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Effective Siting of Waste Treatment Facilities[1]

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A waste treatment plant or another essential but potentially unpleasant facility has to be built in one of n communities. We present a simple auction-like procedure that identifies the best location and determines a system of transfers that provide the host community with adequate compensation. The siting procedure is simple and effective and can be readily applied in real world situations. In addition, it is ex post budget balanced, ex post individually rational, and robust, and it induces bidding the true disutility (or close to it) as a focal strategy in many different environments. © 2001 Elsevier Science (USA)

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1. INTRODUCTION

NIMBYs (not in my back yard) and LULUs (locally unwanted land uses) are a significant source of policy headaches. Often there is public consensus that a development project such as a new facility for treating hazardous waste is desirable, but at the same time every community refuses to accept the facility. How should a site be chosen? U.S. siting procedures emphasize the global costs and benefits of a site, but disregard the local costs and benefits. Given this, the presence of strong local opposition is not surprising. This opposition has proved extremely costly in many cases, raising the need for a reform of siting procedures. In this paper, we propose a simple and effective auction-like procedure for choosing one site among a group of alternatives that can address the problems above.

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Efficient siting involves two basic criteria. First, all other things being equal, construction and operation costs should be minimized. Second, all other things being equal, the loss in welfare to the host community should be minimized. The important difference between these two considerations is that while cost minimization is a technical matter that is unlikely to arouse much controversy, minimizing welfare loss is a subjective matter over which people are very likely to disagree. The problem is exacerbated by the fact that the very subjectivity of peoples' personal disutilities allows them to manipulate others' perceptions of their true magnitudes.

U.S. siting procedures address the first type of efficiency, but largely ignore the second type. In the majority of cases, both the government and the public are wholly uninvolved in decision making until after a site has been chosen. Only after a developer has chosen a site, negotiated the land purchase, and worked up a detailed building plan, does the regulation process begin. At this point, the government either accepts or denies a permit for the project. Typically the permit decision hinges on whether or not the building plans are technically cost minimizing, meet safety requirements, and generate an overall benefit to society. The permit decision does not generally involve a comparison of alternative communities from the point of view of minimizing the local burden placed on the host community.[4]

In this paper, we propose a simple procedure for choosing a site that is a modification of a second price or Vickrey auction. Each of n communities submits a bid representing its disutility from hosting the facility. The cost of building and operating the facility at each site is assumed to be known. The facility is located at the community with the lowest (bid + cost) figure. The communities pay transfer payments that compensate the host of the facility. Specifically, the communities share a payment equal to the second lowest (bid + cost) proportionally, according to the quantities of waste they generate.

Our siting procedure satisfies several important and desirable properties. First, it is easy to apply in real world situations. Second, as we argue, the siting procedure is effective in many environments, both "standard" and "nonstandard." That is, either the facility is sited efficiently in the community that has the lowest true combined cost and disutility figure, or, if not then the efficiency loss that is associated with locating the facility elsewhere is small. Third, the siting procedure is budget-balanced. It neither relies on outside subsidies nor generates a surplus that has to be (wastefully) disposed of. Finally, the siting procedure induces ex post voluntary participation. All the communities prefer to abide by the outcome of the siting procedure rather than to withdraw and not participate even *after* the procedure's recommendation as well as the bids of other communities become known.

It is well known that efficient siting can be achieved with a Vickrey–Clarke–Groves mechanism. But, such mechanisms fail to balance the budget.[5] That is, with probability one such mechanisms either create a deficit and therefore have to rely on outside subsidies or generate a surplus that has to be (inefficiently) disposed of so as not to distort the agents' incentives. The problem of budget balance can be solved by using modified mechanisms such as those introduced by d'Aspremont and Gerard-Varet [3] and Arrow [1], but these latter mechanisms violate voluntary participation, or individual rationality, constraints. Cramton et al. [8] observe that the problem of siting a waste treatment facility is formally equivalent to the problem of

[4] See Davy [9, Chap. 2] for a thorough description of the legal procedures in hazardous waste siting.
[5] See, e.g., Fudenberg and Tirole [13, Chap. 7] and the references therein.

dissolving a partnership. They characterize property rights structures for which efficient, ex post budget-balanced, and (interim) individually rational mechanisms exist, but they restrict their attention to independent and symmetric environments, and the mechanisms they describe depend on details of the environment that are difficult to observe in practice such as, for example, the common prior. This makes it difficult to apply these mechanisms in practical situations. They also consider simple prior independent mechanisms for dissolving a partnership, as does McAfee [28]. However, the efficiency of these simple mechanisms is due to the fact that only symmetric equilibria in symmetric environments are considered. Symmetric equilibria may fail to exist and anyway are less plausible in more general, asymmetric environments.

In general, mechanism design points to a conflict between the two separate objectives of budget balance, or "self-financing," and truthful revelation. In practice, in many cases, self-financing is a more significant policy barrier to efficient siting than truthful revelation of disutilities.[6] In light of this, the approach we take here is to consider a siting procedure that is always budget-balanced, but that may not induce truthful revelation.

What distinguishes our approach from the rest of the mechanism design literature is our emphasis on simplicity and effectiveness in a wide range of environments as opposed to complexity and optimality in some specific environment. The description of the siting procedure we propose is independent of the details of the specific environment in which it is to be used. Such procedures are called robust by Wilson [42] and simple by Cramton et al. [8] and McAfee [28]. We believe that in applied problems where at least some of the standard assumptions routinely employed in mechanism design literature and, in particular, the existence of a commonly known prior, consistent beliefs, and the plausibility of Bayesian–Nash equilibrium may be suspect, there is little point in considering mechanisms that are not robust or simple.

To the best of our knowledge, only a few attempts have been made to explicitly study the problem of the location of waste treatment facilities. Kunreuther and Kleindorfer [23] proposed using a sealed bid auction where the host community would receive its own bid as compensation. In their paper, the communities are *assumed* to employ maximin strategies and to be strictly better off from participating in the auction even under the worst possible outcome.[7] Because in their auction all the communities pay their bids, their auction generates a surplus that has to be inefficiently disposed off so as not to distort the communities' incentives.[8] In another paper, Samuelson [36] investigated Bayesian–Nash equilibrium behavior under a sealed-bid auction where two communities submit bids, the facility is located at the location that submitted the low bid, and the host community receives the high bid as compensation. He restricts his attention to environments with only two communities and assumes that the communities' disutilities are independently and identically distributed. He demonstrates that his auction induces voluntary participation at the interim stage (when each community has learned its own disutility, but before the other community's disutility has been revealed) but unlike the

[6]We thank an anonymous referee for this insight.

[7]Below, we show that maximin strategies may be optimal in an environment where a community is not modeled as a single decision maker, but rather is a collection of individuals with heterogeneous beliefs.

[8]A similar auction was studied in Kunreuther et al. [24] under similar assumptions.

procedure proposed here, it does not induce ex post voluntary participation (that is, after all the communities' disutilities become commonly known).[9,10]

Finally, as pointed out by Sullivan [38] (see also Baumol and Oates [7]), compensation of the host community may distort residential choices which in turn may change the magnitudes of the communities' disutilities. We do not address this issue here. As O'Sullivan [33] notes, it is not likely to be a problem when the scale economies that are associated with the siting of the facility are large relative to the average local disutility and the distortionary cost of compensation.

