Siting Noxious Facilities: Efficiency and Majority Rule Decisions

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Abstract

This paper analyzes the inefficiency of majority-rule voting in making siting decisions for noxious facilities, such as waste treatment facilities, landfills, or nuclear waste repositories. In particular, we demonstrate in a general context that a majority-rule voting process leads localities to make decisions that impose aggregate costs that are larger than aggregate benefits. We develop a robust model to establish the prevalence of such inefficiencies and demonstrate the mechanisms that exacerbate or mitigate them. The model illustrates how the spatial distribution of the population and the severity of disamenity costs can generate outcomes that make the entire locality worse off. Based on these properties, we provide a feasible remedy. Analysis of U.S. census data illustrates the magnitude of potential inefficiencies that arise with simple majority-rule decisions. Such losses can be mitigated using our model, which easily captures the aggregate disamenity cost and can consequently recommend the required voting supermajority to ensure efficiency.

Keywords: Decision support systems; Noxious facilities; Efficient siting; Externalities

1 Introduction

A challenging decision facing policy makers is the allocation of goods that generate externalities, given that market forces alone often lead to inefficient outcomes. Of particular interest is the task of choosing locations for siting noxious facilities such as waste treatment facilities, landfills, and nuclear waste repositories, or even environmentally-friendly operations such as large solar arrays and wind farms. These facilities are often associated with the "Not In My BackYard" (NIMBY) syndrome (O'Hare et al., 1983).[1] While noxious facilities can be important elements of society, individuals are often averse to having these facilities in close proximity. In this paper, we explore the ability of communities to efficiently determine whether or not to host a facility in a particular location. Our analysis focuses on the spatial landscape as a key driver in siting decisions due to a negative impact on housing prices (Farber, 1998; McCluskey and Rausser, 2003; Grislain-Letremy and Katossky, 2014) and evidence of aversion to such facilities based on odor, visual pollution, and air pollution (Kaya and Erol, 2016). Consequentially, Pelekasi et al. (2012) found a lower likelihood of accepting a facility among households that are in close proximity to the facility as they are more concerned with visual impacts. Schively (2007) provides a discussion of the unique difficulties and potential solutions that arise in attempting to remedy NIMBY problems related to siting noxious facilities.

Facility siting represents one type of problem encountered in the provision of public goods, a topic that has received considerable attention. Samuelson (1954, 1955) demonstrate the inability of decentralized markets to efficiently allocate public goods, based on the misalignment of public benefits and private costs. Hardin (1968) also discusses this disconnect between the decisions of individual agents and aggregate outcomes. While some form of collective action is generally necessary to achieve an efficient outcome, such action can be deficient. For example, Olson (1965) argues that collective action will not be rep-

[1]While the discussion is often framed in terms of siting facilities, the idea is equally applicable to allowing particular activities at specific locations, such as changes in land use or resource extraction.

resentative of the entire population, but will instead be dominated by minor interests due to lower costs of coordination among smaller groups. Hardin (1995) similarly questions the effectiveness of collective action, suggesting that groups that are formed based on a shared identity alienate members outside of the group. Given these criticisms, a formal means of aggregate decision-making, such as a democratic vote, is necessary.

In this paper, we analyze the inability of voting decisions to address the facility siting problem. We illustrate how a siting process that relies on a majority-rule vote of the locality's population can lead to an outcome that makes the locality worse off overall. The question of the efficacy of majority-rule dates back to de Borda (1781) and de Condorcet (1785), which examine whether majority-rule decisions can accurately aggregate individual preferences. Arrow (1951) proves that majority rule fails to satisfy a set of criteria that characterizes a desired decision-making outcome, though May (1952) and Dasgupta and Maskin (2008) suggest that majority-rule is associated with properties that make it preferable to other aggregation rules. McKelvey (1979) and Schofield (1983) show that majority-rule decisions over multidimensional alternatives will generally exhibit cycles, whereby voting choices can be specified to reach nearly any decision in the choice space.[2] More formally, these results demonstrate the absence of the core (i.e. a set of outcomes that cannot be improved upon by some group of voters).

A large literature in economics examines the specific problem of optimally siting noxious facilities. When considering the market's ability to site such facilities, one question relates to which locality, defined by political boundaries, should host. Oates and Schwab (1988) show that efficiency is reached when communities compete for private and environmental production and make decisions using a simple-majority rule. These results, however, are driven by the assumption of homogeneous costs in any given locality, which leads to full compensation. Other studies (Mitchell and Carson, 1986; Kunreuther et al., 1987; Sullivan, 1990; O'Sullivan, 1993) provide further evidence of markets as efficient siting mechanisms, but rely

[2] Saari (1997) extends this work to a more general framework.

on two key assumptions: 1) political jurisdictions fully internalize the aggregate disamenities of the facility, and 2) a locality will never accept a facility at a price that reduces aggregate economic surplus in the jurisdiction as a whole. Ingberman (1995), examining square and quarter-circle localities, shows that neither cost internalization nor full compensation result from a simple majority approval process. In such cases, market solutions are likely to lead to an aggregate excess of facilities as well as inefficient site choices.

