^*, c_{-i}\big)\right] \end{aligned}$$

$$
\begin{aligned}
&> \sum_{i \in N \setminus \{k\}} E\left[\sum_{j \in N} c_j \cdot \Phi(c)\right] \\
&= (n-1) E\left[\sum_{i \in N} c_i \cdot \Phi(c)\right].
\end{aligned}
$$

The first equality in the preceding expression follows from that fact that

$$
E_{-k}\left[\left(c_k^* + \sum_{j \in N \setminus \{k\}} c_j\right) \cdot \Phi\left(c_k^*, c_{-k}\right)\right] = 0.
$$

The strict inequality follows from (8). ■

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