The rest of the paper is organized as follows. In Section 2 we provide a brief background of the political controversy surrounding the location of waste treatment facilities. In Section 3 we present the siting procedure. In Section 4, we explain why bidding the true disutility is a focal strategy, and we present environments where bidding is either truthful or close to truthful. In Section 5, we demonstrate that the siting procedure is effective or "nearly" optimal when bidding is close to truthful. In Section 6 we demonstrate that the siting procedure satisfies the demanding notion of ex post voluntary participation. In Section 7, we describe how our siting procedure can be adapted to deal with issues of "environmental justice." Section 8 concludes. All proofs are relegated to the Appendix.

2. HAZARDOUS WASTE SITING PROCEDURES IN THE UNITED STATES

The most important form of opposition to hazardous waste facility sitings is from local governments who delay or deny issuance of permits, licenses, and zoning variances.[11] Other types of opposition include government-issued penalties and citations, class action suits, and various types of political activism.[12] This opposition uses social resources and creates social costs that range from illegal dumping of waste to high fees for the transport of waste to distant facilities. Resources spent by developers on unsuccessful attempts to locate facilities are also significant.[13] Accordingly, there is clear scope for reform of current procedures.

Government authority for siting procedures lies at the state level. Among the states, there are two approaches to handling local opposition.[14] The first approach preempts local opposition by giving state boards the power to override it. This authority ranges from case-by-case exemptions to local legislation to automatic exemptions for all qualifying facilities. Local government intervention is sometimes limited to "positive authority" only: that is, local governments can regulate facilities only if their regulations are weaker than those imposed by the state. A second

[9]This mechanism is also considered by O'Sullivan [33].

[10]Another attempt to address the problem is that of Kleindorfer and Sertel [22] who show that "kth lowest bidder" auctions Nash implement the efficient outcome. They assumed, however, that all the locations' disutilities are commonly known.

[11]Gladwin [16, p. 28].

[12]Ibid.

[13]In Massachusetts, six sitings of hazardous waste facilities were attempted in the period from 1981 to 1990. The process was governed by new sophisticated incentive-based laws. All six attempts failed to result in a siting (Brion, [6, p. 7]). One company wrote off \$16 million in costs from its unsuccessful attempt to obtain a siting for a \$42 million incinerator [6, pp. 13–14].

[14]Except as otherwise indicated, the material in this paragraph is cited from Bacow and Milkey [4, pp. 160–162], and the footnotes therein. See also Jessup [18].

approach uses compensation schemes to provide incentives for host communities to accept the facility. Instead of preempting local authority, an effort is made to eliminate the source of the opposition.[15] Residents in the host community may receive direct cash payments or indirect payments in the form of property value guarantees. The developers may agree to hire local workers or pay taxes to the community. Direct risk-mitigation measures appear to be the most effective form of compensation.[16]

Both of the above approaches have met with limited success. They both also fail a basic efficiency criterion: communities have different disutilities for hosting a facility and efficiency requires that the community with the least disutility (other costs being equal) be the host. The first approach ignores the externality imposed on host communities altogether. In proposing a site, developers need not internalize the preferences of local residents in their cost–benefit analysis.[17] Under the second approach, developers do have an incentive to consider community preferences because of differences in the amount of compensation they expect to pay to different communities. However, this incentive will be imperfect if there are observability problems that prevent a developer from determining the preferences of local residents.

3. THE MODEL AND DESCRIPTION OF THE SITING PROCEDURE

There are $n \geq 2$ communities. Each community has a decision-making body that perceives the local community to have a concave disutility function $d_i: \mathbb{R}_+ \to \mathbb{R}_+$ that describes the community's disutility from processing different quantities of waste in monetary terms. The function d_i is interpreted as the "subjective" disutility from treating waste, however, it may also include an "objective" disutility which is assumed to be common knowledge. For example, the direct cost of building and operating the facility can be considered to be objective cost whereas the total cost that may incorporate in addition, say, the political inconvenience to the decision making body from locating the facility within its jurisdiction is subjective cost. We assume that community i obtains a payoff $t - d_i(w)$ from treating a quantity w of waste and receiving a compensation t. The community is assumed to behave so as to maximize its expected payoff. Each community generates a commonly known quantity of waste $w_i \in \mathbb{R}_+$. If community i refuses to participate in the siting procedure, it suffers a disutility of $d_i(w_i)$ from treating its own waste. Finally, we assume that

[15] [4, p. 167].

[16] Portney [34, p. 59] surveys several towns in Massachusetts to compare how different compensation schemes permute local opposition to sitings. Risk-mitigation measures such as safety inspections and efforts to prevent ground water contamination are consistently more effective than other types of proposals such as property value guarantees, new jobs, tax revenues, and cash payments.

[17] Even when local opposition can be legally overridden, it is, in practice, still a hurdle for developers. Hamilton [17] finds evidence that developers look for sites in areas where they expect little local opposition. To the extent that low opposition results from low local disutility from a siting, then the developer could be internalizing community preferences. However if low opposition results from an inability to engage in collective action that is independent of community preferences, then the developer need not be internalizing the externality.

communities must participate in the siting process in order to be able to use the facility after it is built.[18,19]

Economic efficiency requires that the facility be located in the community that has the smallest disutility from treating the entire quantity of waste, $d_i(\sum_{j=1}^{n} w_j)$. Whenever there is no risk of confusion, we abbreviate and write d_i instead of $d_i(\sum_{j=1}^{n} w_j)$. We use α_i to denote a community's share of the total quantity of waste: $\alpha_i = (w_i / \sum_{j=1}^{n} w_j)$.

The following auction-like procedure can be used to identify the community with the smallest cost d_i and to provide for adequate compensation. Each community has to submit a bid representing its (subjective) disutility d_i. Denote the bid of community i by b_i. Let $[1], [2], \ldots, [n]$ denote the indices of the communities that have the lowest, …, highest bids, respectively. Thus, [1] denotes the community with the lowest bid; [2] denotes the community with the second lowest bid and so on. The facility is located in community [1]. Community i pays community [1] an amount equal to $\alpha_i b_{[2]}$ as compensation. Thus, the communities share the compensation to community [1] proportionally to the quantity of waste they generate and community [1] receives a total compensation equal to $(1 - \alpha_{[1]}) b_{[2]}$.

Two important observations can be made immediately. First, the siting procedure is ex post budget-balanced. The sum of the transfers among the communities is always zero. No deficit ever occurs and no surplus (that has to be diverted so as not to interfere with the structure of incentives) is ever created. Second, if the communities bid truthfully, the siting procedure is efficient. It locates the facility in the community that has the lowest disutility.

4. THE FOCALITY OF BIDDING TRUTHFULLY

To understand the structure of incentives, we first analyze bidding from an ex post perspective. We suppose that all the communities' bids are known and that community i has bid its true disutility.

Suppose that the facility is to be located at i. Then community i would not benefit from a different bid. A lower bid makes no difference. A higher bid either makes no difference (if the bid is below $b_{[2]}$) or causes the facility to be located someplace else with i earning a lower payoff. This is because the payoff to i if it bids its true disutility, $-d_i + (1 - \alpha_i) b_{[2]}$, is at least as high as the payment i must make if the facility is located someplace else, $-\alpha_i b_{[2]}$. That is,

$$\begin{aligned} -d_i + (1 - \alpha_i) b_{[2]} &= -d_i + b_{[2]} - \alpha_i b_{[2]} \\ &\geq -\alpha_i b_{[2]}, \end{aligned}$$

where the inequality follows from $d_i = b_{[1]} \leq b_{[2]}$.

Next, suppose that the facility is to be located someplace else (i.e., $i \neq [1]$). Bidding higher will either have no effect or will increase the compensation that

[18] Bacow and Milkey [4, p. 187] note that this partipication requirement may not be enforceable ex post. That is, if a community refuses to participate in the siting procedure, it may still be allowed to use the facility if ex post it is efficient to do so. We ignore these issues of renegotiation for now.