The problem of optimally siting noxious facilities has also been addressed in the operational research literature, originally as a subset of facility location problems, which historically focused on distance minimization in favor of proximity. Thus, it was necessary to distinguish between desirable facilities, for which closeness is attractive versus undesirable facilities, for which closeness is repelled. Furthermore, it was insightful to classify undesirable facilities as noxious when they threaten well-being and obnoxious when they diminish enjoyment (Erkut and Neuman, 1989). Nevertheless, many facilities can be characterized as semi-obnoxious as they exhibit a combination of desirable and undesirable features; consequently, being too close or too far away are undesired (Berman and Wang, 2008; Coutinho-Rodrigues et al., 2012). Comprehensive surveys of operational research studies can be found in Erkut and Neuman (1989) and Church and Drezner (2022). Focusing on individuals' perception, Fernandez et al. (2000) develop a global location choice model to minimize residents' opposition to host a proposed facility. Other studies consider the NIMBY problem in the context of a broader siting decision. Eiselt and Marianov (2014) construct a minimization problem that includes pollution, as well as transportation costs between the facility and its consumers. Similarly, Demesouka et al. (2019), develop spatial multicriteria decision support to identify potential sites to host undesirable facilities, emphasizing the tremendous influence of the NIMBY syndrome.

Some solutions have been proposed to overcome inefficient siting without a centralized decision. Perez-Castrillo and Wettstein (2002) develop a multibidding mechanism that allows individuals to simultaneously bid different values for multiple potential projects. Kunreuther and Kleindorfer (1986) and Mueller (2017) discuss sealed-bid auction mechanisms in which localities compete against one another to host the facility. While the focus of these analyses is on competition among localities, extending these results to a household decision model would require full elicitation of the true willingness to pay. In the situation where households can precisely convey their willingness to pay, Minehart and Neeman (2002) combine a bidding procedure with monetary transfers that act as both incentives and compensation to generate an efficient siting outcome. More generally, Laurent-Lucchetti and Leroux (2009) point out that solutions to the siting problem are consistent with Lindahl pricing, in which consumers pay an amount equal to their marginal willingness to pay. Such an approach, though, may be difficult to implement due to consumers' incentives to under-report their valuation of a public good (Loomis, 2011).

Our study, therefore, considers a vote among residents of a locality to accept or not accept a proposed facility. Examples of such direct general include cases of siting hazardous waste treatment facilities (Castle, 1993; Harris, 1994), nuclear waste storage (Kraft, 2007; Kim and Kim, 2014), airports (The Economist, 2018), and energy plants (Stevenson, 2019; Tsolova, 2013). Also, due to the difficulty in eliciting true values and political constraints, we do not analyze scenarios in which voters can be compensated at different individual values. The previously cited examples primarily deliver compensation through a general increase in local tax revenues. While there are potentially other considerations in an individual's decision, such as social norms (Ullman-Margalit, 1977) or the decision-making process (Aitken, 2010), we focus on community compensation as the primary driver, as was demonstrated to be effective in eliciting individuals' trust and support (Sorensen et al., 1984; ter Mors et al., 2012).

In this paper, we consider a cost-minimizing firm that seeks approval of a locality to host a facility in exchange for a community compensation. We illustrate how a siting process that relies on a vote of the locality's population can lead to inefficient outcomes. The siting inefficiency is driven by the binary nature of the voting process, in which the vote of an individual with a large loss is weighted equally with that of an individual who may receive only minimal benefits. Thus the majority-rule mechanism is not aligned to properly compensate the locality as a whole. We develop a robust model that captures the geographical distribution of residents as well as the potential damages to which they may be subjected, and consequently guide decision makers on how to remedy this problem using a supermajority vote. We outline properties of the siting decision and siting location that determine when inefficient siting will prevail and offer a solution. Our analysis operates within a simple voting framework to account for operational constraints.

The model directly links siting inefficiency to the spatial distribution of the population and the rate of distance decay in the disamenity. Interestingly, we are able to find upper bounds for the level of inefficiency for limiting cases. Our analysis establishes general criteria for the spatial distribution of the population that will lead to inefficient siting decisions and provides a solution to inefficient siting using a supermajority voting rule.

Following our model of voters and the firm, we demonstrate the potential magnitude of inefficiency using population data from counties in New York and Pennsylvania to estimate model parameters. Our results indicate potentially large inefficiency costs, but suggest simple solutions via a modification to the voting mechanism.

The remainder of the paper is organized as follows. In Section 2 we develop a model of facility siting that captures the geographical distribution of residents across the locality and the potential damage that they will incur, and derive equilibrium voting outcomes. Section 3 details our main results related to the inefficiency of majority-rule decisions, followed by a discussion of a potential supermajority solution in Section 4. Section 5 presents functional equations for the model to examine specific mechanisms behind the siting problem. We then use data from 118 counties to demonstrate the power of the suggested model to facilitate collective siting decisions in Section 6. Finally, Section 7 concludes with a discussion of our results.

2 Model

A profit-maximizing firm desires to site a noxious facility within a locality. In order to secure permission, the firm offers a payment to the locality and subsequently households vote on whether or not to accept and host the facility at a specific location. The process does not include bargaining on the part of the locality, a reasonable assumption when there is potential competition with other localities. We also assume that the firm's location decision is not impacted by other amenities within the locality.

There are n voters distributed throughout the locality, whose decision whether to approve a proposed facility is determined by comparing their disamenity cost, which depends on proximity to the facility, and the benefit that they receive from the firm's payment. Define the cost function $c(d)$ as the disamenity cost experienced by a resident located at distance d from the proposed facility location. Benefits from siting are in the form of a host fee P, paid by the firm. The aggregate community compensation is paid to the locality's government and its benefits are equally shared among residents by providing them common benefits, such as investments in school systems, habitat management, and local festivals, providing free garbage collection services, and local employment (Simon, 1990; Cass et al., 2010). Hence, each individual derives a benefit valued at $p = \frac{P}{n}$. An individual at distance d votes in favor of hosting the facility only if $p \geq c(d)$.[3] Disamenity costs are nondecreasing in proximity to the facility. We also assume that $c(d)$ is weakly convex: $c' \leq 0$, $c'' \geq 0$, suggesting that the costs increase at an increasing rate as one becomes closer to the facility.[4]

The firm, being a profit maximizer, seeks to minimize the required payment P. Since the host fee compensates for distance-related costs, the minimum host fee depends on the facility location and the distribution of the individual voters from the proposed location.

Employing a simple majority voting rule, approval by greater than 50% of individuals

[3]This assumes that an indifferent individual will accept the facility.

[4]Such a specification serves as the basis for much of the previously mentioned empirical literature that estimates costs through the impact on housing values. In addition, Rossi-Hansberg et al. (2010) use non-parametric techniques and find evidence that amenities are capitalized into housing prices in a convex manner.

is required. As the disamenity cost decreases with distance, a facility may be established only if the median voter agrees to the proposed compensation, where the median voter is the individual located at distance d_m from the proposed facility. A host fee of P^* such that each individual gets benefit $\frac{P^*}{n} = c(d_m)$ is the minimum fee that will lead to voter approval. Since the cost function is nondecreasing in proximity, the firm seeks to minimize $c(d_m)$ by choosing the location that maximizes d_m.

3 Equilibrium Inefficiency

We first study the mechanism by which simple majority voting tends to lead to inefficiencies in siting decisions. An inefficiency in this context refers to a decision that generates aggregate costs that are greater than the host fee. Thus we focus on the potential for siting decisions that create a net loss for the locality.

The equilibrium host fee ensures that those individuals who are at least median distance from the facility will gain positive net benefits from siting and consequently vote in favor of hosting the facility. Individuals that are located closer than median distance will gain negative net benefits, as they receive the same uniform host fee but suffer costs $c(d) > p$ and will therefore vote against. To avoid an aggregate loss to the locality, compensation must cover aggregate costs, or $p \geq \bar{c}$, where $\bar{c}$ denotes mean disamenity cost. However, as the firm seeks to minimize its host fee and offers $p = c(d_m)$, we demonstrate in the following subsection that under plausible conditions a simple majority decision will lead to an inefficient siting equilibrium, such that $c(d_m) < \bar{c}$.

3.1 Conditions for Inefficient Siting

Our analysis is general as it accounts for a variety of locality shapes and spatial distributions of their population. We assume a monotonically decreasing and weakly convex disamenity cost function. We claim that inefficient siting is prevalent as suggested in the following proposition:

Proposition 1. *If the locality's boundaries encompass a convex set of points and the population is uniformly distributed within its space, a simple majority-rule vote will result in an inefficient siting decision.*

Proof. See Appendix A.1. □

Proposition 1 establishes that inefficient siting will occur due to the shape of the locality and the spatial distribution of the population. As the firm seeks to minimize host fees by siting the facility in a location that minimizes exposure of the median voter, the distribution of distance becomes negatively skewed so that mean costs are greater than median costs. This result generalizes that of Ingberman (1995), which demonstrated inefficient siting for square and quarter-circle localities with a uniformly distributed population.

Since a spatially uniform population distribution may not always be observed, we relax this restriction and establish the following:

Proposition 2. *If the locality's boundaries encompass a convex set of points and the density function of the population's distance from the facility is concave, a simple majority-rule vote will result in an inefficient siting decision.*

Proof. See Appendix A.2. □

The primary component of the siting process that leads to inefficient outcomes is the distribution of the distance of voters from the facility. A negatively-skewed distance distribution and weakly convex cost function generate inefficient siting under simple majority rule decisions. The preceding propositions capture prevalent cases of spatial distributions that will create such a negatively-skewed distance distribution which, nevertheless, may be featured by other spatial distributions and shapes.

The framework developed in Appendix A.1 can be utilized to examine the mechanism that drives inefficient siting. Consider an established facility, located such that a relatively high concentration of “yes” voters reside just beyond the median distance. Compared to a more even distribution of residents beyond the median, this will drive up mean disamenity costs. Similarly, a high concentration of “no” voters in close proximity to the facility will also increase mean costs. For these examples, as long as changes to spatial concentrations take place exclusively on one side of the median distance line, they will have no impact on the necessary host fee, therefore exacerbating the inefficiency. Cases in which inefficient siting will *not* take place are also evident in our framework. For a given median distance, a high concentration of “yes” voters at extremely far distances or a high concentration of “no” voters just within median distance will work to alleviate siting inefficiency by reducing mean disamenity costs.