[19] We consider a "private-values" model. While different communities' disutilities may well be correlated, learning another community's disutility does not affect a community's own disutility. For additional discussion about the differences between private and common values models, see Milgrom and Weber [30].

i pays to have its waste treated. However, i could benefit from decreasing its bid to $b_i \in (b_{[1]}, b_{[2]})$ because its payment would then decrease from $\alpha_i b_{[2]}$ to $\alpha_i b_i$.

We conclude that i has an ex ante incentive to understate its disutility. However, understating the disutility involves risk. When i submits its bid, it does not know the other communities' bids. By bidding below its true disutility, a community risks hosting the facility for little compensation. As we show below, the existence of this risk means that there are many very different environments where communities do well by submitting bids "close" to their true disutilities.

A common environment considered in the economic literature is where communities' disutilities are identically and independently distributed (i.i.d.). In a symmetric equilibrium, the siting procedure is efficient even if communities do not bid truthfully, because the community with the lowest disutility submits the lowest bid and hosts the facility.[20] However, the i.i.d. assumption does not seem likely to obtain in practice.

In the next sections, we argue that our siting procedure works well for a diverse set of environments. We first consider environments where each community has a disutility that is independently distributed. For general, asymmetric, environments, we show that the economic benefit from underbidding is small, at least when there are many communities. That is, bidding truthfully is an ε-equilibrium for a small ε. For symmetric environments, we show when the symmetric Bayesian–Nash equilibrium involves close to truthful bidding. This provides some insight into asymmetric environments where the equilibrium may not be calculated analytically. We next consider environments where a community is viewed not as a single decision maker, but as a collection of heterogeneous individuals. We present an axiomatization where maximin bidding is optimal, and we demonstrate that maximin bidding is truthful. We also take a behavioral approach to the problem faced by a decision maker who must choose a bid for his or her community. We argue that a loss-averse decision maker has an incentive to minimize any understatement of the true disutility.

4.1. *An ε-Equilibrium*

Bidding the true disutility, or truthful bidding, is a transparent, simple strategy. If it yields close to the highest possible payoff, then it seems reasonable that a community would adopt it. In this section, we show that when there are a large number of communities, each community cannot do much better than to bid truthfully. We also demonstrate in examples that the gain from underbidding is small even when there are only a few communities.

We assume that communities have common beliefs about the disutilities of the other communities. Communities (other than i) believe that d_i is independently distributed according to F_i, where F_i is one of a finite set of distributions: $F^1, F^2, \ldots, F^N$.[21] Each F^j has a continuous probability density function f^j that is strictly positive on some interval $[a, b]$ where $0 \leq a < b \leq \infty$.

[20] Cramton et al. [8] prove this result for partnerships. See also [28]. Many simple auction-like procedures are efficient in the i.i.d. environment.

[21] We specify beliefs over the disutility $d_i = d_i(\sum_{j=1}^{n} w_j)$. Formally, communities have beliefs about the entire concave function $d_i(w)$. However, we will only need to know the beliefs about d_i. Note also that if there are more than N communities, some communities must have the same distribution.

The communities calculate their expected payoffs given their beliefs. We let $U_i(d_i, b_i, \alpha_i)$ denote community i's expected payoff when its true disutility is d_i, it bids b_i, it has a share α_i of the total quantity of waste, and other communities bid truthfully. We say that truthful bidding is an "ε-equilibrium" if, when other communities bid truthfully, the most a community expects to gain from shading its bid is ε. That is, for every disutility d_i in the support of F_i, for every bid b_i, and for every share α_i,

$$U_i(d_i, b_i, \alpha_i) - U_i(d_i, d_i, \alpha_i) < \varepsilon.$$

Proposition 1 below shows that no matter how small ε is, there is a number of communities m, such that if the number of communities is larger or equal to m, truthful bidding is an ε-equilibrium. The intuition for the result is that when there are many communities, the "gap" between the lowest and second lowest bids is small, which makes it difficult to manipulate the second lowest bid without bearing a great risk.

PROPOSITION 1. *For every $\varepsilon > 0$, there exists an integer m such that if there are at least m communities, there is an ε-equilibrium in which each community bids truthfully in the siting procedure.*

The proposition tells us that truthful bidding is a plausible outcome when many communities are involved in the siting procedure. This is important because when communities bid truthfully, the siting procedure locates the facility efficiently. Still, the number of a communities required for truthful bidding to be an ε-equilibrium for a small ε may be large.

In the next examples, we demonstrate that truthful bidding is plausible also when the number of communities is quite small. Since the size of ε does not have any a priori meaning, we focus our attention on the ratio

$$\frac{U_i(d_i, b_i^*, \alpha_i) - U_i(d_i, d_i, \alpha_i)}{U_i(d_i, b_i^*, \alpha_i) - (-d_i(w_i))},$$

where b_i^* is the bid that maximizes community i's payoff. This ratio describes the difference between community i's expected payoff when bidding optimally and bidding truthfully, relative to the additional expected payoff that bidding optimally generates beyond the stand alone payoff $-d_i(w_i)$. For example, if this ratio is 5%, then relative to the expected payoff from participating in the siting procedure, bidding truthfully results in an expected payoff that is 5% lower than bidding optimally.

The first example considers communities with two types of communities and equal numbers of each type.[22]

[22]Details of the examples are available from the authors on request. We assume that the stand-alone payoff $d_i(w_i)$ is $\alpha_i d_i$. Any other specification of $d_i(w_i)$ would yield a lower gain to underbidding. To see this, note that given the concavity of $d_i(\cdot)$ we have $d_i(w_i) \geq \alpha_i d_i$ where $d_i = d_i(\sum_{j=1}^{n} w_j)$ and $w_i = \alpha_i w$. It follows that

$$\frac{U_i(d_i, b_i^*, \alpha_i) - U_i(d_i, d_i, \alpha_i)}{U_i(d_i, b_i^*, \alpha_i) - (-d_i(w_i))} \leq \frac{U_i(d_i, b_i^*, \alpha_i) - U_i(d_i, d_i, \alpha_i)}{U_i(d_i, b_i^*, \alpha_i) - (-\alpha_i d_i)}.$$

Example 1. There are m communities. Half of the communities have a disutility that is commonly believed to be distributed according to the exponential distribution $F(d) = 1 - e^{-d}$ for $d \in [0, \infty)$. The other half have a disutility that is commonly believed to be distributed according to the exponential distribution $F(d) = 1 - e^{-2d}$ for $d \in [0, \infty)$. The communities have equal shares $\frac{1}{m}$ of the waste. When $m = 6$, the largest gain to any community from underbidding is 5.8%. When $m = 8$, the largest gain is 3.3%. When $m = 12$, the largest gain is 1.5%.

Communities may also have different shares of the waste. The larger is a community's share of the waste α, the greater is its incentive to underbid. This is because the payment $\alpha b_{[2]}$ that the community makes when its bid determines the price is larger when its α is larger. Our next example illustrates this point.

Example 2. There are eight communities with disutilities as in Example 1. If the communities have equal shares $\alpha = \frac{1}{8}$, then from Example 1, the largest gain to any community from underbidding is 3.3%. If the largest share of any community is $\alpha = \frac{1}{6}$, then the largest gain to any community from underbidding is 4.9%. If the largest share of any community is $\alpha = \frac{1}{5}$, then the largest gain from underbidding is 6.3%.