In general, our results suggest that the potential for inefficient siting decisions is not limited to exceptional circumstances. Rather, there are frequent combinations of geographic shapes and spatial distributions for which inefficient siting will occur. This is also demonstrated in Section 6 using observed population data, and a further discussion of these outcomes is provided in Appendix A.3 using the framework developed for Proposition 1.

4 A Supermajority Solution to Efficient Siting

In order to correct the emergence of excess costs, we propose an efficient supermajority M, which is equal to some percent of the population that would agree to site a facility in a particular location such that the aggregate host fee is equal to the aggregate disamenity costs. The efficient supermajority M should generate a pivotal voter who experiences mean costs. If d_* as the distance at which mean costs are incurred so that $c(d_*) = \bar{c}$, then the required supermajority is $M = 1 - F(d_*)$, where $F(d)$ is the cumulative distribution function of population distance d to the proposed facility location.

The supermajority M may be useful as a measure of the inefficiency that could result from a simple majority decision or as a measure of the inefficiency in a simple majority vote that has already taken place. More importantly, however, M provides a potential solution. Such a change to the voting rule would ensure an outcome that compensates the locality as a whole appropriately. Any change in the voting process that takes place before the firm chooses the facility's potential location, however, will alter the firm's decision. As the voter at the $(1-M)^{th}$ distance percentile which replaces the median voter as the pivotal decision-maker depends on the proposed facility location, the firm will take this into consideration when deciding on the optimal location based on the necessary host fee. Hence, simultaneous strategic behavior on the part of the firm and locality results in an efficient equilibrium:

Proposition 3. *If the locality operates a voting process for siting a noxious facility that relies on the efficient supermajority, rather than a simple majority, then i) the facility will be located at the point that minimizes disamenity costs to the locality and ii) siting of the facility will be accepted by the vote only if the aggregate host fee is greater than aggregate disamenity costs.*

Proof. The locality's objective, to ensure that inefficient siting does not take place, is obtained by enacting a supermajority M such that the $(1-M)^{th}$ distance percentile voter endures mean costs. Since the distance distribution is measured from a single point, the firm, which seeks to minimize the required host fee, will choose the point that maximizes the distance of the voter who suffers mean cost and subsequently the locality will determine M^* based on that distribution. The pivotal voter at the $(1-M^*)^{th}$ distance percentile determines the necessary host fee for the facility to be sited. Therefore, distance of the voter who suffers mean costs is maximized, which leads to minimum aggregate disamenity costs. □

Anticipating enactment of an efficient supermajority will lead the firm to choose a location and offer a host fee that will make the locality no worse off. The simple majority $M = 0.5$ creates an incentive for a firm to locate at a point where the pivotal voter is further away than the voter who suffers mean costs. The supermajority, however, not only ensures that the host fee is sufficient to compensate for aggregate costs, but also aligns the incentives of the firm and the locality so that the host fee and costs are simultaneously minimized.

5 Functional Model

We develop a generic parametric model that can capture many potential forms of the population distribution throughout the locality regardless of its shape. Since the impact on residents is based on their distance from the facility, and any bivariate distribution of coordinates in two-dimensional space can be transformed to a univariate distribution of the Euclidean distance between each point and the proposed location of the facility, we focus on this measure of distance that allows us to retain generality in terms of the shape of the locality and the explicit distribution of its population across space.

To model the distribution of a voter's distance from a facility we use the Beta distribution, denoted as Beta(α, β). Since this distribution has support [0,1], we normalize distance so that the maximum distance is equal to 1. The Beta distribution is very flexible, as parameter combinations can generate probability density functions that are increasing, decreasing, or non-monotonic, along with different degrees of convexity. The density function of distance d is expressed as

$$f(d; \alpha, \beta) = \frac{1}{B(1; \alpha, \beta)} d^{\alpha-1}(1-d)^{\beta-1};\ 0 \leq d \leq 1;\ \alpha > 0, \beta > 0 \tag{1}$$

and the cumulative distribution function is

$$F(d; \alpha, \beta) = \frac{B(d; \alpha, \beta)}{B(1; \alpha, \beta)}, \tag{2}$$

where $B(x; \alpha, \beta)$ is the incomplete Beta function.

Equilibrium siting in a square locality with a uniform spatial distribution, as in Ingberman (1995), generates a density function of distance from the facility that is negatively skewed and can be approximated using a Beta distribution with $\alpha \approx 2.67$ and $\beta \approx 2.29$. Different shapes and spatial distributions will lead to distance distributions characterized by concentrations of households at different distances that can be approximated with a Beta distribution. Using Beta(3,2) as a reference, an increase in the first parameter models a population that is concentrated further from the facility, whereas an increase in the second parameter models a population that is more highly concentrated around a particular distance. Overall, the Beta distribution offers a robust way to capture the scalar variable of interest.

In addition to the population distribution, we define the disamenity cost function as[5]

$$c(d) = d^{\gamma}(1-d)^{\delta};\ \gamma \leq 0, \delta \geq 1. \tag{3}$$

The special case in which $\gamma = 0$ and $\delta = 1$ results in a linear cost function in which marginal costs are constant. The cost function becomes convex as γ decreases below 0 and as δ increases above 1.[6] When γ decreases, the convexity manifests as a very sharp decrease in costs at close proximity, implying a disamenity that causes considerable damages concentrated near the facility. As δ increases, the cost function flattens out at farther distances. This reflects the case in which costs approach 0 within the locality and, beyond this point, the site causes very little damage. In general, the structure of Equation (3) is quite flexible and capable of capturing a wide variety of possible cost patterns.