4.2. *Bayesian–Nash Equilibrium*

In this section, we consider Bayesian–Nash equilibria of the siting procedure. In asymmetric environments, it is difficult to calculate a Bayesian–Nash equilibrium analytically.[23] Instead, we consider symmetric environments in order to provide some intuition about asymmetric environments.[24]

We assume that there are m communities. The communities have common beliefs about the disutilities of the other communities. Communities (other than i) believe that d_i is independently distributed according to some distribution function F, where F has a continuous probability density function f that is strictly positive on its support which is an interval $[a, b]$ where $0 \leq a \leq b \leq \infty$. The communities are assumed to have equal shares of the waste.

The bidding strategy $b(d)$ in the symmetric Bayesian–Nash equilibrium is given by[25]

$$b(d) = d - \frac{\int_a^d F(x)^m dx}{F(d)^m}.$$

When the quantity $\int_a^d F(x)^m dx / F(d)^m$ is small, a community bids close to its true disutility. It is easy to see that as the number of communities grows, bids approach

[23] The calculation requires solving a system of n partial differential equations for which no analytic solution is known to exist.

[24] As discussed, the siting procedure is efficient in symmetric environments. When communities have identical bidding functions, the community with the lowest disutility submits the lowest bid. When bidding functions are not identical, bids need to be close to the true disutility to guarantee effectiveness of the siting procedure.

[25] Techniques presented in [8] can be used to derive this formula. A proof is available from the authors on request. There is a continuous family of symmetric equilibria, but only the one presented here involves bounded strategies.

the true disutilities.[26,27] For example, if the disutilities are uniformly distributed on [0, 1], then

$$b(d) = \frac{m}{m+1} d.$$

In Section 5, we use the closeness of bids to the true disutility to develop a measure of efficiency.

4.3. *The Axiomatic Approach*

Our previous analysis requires that each community has a disutility d_i and beliefs about the disutilities of other communities. However, each community is a collection of individuals, with potentially distinct disutilities and beliefs. In this section, we justify truthful bidding when a community's bid reflects the preferences of all its members.

We assume that the individuals agree on the disutility suffered if the facility were to be built in their community. They disagree, however, in their beliefs about the disutility and bidding behavior of the other communities that are participating with them in the siting procedure. We have in mind a small community where people know each other's preferences and agree on a method for aggregating their preferences. In such a community, if in addition to agreeing over preferences, the individuals also agreed about their beliefs, then they would have submitted the bid that maximizes their expected payoff given their joint belief. The fact that the individuals hold different beliefs raises the question of how these beliefs are to be aggregated and incorporated into the community's bid.[28]

Since different individuals hold different beliefs, every bid made by the community yields a different expected payoff according to each individual's belief. Thus, with every bid, we associate a vector of real numbers that represents the different expected payoffs of this bid under individuals' beliefs. For example, if the community consists of three individuals, a bid has three different expected payoffs, u_i, one for each individual's belief. The bid is associated with the vector $\vec{u} = \{u_1, u_2, u_3\}$.

[26] For any $\varepsilon > 0$, write

$$\frac{\int_a^d F(x)^m dx}{F(d)^m} = \frac{\int_a^{d-\frac{\varepsilon}{2}} F(x)^m dx}{F(d)^m} + \frac{\int_{d-\frac{\varepsilon}{2}}^d F(x)^m dx}{F(d)^m}.$$

We show that for every large enough m, each of the previous two terms is smaller than $\frac{\varepsilon}{2}$. For every m, we have

$$\frac{\int_{d-\frac{\varepsilon}{2}}^d F(x)^m dx}{F(d)^m} \leq \frac{(\frac{\varepsilon}{2})F(d)^m}{F(d)^m} \leq \frac{\varepsilon}{2}.$$

For m sufficiently large, we also have

$$\frac{\int_a^{d-\frac{\varepsilon}{2}} F(x)^m dx}{F(d)^m} \leq \left(d - \frac{\varepsilon}{2} - a\right)\left[\frac{F(d-\frac{\varepsilon}{2})}{F(d)}\right]^m < \frac{\varepsilon}{2}$$

since the fact that f has a strictly positive density on its support implies that $(F(d-\frac{\varepsilon}{2})/F(d)) < 1$.

[27] In a different environment, that of double auctions, Rustichini et al. [35] identify the rate of convergence of buyers' and sellers' bids to valuations.

[28] We assume that the agents' different beliefs already incorporate all the available information. They therefore cannot reconcile their different priors into one prior. That is, they agree to disagree on their different priors.

In order to decide what bid to submit, the community has to agree on its preference ordering over the space V of such vectors.[29]

In the Appendix, we present a set of six axioms (A1–A6) that the community's preference ordering $\succeq$ could satisfy. Four of these axioms are standard (namely, weak-order, symmetry, continuity, and independence). The fifth axiom is a form of "uncertainty aversion." Informally it requires that, other things being equal, the community prefers to base its decision on a broader sample of individuals. The sixth axiom requires that if a new individual has a more negative opinion of a bid than existing community members, the community's evaluation of the bid is pulled down.[30] Informally, the axiom implies a concern for pessimistic individuals.

For obvious reasons, we are interested in preference orderings over V that induce the standard monotone preference ordering over $\mathbb{R}$, $\geq$. We have the following proposition.

PROPOSITION 2. *A preference relation $\succeq$ over V that is an extension of the binary relation $\geq$ over $\mathbb{R}$ satisfies* A1–A6 *if and only if it is the maximin decision rule. That is, for every $\vec{u}, \vec{v} \in V$*

$$\vec{u} \succeq \vec{v} \text{ if and only if } \min\{u_i\} > \min\{v_i\}.$$

There is a rich literature that identifies the maximin rule as a good rule to employ in conditions of "complete ignorance" where the decision maker cannot determine the probabilities of various events and can only compare the different sets of outcomes that are associated with his or her choices. We discuss this literature in the Appendix.

Proposition 2 axiomatizes the maximin rule where the maximin is taken with respect to the beliefs of the members of the community. The larger the number of community members and the richer the range of beliefs they hold, the closer will the maximin bid with respect to the community members' beliefs be to the global maximin bid which, as the next proposition proves, is equal to the true disutility.

PROPOSITION 3. *The maximin bid of a community over the space of all possible beliefs under the siting procedure described above is the community's true disutility.*

Generally, the maximin strategy is the best response strategy of a pessimistic player who believes that the other players can observe his or her strategy and choose a profile of actions that would minimize his or her payoff. While such a belief may be rather extreme in some situations, the maximin strategy is the most prudent of strategies and is a reasonable heuristic in adversarial situations. Moreover, in the context discussed here, it is the only strategy that is consistent with axioms A1–A6 above.

4.4. *The Behavioral Approach*

In this section, we assume that there is a single decision maker who represents the community in the siting procedure. One of the observed regularities described by

[29] $V = \mathbb{R} \cup \mathbb{R}^2 \cup \mathbb{R}^3 \cup \cdots$ is the space of finite dimensional vectors of real numbers. Its topology is inherited from each of the $\mathbb{R}^n$ spaces. A community's preference order is given by a binary relation $\succeq$ on V. See the Appendix.

[30] The last axiom is part of what is known as the Gärdenfors principle [14].

Prospect Theory [19, 39] is that people weigh losses more heavily than corresponding gains. In fact, empirical estimates find that losses are weighted about twice as strongly as gains [20, 39]. Many people, for example, reject a 50–50 chance to win \$200 or lose \$100, even though the gain is twice as large as the loss [40]. Preferences that weigh losses more heavily than gains are said to exhibit "loss aversion."