Using Equations (1) and (3), mean disamenity costs $\bar{c}$ are calculated as[7]

$$\bar{c} = \int_0^1 c(x) f(x;\alpha,\beta)\mathrm{d}x = \frac{B(1;\alpha+\gamma,\beta+\delta)}{B(1;\alpha,\beta)}. \tag{4}$$

Median disamenity costs, c_m, are found directly using median distance from the proposed facility. Since the cost function is a monotonic transformation of distance, the individual that is median distance from the facility will suffer median costs and thus be the pivotal

[5]For simplicity and without loss of generality, we omit any parameter that might scale the cost function.

[6]Section A of the online supplementary materials provides plots of various parameterizations of the cost function.

[7]See Section B of the online supplementary materials for details.

voter. Median distance, d_m, in the Beta distribution is implicitly defined as

$$0.5 = \frac{B(d_m; \alpha, \beta)}{B(1; \alpha, \beta)}, \tag{5}$$

Median costs are then calculated as

$$c_m = c(d_m) = d_m^{\gamma}(1 - d_m)^{\delta} \tag{6}$$

As the firm seeks to minimize the host fee it will select a location where the median cost is the lowest. The distribution of the population from such a location is negatively skewed as was previously discussed, hence, in such cases $\alpha \geq \beta$. Mean distance in the Beta distribution is defined as $\frac{\alpha}{\alpha+\beta}$, while median distance can be approximated by $\frac{\alpha-1/3}{\alpha+\beta-2/3}$. This implies that the mean distance is smaller than the median distance, leading to inefficiencies.

5.1 *The Efficient Supermajority*

The required voting supermajority that will ensure a host fee that fully compensates for aggregate disamenity costs is dependent on the parameters of the model. While a closed-form expression that defines the supermajority as a function of model parameters does not generally exist, there are special cases that illustrate more general conclusions. We first present the case of linear costs to examine the role of population concentration. We then present specific distance distributions to examine the role of convex costs and the interaction of the the cost function and population distribution.

5.1.1 Linear Disamenity Costs

Linear disamenity costs are defined by $\gamma = 0$ and $\delta = 1$ so that the cost function reduces to $c(d) = 1 - d$. In this case, the voter who is located at mean distance from the proposed location, $\bar{d} = \alpha/(\alpha + \beta)$, suffers mean costs[8]. The parameters α and β allow for many

[8]See section C of the online supplementary materials.

potential scenarios of the distance distribution.

We first focus on distributions that are concentrated further and further away from the proposed site, which are portrayed with $\alpha \in [2, \infty]$, $\beta = 1$. The parameter subset $[\alpha, \beta] = [2, 1]$ denotes a positively-sloped straight line density function for distance, $f(d) = 2d$. Mean distance is $\bar{d}= 2/3$ so that the efficient supermajority is 5/9. Therefore, if the locality requires a 5/9 supermajority to allow the facility to operate, the host fee that satisfies the pivotal voter will be equal to the total costs generated by the facility. As the population becomes more concentrated away from the proposed facility (i.e., as α increases), a larger density of voters are located in places with relatively lower costs, which drives down the firm's required host fee. The supermajority is based on the value of α, and is contained within the following bounds[9]:

$$M = \left[\frac{5}{9}, \frac{e-1}{e}\right] \text{ for } \alpha \in [2, \infty]. \tag{7}$$

The required supermajority increases with α but is bounded within a relatively small range of $0.555 - 0.632$.

Next, we investigate populations that are centralized around particular areas that are not the farthest from a polluting facility. For example, populations often concentrate around central business districts or community centers within a locality. Using the parameter combinations $\alpha \in (3, \infty)$, $\beta = 3$, we derive the bounds for an efficient supermajority[10]:

$$M = \left(\frac{1}{2}, \frac{e^3 - 8.5}{e^3}\right) \text{ for } \alpha \in (3, \infty). \tag{8}$$

The upper limit of 0.577 is even smaller than the previous case where the population is concentrated at the farthest possible distances. The case of a symmetric distribution $\alpha = 3$, $\beta = 3$ that leads to $M = 0.5$ can be ruled out based on convexity of the locality.

An alternative perspective of the changes in the required host fee can be offered through the population distribution. As the population concentrates at an area relatively closer to

[9] See section D of the online supplementary materials for full derivation.
[10] See section D of the online supplementary materials for full derivation.

the facility, the median distance decreases and a higher host fee is required to secure a majority vote. It should be noted that the mean decreases as well, though at a slower rate than that of the median (and the two converge as a symmetric distribution is approached), so that median costs increase more rapidly. This implies an increase in the host fee relative to mean costs, mitigating the magnitude of the inefficiency in a simple majority decision.