As explained above, the party who is responsible for submitting the bid for community i, say the mayor of community i, can bid truthfully or can submit a bid below community i's true disutility. This may result in community i paying less—a gain—but it may also result in the facility being located at community i without it being adequately compensated—a loss. The fact that losses loom larger than gains (by a factor of approximately 2) enhances the attractiveness of bidding truthfully. One may wonder about the reason that community i's mayor defines gains and losses with respect to bidding truthfully and not with respect to some other benchmark. We believe that such an approach follows naturally from the fact that when the mayor prepares the bid, he or she is likely to ask for an estimate of the true disutility to the community which provides him or her with a natural point of comparison.

Thus, loss aversion on the part of community i's mayor may make bids that are close to the community's true disutility relatively more attractive. Another reason community i's mayor may perceive different gains and losses than those defined in Section 3 above is that the preferences of the members of community i may exhibit loss aversion. Furthermore, suppose that the mayor of community i attempts to maximize the community's expected utility, taking the loss aversion of its members as given. Suppose that he or she submits a bid below the community's true disutility and as a consequence succeeds in paying less. Since the gain accrues to the community rather than to the mayor personally, the mayor cannot fully appropriate the entire gain and would consequently value it less highly. Furthermore, in the case of a loss, the mayor is more likely to be held personally responsible for the loss in utility to the community's residents, which could cost his or her political career. Thus, gains will be valued less highly and losses will be valued more highly than before, rendering bids that are close to the community's true disutility even more attractive.

Finally, as Kunreuther et al. [24] demonstrated, subjects in experiments rapidly converge to approximately playing their maxmin strategies in a similar auction environment.

5. EFFECTIVENESS

Define the effectiveness of a mechanism as the ratio between expected total welfare under the mechanism and expected total welfare under the first-best outcome. The arguments presented in the previous section suggest that while communities may want to bid somewhat below their true disutilities from hosting the facility, they do not want to bid very much below their true disutilities. In this section we note the straightforward fact that if every community submits a bid that is "close" to its true disutility, then the siting procedure is highly effective. Either the facility is located at the community that has the lowest true disutility figure, or, if not, then the efficiency loss that is associated with locating the facility elsewhere is small. We state this fact more formally in the following proposition. Recall that locations do not perceive an incentive to bid above their true disutility.

PROPOSITION 4. *Suppose that every community's bid, b_i, is not lower than r times the community's true disutility for some $r \leq 1$. Then, the efficiency loss under the siting procedure described in Section 3 above is no larger than $\frac{1-r}{r}$ times the lowest true disutility.*

Thus, for example, if all the communities submit bids that are no lower than 15% below their true disutilities, the maximum efficiency loss is no more than 17.6% of the true disutility and probably less as the worst case occurs when the community with the lowest disutility bids its true disutility whereas the community with the second lowest disutility submits a bid that is 15% lower than its true disutility.[31]

6. VOLUNTARY PARTICIPATION

In many situations, the state does not have the power to coerce communities to participate in the siting procedure. In such cases the siting procedure should induce the communities into voluntarily submitting to its outcomes. This would also minimize public opposition to the siting decision in those cases where the state has coercive power. As noted in Section 2 above, public opposition has been a major contributing factor to the fact that in spite of the high demand, so few hazardous waste facilities have been constructed recently.

In this section we demonstrate that truthful bidding in the siting procedure satisfies the demanding notion of ex post voluntary participation. In the literature, one finds two notions of voluntary participation: interim voluntary participation which implies that communities are willing to participate in the siting procedure before they know its recommendations, and the more demanding notion of ex post voluntary participation which implies that even after learning the outcome under the procedure, communities cannot do better by refusing to submit and handling their own waste separately.

Proposition 5 establishes the ex post individual rationality of the siting procedure that we propose. Each community prefers to participate in the auction rather than to treat its waste on its own. The result follows immediately from the concavity of the function d_i.

PROPOSITION 5. *The siting procedure is ex post individually rational.*

7. FAIRNESS

Our siting procedure can be easily adapted to deal with environmental racism issues. The term "environmental racism" refers to the pattern of siting LULUs in poor and minority communities. Hamilton [17] finds evidence that firms take into account a community's potential for collective action in deciding where to expand hazardous waste processing facilities. By giving each potential community an equal voice in the bidding, this bias could be mitigated under our mechanism. There remains the possibility, however, that poor and minority communities may have a

[31] In the example of Section 4.2, the bids are less than 15% below the true disutilities if there are at least six communities. Of course, in the example the siting procedure is efficient because the equilibrium is symmetric. But, the point is that the number of communities need not be very large for bidding to be close to the true disutility.

lower disutility for hosting a hazardous waste facility, since they have more to gain from the economic benefits (taxes and jobs) it could bring in. Economic efficiency may result then in poor communities receiving the hazardous waste facilities more often than wealthier communities. If fairness is a separate social goal, then it may be desirable to sacrifice some efficiency for a more equal distribution of the facilities. One way to accomplish this would be to "weigh" the payments of each community differently. That is, a \$1 bid by a poor community could be scaled up, so that it is equivalent to an \$$\alpha$ bid by a wealthy community where $\alpha > 1$.[32]

8. CONCLUSION

In this paper, we presented a simple and effective auction-like procedure for the siting of waste treatment facilities. As argued by Frey et al. [12], recent studies have shown that citizens, moved by a sense of "public spirit," may well agree to hosting waste treatment and other NIMBY projects in their communities. Residents have been shown to be willing to vote in favor of hosting a NIMBY project if there is a "need" for such a facility [27], if their own site is safer than sites in other available communities [10, 25], and if the site selection process allocates the burden "fairly" [11]. There is no doubt that actual siting of NIMBYs is a complex problem. However, we believe that a siting procedure based on the one proposed in this paper that in addition is sensitive to issues of "environmental justice" and other moral considerations such as those discussed in [12] could well provide an acceptable and satisfactory solution.

9. APPENDIX

The Appendix contains all proofs and our analysis of the axiomatic approach in Section 4. The Appendix is divided into sections that correspond to sections in the text.

An ε-Equilibrium

Proof of Proposition 1. Fix $\varepsilon > 0$. We assume that $m \geq 3$. We use $i = 1, \ldots, m$ to index the communities. In (i), we assume that there is a single distribution F such that $F_i = F$ for all i. In (ii) we generalize the results to the case that each community has one of the N distributions $F^1, F^2, \ldots, F^N$.

(i) We have

$$U_i(d_i, b_i, \alpha_i) = (m-1)\int_{b_i}^{\infty}[-d_i + (1-\alpha_i)x]f(x)(1-F(x))^{m-2}dx$$
$$-(m-1)\alpha_i b_i F(b_i)(1-F(b_i))^{m-2}$$
$$-(m-1)(m-2)\int_0^{b_i}\alpha_i x f(x)F(x)(1-F(x))^{m-3}dx.$$

The expression has three terms. The first arises when i's bid is $b_{[1]}$ and the facility is located in i's area. The second term arises when i's bid is $b_{[2]}$, so that i determines the compensation level. The third term arises when i's bid is $b_{[j]}$ for $j \geq 3$.

[32]A similar procedure was followed in the auctioning of the spectrum. See Milgrom [29].

To demonstrate an ε-equilibrium, we show that $U_i(d_i, b_i, \alpha_i) - U_i(d_i, d_i, \alpha_i) < \varepsilon$ for m sufficiently large for every d_i, for every bid $b_i \in [0, d_i]$, and for every $\alpha_i \in (0, 1]$. As discussed at the beginning of Section 4, the bid that maximizes community i's payoff is less than d_i, so this is sufficient.

We have

$$\begin{aligned}
&U_i(d_i, b_i, \alpha_i) - U_i(d_i, d_i, \alpha_i)\\
&\quad = (m-1)\int_{b_i}^{d_i} [-d_i + (1-\alpha_i)x] f(x)(1-F(x))^{m-2}dx\\
&\qquad + (m-1)\alpha_i d_i F(d_i)(1-F(d_i))^{m-2} - \alpha_i b_i F(b_i)(1-F(b_i))^{m-2}\\
&\qquad + (m-1)(m-2)\int_{b_i}^{d_i} \alpha_i x f(x)F(x)(1-F(x))^{m-3}dx.
\end{aligned}$$

The integral on the first line is negative as is the second term on the second line. Eliminating these terms, we have

$$\begin{aligned}
&U_i(d_i, b_i, \alpha_i) - U_i(d_i, d_i, \alpha_i)\\
&\quad \le (m-1)\alpha_i d_i F(d_i)(1-F(d_i))^{m-2}\\
&\qquad + (m-1)(m-2)\int_{b_i}^{d_i} \alpha_i x f(x)F(x)(1-F(x))^{m-3}dx.
\end{aligned}$$

We show that each of the two terms on the right-hand side of the inequality above tends to zero as m tends to infinity. The first term is less than $(m-1)d_i(1-F(d_i))^{m-2}$. Because d_i is in the support of F, $F(d_i) > 0$, and it follows that $(m-1)d_i(1-F(d_i))^{m-2}$ tends to zero as m tends to infinity.

We now bound the second term in the inequality above:

$$\begin{aligned}
&(m-1)(m-2)\int_{b_i}^{d_i} \alpha_i x f(x)F(x)(1-F(x))^{m-3}dx\\
&\quad \le (m-1)(m-2)\int_{0}^{\infty} x f(x)F(x)(1-F(x))^{m-3}dx.
\end{aligned}$$

By the Lebesgue convergence theorem, since for every $x \in [0, \infty)$, $(m-1)(m-2)x f(x)F(x)(1-F(x))^{m-3} \searrow_{m \nearrow \infty} 0$, the expression above converges to 0 as well.

(ii) We generalize the result to the case that each community has one of the N distributions $F^1, F^2, \ldots, F^N$. We have

$$\begin{aligned}
&U_i(d_i, b_i, \alpha_i) - U_i(d_i, d_i, \alpha_i)\\
&\quad = \sum_{\substack{k=1\\k\neq i}}^{m}\int_{b_i}^{d_i}[-d_i + (1-\alpha_i)x] f_k(x) \prod_{j=1, j\neq i,k}^{m}(1-F_j(x))dx\\
&\qquad + (\alpha_i d_i)\sum_{\substack{k=1\\k\neq i}}^{m} F_k(d_i)\prod_{j=1, j\neq i,k}^{m}(1-F_j(d_i)) - \alpha_i b_i \sum_{\substack{k=1\\k\neq i}}^{m} F_k(b_i)\prod_{j=1, j\neq i,k}^{m}(1-F_j(b_i))\\
&\qquad + \sum_{\substack{k=1\\k\neq i}}^{m}\sum_{\substack{j=1\\j\neq i,k}}^{m}\int_{b_i}^{d_i}\alpha_i x f_k(x)F_j(x)\prod_{l=1, l\neq j,k,i}^{m}(1-F_l(x))dx.
\end{aligned}$$

As before, we eliminate the negative terms to arrive at

$$U_i(d_i,b_i,\alpha_i)-U_i(d_i,d_i,\alpha_i)\le\alpha_i d_i\sum_{\substack{k=1\\k\neq i}}^{m}F_k(d_i)\prod_{j=1,j\neq i,k}^{m}(1-F_j(d_i))$$
$$+\sum_{\substack{k=1\\k\neq i}}^{m}\sum_{\substack{j=1\\j\neq i,k}}^{m}\int_{b_i}^{d_i}\alpha_i x f_k(x)F_j(x)\prod_{l=1,l\neq j,k,i}^{m}(1-F_l(x))dx.$$

Define the piecewise continuous function $F^{\min}(x)=\min_{j\in\{1,\ldots,m\}}\{F^j(x)\}$ on $x\in[0,\infty)$. By the assumption on our distributions, $F^{\min}(x)$ has a piecewise continuous density function that is strictly positive on the support $[a,b]$ where $0\le a<b\le\infty$. Each community i has $F_i\in\{F^1,F^2,\ldots,F^N\}$. It follows that $F_i(x)\ge F^{\min}(x)$ on $x\in[0,\infty)$. We have

$$U_i(d_i,b_i,\alpha_i)-U_i(d_i,d_i,\alpha_i)\le(m-1)d_i(1-F^{\min}(d_i))^{m-2}$$
$$+(m-1)(m-2)\int_0^{\infty}xf^{\min}(x)(1-F^{\min}(x))^{m-3}dx.$$

We can now finish the proof as in (i). ∎

The Axiomatic Approach

First, we present some necessary notation. Let $V=\mathbb{R}\cup\mathbb{R}^2\cup\mathbb{R}^3\cup\cdots$ denote the space of finite dimensional vectors of real numbers. We endow V with the topologies inherited from the $\mathbb{R}^n$'s, respectively. That is, two vectors of arbitrary dimension, $\vec{a},\vec{b}\in V$, are "close" if (i) they are of the same dimension, $\vec{a},\vec{b}\in\mathbb{R}^n$ for some n, and (ii) if they are close in $\mathbb{R}^n$. A typical vector in V is denoted $\vec{a}=(a_1,\ldots,a_n)$; we refer to each a_i as an "element" of a and write $a_i\in\vec{a}$. We define *concatenation* of vectors. For any $\vec{a}=(a_1,\ldots,a_n)$ and $\vec{b}=(b_1,\ldots,b_m)$, $\vec{a}\cup\vec{b}=(a_1,\ldots,a_n,b_1,\ldots,b_m)\in\mathbb{R}^{n+m}$.

A community's preference order is given by a binary relation on V, denoted $\succeq$. The relation has symmetric and asymmetric parts denoted by $\succ$ and $\sim$, respectively. We impose the following axioms on the community's preference ordering.

A1. $\succeq$ is a weak order, i.e., complete and transitive: For every $\vec{a},\vec{b}\in V$, either $\vec{a}\succeq\vec{b}$ or $\vec{b}\succeq\vec{a}$, and for every $\vec{a},\vec{b},\vec{c}\in V$, if $\vec{a}\succeq\vec{b}$ and $\vec{b}\succeq\vec{c}$, then $\vec{a}\succeq\vec{c}$.

A2. $\succeq$ is symmetric across individuals: For every $\vec{a}\in V$ and permutation of $\{1,\ldots,n\}$, σ, $\vec{a}\sim\vec{a}_\sigma$ where $\vec{a}_\sigma=(a_{\sigma(1)},\ldots,a_{\sigma(n)})$.

Symmetry across individuals implies that the identity of individuals does not affect the community's ranking of bids.

A3. $\succeq$ is continuous: For every sequence of vectors $\{a^k\}\subseteq V$ converging to a vector $\vec{a}\in V$, if $a^k\succ\vec{b}$ for all k, then $\vec{a}\succeq\vec{b}$.

A4. $\succeq$ is independent: For every $\vec{a},\vec{b}\in V$, and $x\in\mathbb{R}$, if $\vec{a}\succeq\vec{b}$, then $\vec{a}\cup x\succeq\vec{b}\cup x$.[33]

[33] This axiom is called monotonicity by Kanai and Peleg [21] and strong independence by Nehring and Puppe [32].