5.1.2 Nonlinear Disamenity Costs

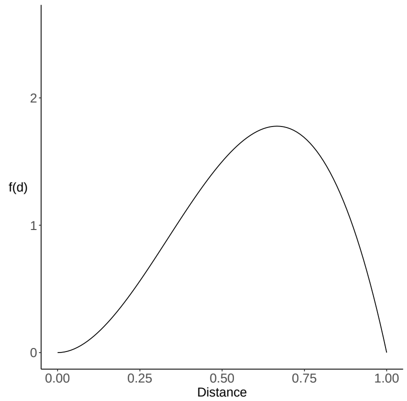
We have so far established that the population distribution leads to a siting outcome in which mean distance from the proposed facility is less than median distance. A decreasing cost function implies that mean disamenity costs are greater than median disamenity costs, generating a net loss. The analysis in the previous section demonstrated the effect of different population distributions on the efficient supermajority when the disamenity cost function is linear. With a nonlinear cost function, however, the interaction between the population distribution and the cost function becomes increasingly complex. For some cost functions, a population concentration further from the potential facility can mitigate the problem (i.e., reduce the effecient supermajority).

In order to explore the effect of population distribution within the locality under convex disamenity costs we use two specific parameterizations of the distance distribution: Beta(3,2) and Beta(6,3).[11] Both of these distributions lead to an inefficient siting outcome in the case of linear disamenity costs. Tables 1 and 2 show the efficient supermajority for the two density functions of the population distance from the facility location for various disamenity cost functions.[12] The density functions are plotted alongside the tables.

The top left corner of Tables 1 and 2 replicates the case of linear costs. As δ increases or γ decreases, the necessary supermajority quickly increases, requiring a large portion of the population to support siting the facility in order to obtain efficiency. Convexity in the

[11] In the following section, we show that these parameterizations represent plausible values for observed populations.

[12] We use a bisection algorithm to numerically solve for the efficient supermajority.



		δ				
		1	2	4	6	8
γ	0	0.525	0.604	0.713	0.781	0.828
	-0.2	0.561	0.63	0.731	0.795	0.839
	-0.4	0.595	0.656	0.749	0.81	0.851
	-0.6	0.627	0.682	0.768	0.824	0.862
	-0.8	0.658	0.707	0.786	0.838	0.873
	-1	0.688	0.732	0.805	0.852	0.885

The table on the right presents the efficient supermajority for various parameterizations of the the cost function when distance to the facility follows a Beta(3,2) distribution. This distance distribution is shown in the left panel. The cost function becomes more convex when γ decreases and/or δ increases.

Table 1: Efficient Supermajority: $\alpha = 3, \beta = 2$

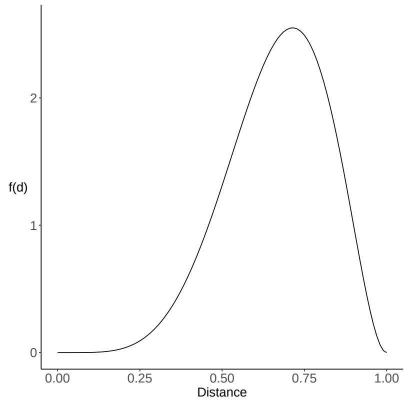
cost function epitomizes the general siting problem. Costs are disproportionately incurred by those relatively close to the facility, generating a majority that is willing to host for a low host fee.

A convex function can reflect scenarios in which costs reach 0 within the locality. Households who are far enough away from the facility do not incur any disamenity cost. If 50% of the population are beyond this distance, the median cost becomes zero. Thus, any proposed facility vote can be successfully passed via a simple majority as long the distance-related disamenity is localized enough. A supermajority is necessary to capture support from those households that incur non-zero costs, as well as additional households to generate sufficient community compensation.

5.2 Implementation

Our model provides a useful tool for policy-makers to determine the optimal supermajority. Using available census data, the locality can estimate the parameters α and β of its population distribution based on observed distances[13]. Next, given the specifics of the proposed facility, its potential disamenity is expressed through parameters γ and δ. It is only

[13]See section E of the online supplementary materials for details of estimation.



		δ				
		1	2	4	6	8
γ	0	0.532	0.608	0.719	0.795	0.846
	-0.2	0.554	0.624	0.731	0.803	0.853
	-0.4	0.574	0.639	0.742	0.812	0.860
	-0.6	0.594	0.655	0.754	0.821	0.867
	-0.8	0.613	0.670	0.765	0.830	0.874
	-1	0.631	0.685	0.776	0.838	0.880

The table on the right presents the efficient supermajority for various parameterizations of the the cost function when distance to the facility follows a Beta(6,3) distribution. This distance distribution is shown in the left panel. The cost function becomes more convex when γ decreases and/or δ increases.

Table 2: Efficient Supermajority: $\alpha = 6, \beta = 3$

required that the locality determines the curvature of the disamenity cost function, since any scalar transformation of costs will have no effect. Therefore, the locality must determine how quickly costs decrease with distance to the facility based on the specific impacts of the facility (noise, air pollution, appearance, etc...).

Given the set of parameters (α, β, γ, δ), the locality can apply the following three steps:

1. Evaluate the average cost, $\bar{c}$, using Equation (4).
2. Identify the location (distance) of the pivotal voter, $d*$, using Equation (3).
3. Determine the required supermajority, M, using Equation (2). Alternatively, M can be approximated as $M = (1 - (d*)^{\alpha})^{\beta}$ (Kumaraswamy, 1980).