If a community prefers one bid over another, then the fact that a member that is indifferent between the two bids joins the community should not change its ranking. The next axiom is a form of "uncertainty aversion." A community prefers a bid that two of its members have identical opinions about to a bid that only one member has such an opinion about. That is, the community prefers to base its decision on a broader sample of public opinion.

A5. $\succeq$ exhibits uncertainty aversion: For any $x \in \mathbb{R}$, $(x, x) \succeq x$.

Finally, the last axiom implies that the addition of a more negative opinion must pull the community's evaluation of a bid down.

A6. $\succeq$ is such that if $x < a_i$ for all $a_i \in \vec{a}$, then $\vec{a} \cup x \prec \vec{a}$.

The last axiom is part of what is known as the Gärdenfors principle (Gärdenfors [14]).[34]

For obvious reasons, we are interested in preference orderings over V that induce the standard monotone preference ordering over $\mathbb{R}$, $\geq$. We restate Proposition 2 before proving it.

PROPOSITION 2. *A preference relation $\succeq$ over V that is an extension of the binary relation $\geq$ over $\mathbb{R}$ satisfies* A1–A6 *if and only if it is the maximin decision rule. That is, for every $\vec{u}, \vec{v} \in V$,*

$$\vec{u} \succeq \vec{v} \text{ if and only if } \min\{u_i\} > \min\{v_i\}.$$

As discussed in the text, there is a rich literature that identifies the maximin rule as a good rule to employ in conditions of "complete ignorance." In a statistical decision problem with an unknown prior, Wald [41] advocated the use of the minimax loss criterion which is equivalent to maximin utility and Savage [37, Chap. 9] the closely related minimax regret criterion. Milnor [31] includes an axiomatization of the maximin rule. More recently, Gilboa and Schmeidler [15] obtained an axiomatization of the maximin rule. They present a set of axioms on preferences that characterizes choice according to maximin expected utility with respect to a set of priors. In a more specific context, Linhart and Radner [26] discuss the plausibility of maximin behavior in the related problem of a double auction.

Our argument is more closely related to the type of arguments that appear in [2, 5, 31, 32] and the references therein. Milnor [31] axiomatizes the maximin rule for vectors of a given length. Arrow and Hurwicz [2] axiomatize a decision rule where the result of a comparison between any two vectors $\vec{a}, \vec{b} \in V$ depends only on the comparison between $(\min\{a_i\}, \max\{a_i\})$ and $(\min\{b_i\}, \max\{b_i\})$. Barberà and Jackson [5] present an alternative axiomatization of the maximin rule and Nehring and Puppe [32] discuss the general question of how to obtain a continuous extension of an order on a set to an order over the power set. We rely on somewhat different axioms than those employed in these four papers that are more appropriate in the particular context discussed here. Specifically, we consider vectors of different

[34]The Gärdenfors principle usually includes two conditions, the negative one stated above and a positive counterpart: If $x > a_i$ for all $a_i \in a$, then $a \cup x \succ a$. As shown by Kanai and Peleg [21], the two assumptions are mutually inconsistant in the sense that there does not exist a complete, transitive, reflexive binary relation on V satisfying both conditions. Our selection of the negative condition implies that the community has more concern for pessimistic individuals than for optimistic ones.

lengths. We do not impose an axiom of column duplication as in [31] or independence of duplicated states as in [2] and [5] which implies that adding members to a community that prefers one bid over another should not affect the community's choice. Finally, we rely on a different notion of continuity and obtain our result on the space of finite dimensional vectors while Nehring and Puppe [32] consider the space of finite sets.

Proof of Proposition 2. It is straightforward to verify that the maximin rule satisfies A1–A6. We show that A1–A6 imply the maximin rule. By A2 no loss of generality is involved with treating every vector $\vec{a} \in V$ as if its elements are in descending order: $\vec{a} = (a_1, \ldots, a_n)$ where $a_i \geq a_{i+1}$ for all i. Then $a_1 = \max\{a_i\} = a_{\max}$ and $a_n = a_{\min}$.

LEMMA 1. *If $a_i \geq b_i$ for $i = 1, \ldots, n$, then $(a_1, \ldots, a_n) \succeq (b_1, \ldots, b_n)$.*

Proof. The proof consists of two steps.

Step 1. For every $\vec{a} \in V$ and $x, y \in \mathbb{R}$, if $x \geq y$, then $\vec{a} \cup x \succeq \vec{a} \cup y$. By A4, $x \geq y$ implies that $(x, a_1) \succeq (y, a_1)$. Again by A4, $(x, a_1, a_2) \succeq (y, a_1, a_2)$. Repeating this argument and invoking A2 gives $\vec{a} \cup x \succeq \vec{a} \cup y$.

Step 2. By the result of step 1, we have that $(a_1, \ldots, a_n) \succeq (a_1, \ldots, a_{n-1}, b_n)$. Applying the result of Step 1 again and invoking A2 implies that $(a_1, \ldots, a_{n-1}, b_n) \succeq (a_1, \ldots, a_{n-2}, b_{n-1}, b_n)$. By transitivity $(a_1, \ldots, a_n) \succeq (a_1, \ldots, a_{n-2}, b_{n-1}, b_n)$. Repeated applications of this argument imply that $(a_1, \ldots, a_n) \succeq (b_1, \ldots, b_n)$. ∎

LEMMA 2. *For every $a \in \mathbb{R}$ and $(a, a, \ldots, a) \in \mathbb{R}^n$, $(a, a, \ldots, a) \sim a$.*

Proof. By A5, $(a, a) \succeq a$. By A6, $(a, a - \frac{1}{n}) \prec a$. Letting $n \to \infty$, we have by A3 that $(a, a) \preceq a$, so it must be that $(a, a) \sim a$. Now, by A4, $(a, a, a) \sim (a, a)$. So by transitivity $(a, a, a) \sim a$. Repeating the last argument gives $(a, a, \ldots, a) \sim a$. ∎

LEMMA 3. *For every vector $\vec{a} \in V$,*

$$\vec{a} \sim (a_{\max}, a_{\min}).$$

Proof. Fix some $\vec{a} \in V$. By Lemma 1,

$$(a_{\max}, a_{\max}, \ldots, a_{\max}, a_{\min}) \succeq \vec{a} \succeq (a_{\max}, a_{\min}, \ldots, a_{\min})$$

where all the vectors above have the same length. By Lemma 2, $(a_{\max}, a_{\max}, \ldots, a_{\max}, a_{\max}) \sim a_{\max}$. By A4, $(a_{\max}, a_{\max}, \ldots, a_{\max}, a_{\min}) \sim (a_{\max}, a_{\min})$. Similarly, by Lemma 2, $(a_{\min}, \ldots, a_{\min}) \sim a_{\min}$, and by A4, $(a_{\max}, a_{\min}, \ldots, a_{\min}) \sim (a_{\max}, a_{\min})$. Thus, $(a_{\max}, a_{\min}) \succeq \vec{a} \succeq (a_{\max}, a_{\min})$. The conclusion follows. ∎