The analysis conducted in this work relates to siting a single facility, as is frequently practiced and studied. Nevertheless, sometimes, there are scenarios that due to various constraints the firm may seek to site multiple facilities, while still attempting to minimize the fee. The robust model that was suggested above can be also be employed in such cases and foster efficiency. For example, consider two facilities, one with cost parameters γ and δ, and the other with γ' and δ'. Similarly, two potential locations to site these facilities, with population distribution parameters α and β for one, and α' and β' for the other. Equation (4) may be applied twice, once with parameters α, β, γ, and δ to determine the average cost imposed by the first facility, $\bar{c}_1$, and then with parameters α', β', γ', and δ' to determine the average coat imposed by the second facility, $\bar{c}_2$. Consequently, the total average cost imposed by the two facilities is the sum, $\bar{c}_1 + \bar{c}_2$. Next, through a two-dimensional search over the grid the curve that contains the residents who experience cost equal to the mean can be identified and consequently the voters who reside beyond establish the required supermajority.

This approach can also be extended to scenarios where additional costs are imposed by other elements such as the transportation routes to the facility. In such cases, the additional costs can be captured by a separate cost function. Another extension involves a case where voters are compensated via a spatially-dependent public good, where the benefit to siting also depends on a voter's location. This scenario can be analyzed in an identical manner to the case of multiple facilities, treating the public good as a facility with a negative cost function.

6 Empirical Analysis

In order to verify the applicability of the proposed model, we analyze data from 118 counties across New York and Pennsylvania. Summary statistics for counties and census blocks, respectively, are presented in Table 3. For each county, we create a hypothetical location for a facility. This location is chosen as the point within the county that maximizes the median distance of households from the facility, simulating the firm's optimal decision when majority vote is practiced. Using publicly available U.S. Census data, a household's location within the county is approximated by the geographic center of its census block. This approximation is highly accurate since blocks are geographically small and contain small populations relative to the whole county. We assume that each household represents a single vote.

To identify the firm's optimal location, we search over a constructed grid of locations in each county. The grid in each county consists of geographic points evenly spaced throughout the county at distances of approximately 100 meters in both east-west and north-south

Counties	mean	std. dev.	10^{th} perc.	median	90^{th} perc.
# of blocks	4,302	3,300	1,623	3,369	8,719
population	157,984	228,817	30,531	80,993	349,955
size (sq. km)	1,928	993	917	1,722	3,022
Blocks					
population	36.725	74.857	0.000	15.000	92.000
size (sq. km)	0.448	2.100	0.004	0.029	1.119

Table 3: Summary statistics

directions.[14] For each point, we calculate distance to each block centroid and choose the point with the largest median population-weighted distance. Given a location for the hypothetical facility, we use maximum likelihood estimation separately for each county to estimate α and β parameters.

Of the 118 fitted distributions, only 2 are positively skewed. As discussed earlier, however, such a result is expected in certain circumstances. Focusing on the 116 cases (98.3%) which are prone to inefficiencies due to the negative skewness of their population distance distributions, we assess their parameters and then the robustness of the supermajority rule. Table B.1 in Appendix B summarizes the 116 sets of estimated parameters and the skewness of each population distribution. The inequality $\alpha > \beta$, which is necessary for skewness, is statistically significant for all 116 counties.

Next, using the parameters of the population spatial distribution we determine the efficient supermajorities necessary to ensure a solution in which the host fee is equal to total costs imposed on the county in the case of linear disamenity costs. The required supermajorities range from 50.15% to 58.93% across the 116 counties, with a median optimal supermajority of 52.45% and 10^{th} and 90^{th} percentiles of 51.27% and 54.45%, respectively. This remarkably narrow range suggests the possibility that a uniform supermajority, which

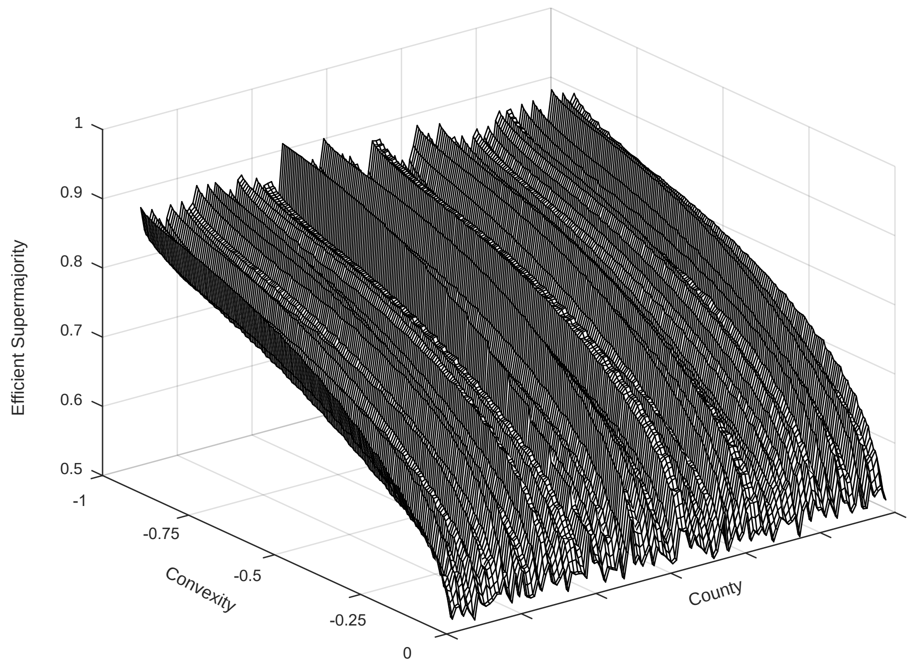
[14] The distance between points in the generated grid varies across counties since the grid is defined by a fixed number of points (250,000) within the county's borders. The 10^{th} and 90^{th} percentiles for distance between grid points are 37.38 and 139.61 meters, respectively, with a maximum of 364.77 meters in the largest county.