We are now in a position to prove the proposition. Fix some $\vec{a} \in V$. By Lemma 1, $(a_{\max}, a_{\max}) \succeq (a_{\max}, a_{\min}) \succeq (a_{\min}, a_{\min})$. By Lemma 2, $a_{\max} \succeq (a_{\max}, a_{\min}) \succeq a_{\min}$. There exists some $\lambda \in \mathbb{R}, a_{\max} \geq \lambda \geq a_{\min}$, such that $\lambda \sim (a_{\max}, a_{\min})$. Suppose otherwise that for all $\lambda \in [a_{\min}, a_{\max}]$, either $\lambda \succ (a_{\max}, a_{\min})$ or $\lambda \prec (a_{\max}, a_{\min})$. Let $O = \{\lambda \in [a_{\min}, a_{\max}] : \lambda \succ (a_{\max}, a_{\min})\}$ and $D = \{\lambda \in [a_{\min}, a_{\max}] : \lambda \prec (a_{\max}, a_{\min})\}$. By assumption, $O \cup D = [a_{\min}, a_{\max}]$. Recall that $\succeq$ is an extension of $\geq$. Therefore, $\lambda' > \lambda''$ implies that $\lambda' \succ \lambda''$. By completeness (A1), either O has a minimal element or D has a maximal element. Suppose that D has a maximal element λ^*. Consider a sequence $\lambda_n \searrow \lambda^*$. The fact that $\lambda_n > \lambda^*$ for every n implies that $\lambda_n \succ (a_{\max}, a_{\min})$ for every n. By continuity (A3), it follows that

$\lambda^* \succeq (a_{\max}, a_{\min})$, a contradiction to the fact that $\lambda^* \in D$. A similar contradiction can be established if O has a minimal element.

Now, by A4, $(\lambda, a_{\min}) \sim (a_{\max}, a_{\min}, a_{\min})$. By Lemma 3, $(a_{\max}, a_{\min}, a_{\min}) \sim (a_{\max}, a_{\min})$, so $(\lambda, a_{\min}) \sim (a_{\max}, a_{\min})$. By assumption, $(a_{\max}, a_{\min}) \sim \lambda$. So we have $(\lambda, a_{\min}) \sim \lambda$. We know that $\lambda \geq a_{\min}$. Suppose that $\lambda > a_{\min}$. Then by A4, $\lambda \succ (\lambda, a_{\min})$, a contradiction. Therefore $\lambda = a_{\min}$. That is, $(a_{\max}, a_{\min}) \sim a_{\min}$. Together with Lemma 3, this implies that

$$\vec{a} \sim a_{\min}$$

which implies the conclusion of the proposition. ∎

Proof of Proposition 3. Fix community i's disutility d_i. The maximin strategy for i is given by

$$v_i(d_i) = \arg\max_{b_i \in \mathbb{R}_+} \min_{b_{-i} \in \mathbb{R}_+^{n-1}} U_i(b_i, d_i).$$

Community i's payoff when it bids the true disutility d_i depends on other communities' bids by

if	$i = [1]$	$i = [2]$	$i = [3], \ldots, [n]$
payoff is	$-d_i + (1 - \alpha_i) d_{[2]}$	$-\alpha_i d_i$	$-\alpha_i d_{[2]}$.

Because when $i = [1], -d_i + (1 - \alpha_i) d_{[2]} \geq -d_i + (1 - \alpha_i) d_i = -\alpha_i d_i$ and when $i = [3], \ldots, [n], -\alpha_i d_{[2]} \geq -\alpha_i d_i$, the minimum payoff when i bids truthfully is $-\alpha_i d_i$. It is straightforward to verify that bidding above the true disutility is dominated by bidding the true disutility for every i. It follows that the minimum payoff associated with bidding above the valuation is lower than $-\alpha_i d_i$. We show that the same is true for bidding below the valuation. Suppose that i bids $b_i < d_i$. In this case, the minimum payoff is given by

if	$i = [1]$	$i = [2]$	$i = [3], \ldots, [n]$
payoff is	$-d_i + (1 - \alpha_i) b_i$	$-\alpha_i b_i$	$-\alpha_i d_{[2]}$.

We show that the minimum payment obtained in this case is smaller than the minimum payment obtained under truthful bidding. It is sufficient to show that

$$-d_i + (1 - \alpha_i) b_i < -\alpha_i d_i.$$

But this follows immediately from the fact that $b_i < d_i$ and $\alpha_i \in [0, 1]$ for all i. ∎

Effectiveness

Proof of Proposition 4. Let γ denote the disutility of the community with the lowest disutility. Since all the communities' bids are bounded from below by $r \cdot d_i$, the highest a community's disutility can be such that it still submits the lowest bid is $\frac{\gamma}{r}$. Therefore, as a fraction of the true combined disutility, γ, the efficiency loss is bounded from above by $\frac{(\gamma/r)-\gamma}{\gamma} = \frac{1-r}{r}$. ∎

Voluntary Participation

Proof of Proposition 5. The proof follows from the next two lemmas.

LEMMA 4. *For every set of concave disutility functions, $d_1, \ldots, d_n$, non-negative wastes $w_1, \ldots, w_n$, and $i \in \{1, \ldots, n\}$ such that the facility is not located at i,*

$$-\frac{w_i}{\sum_{j=1}^n w_j}\left(d_{[2]}\left(\sum_{j=1}^n w_j\right)\right) \geq -d_i(w_i).$$

Proof. We have

$$\begin{aligned}\frac{w_i}{\sum_{j=1}^n w_j}\left(d_{[2]}\left(\sum_{j=1}^n w_j\right)\right) &\leq \left(1-\frac{w_i}{\sum_{j=1}^n w_j}\right)(d_{[2]}(0)) + \frac{w_i}{\sum_{j=1}^n w_j}\left(d_{[2]}\left(\sum_{j=1}^n w_j\right)\right)\\ &\leq d_{[2]}\left(\frac{w_i}{\sum_{j=1}^n w_j}\sum_{j=1}^n w_j\right)\\ &\leq d_{[2]}(w_i)\\ &\leq d_i(w_i).\end{aligned}$$

The second inequality follows from the concavity of d_i and the last one from the fact that the facility is not located at i. ∎

LEMMA 5. *For every set of concave disutility functions $d_1, \ldots, d_n$, non-negative wastes $w_1, \ldots, w_n$, and i such that the facility is located at i,*

$$-d_i\left(\sum_{j=1}^n w_j\right) + \left(1-\frac{w_i}{\sum_{j=1}^n w_j}\right)\left(d_{[2]}\left(\sum_{j=1}^n w_j\right)\right) \geq -d_i(w_i).$$

Proof. We have

$$\begin{aligned}&d_i\left(\sum_{j=1}^n w_j\right) - \left(1-\frac{w_i}{\sum_{j=1}^n w_j}\right)\left(d_{[2]}\left(\sum_{j=1}^n w_j\right)\right)\\ &\quad\leq d_{[1]}\left(\sum_{j=1}^n w_j\right) - \left(1-\frac{w_i}{\sum_{j=1}^n w_j}\right)\left(d_{[1]}\left(\sum_{j=1}^n w_j\right)\right)\\ &\quad\leq \frac{w_i}{\sum_{j=1}^n w_j}\left(d_{[1]}\left(\sum_{j=1}^n w_j\right)\right)\\ &\quad\leq \left(1-\frac{w_i}{\sum_{j=1}^n w_j}\right)(d_{[1]}(0)) + \frac{w_i}{\sum_{j=1}^n w_j}\left(d_{[1]}\left(\sum_{j=1}^n w_j\right)\right)\\ &\quad\leq d_{[1]}\left(\left(1-\frac{w_i}{\sum_{j=1}^n w_j}\right)0 + \frac{w_i}{\sum_{j=1}^n w_j}\sum_{j=1}^n w_j\right)\\ &\quad= d_{[1]}(w_i)\\ &\quad= d_i(w_i).\end{aligned}$$

The fourth inequality follows from concavity of d_i. ∎

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