is perhaps more politically appealing, could be applied to all localities with only modest aggregate deviations. Note that the 90^{th} percentile proposed increase to M = 54.45% is the equivalent of an additional 11,205 voters in that particular county. Depending on the type of facility, this could imply considerable excess costs on the locality. We use bootstrapping methods (with 10,000 random draws) to calculate confidence intervals for efficient supermajorities in each county following Krinsky and Robb (1986). All 95% confidence intervals are within a range of less than 0.0063.

The degree of convexity in the cost function affects mean costs and thus the efficient supermajority. For each combination of county population distribution parameters and possible parameters of convex cost function (as previously discussed), we calculate mean costs in order to find the required supermajority that will ensure efficiency, as illustrated in Figure 1. The degree of convexity here refers only to variation in the γ parameter. For disamenities that are highly convex in distance, it is clear that the necessary supermajority is a substantial portion of the population. This suggests that considerably large costs could arise in majority-rule decisions.

It is also evident that convex costs and population distributions have a complex relationship in generating siting inefficiencies, as there is not a consistent ranking (in terms of required supermajority) of counties across different cost functions. While the efficient supermajority increases with independent increases in convexity and skewed population distance distributions, the impact of convexity is not independent of the distance distribution, and vice versa.

Finally, we use population distribution parameters to calculate the relative under-compensation for each county if a simple majority would have been used, $\bar{c}/c_m$, illustrated in Figure 2. While some counties in the study sample may experience only minor under-compensation, particularly with linear costs, other counties see under-compensation as high as 1.26 with linear costs (90^{th} percentile equal to 1.10) and over 2 with highly convex costs. This implies the potential for considerable aggregate losses in majority-rule settings.



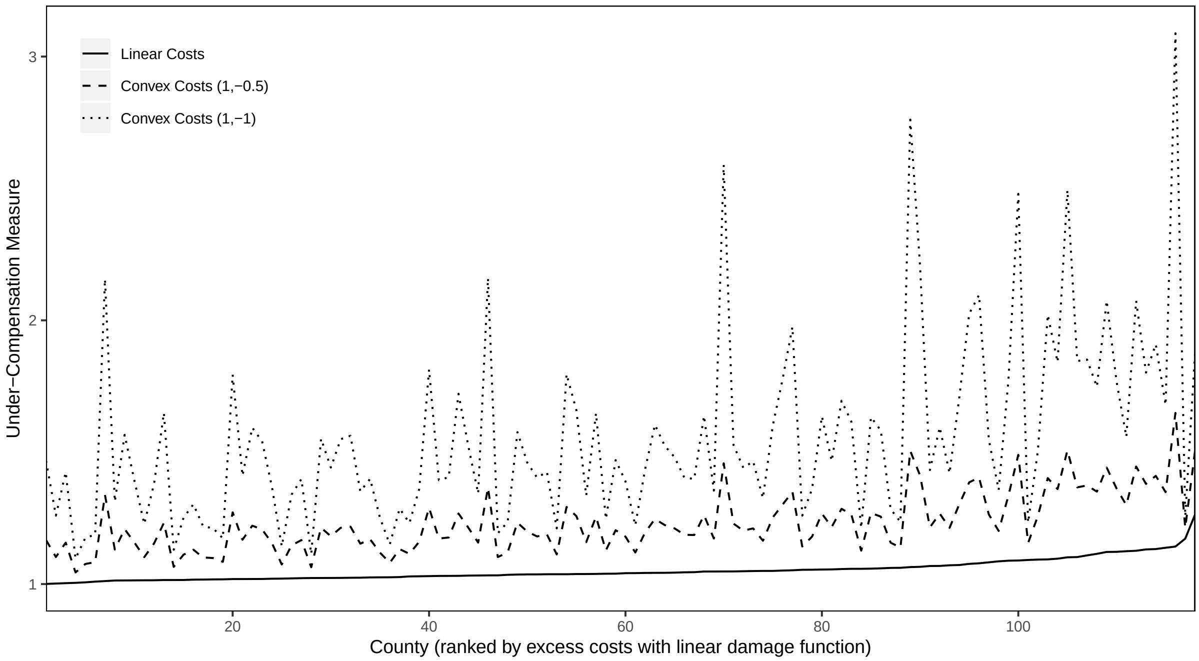
The efficient supermajority is plotted for each county under different levels of convexity in the disamentiy cost function. Counties are arranged in no particular order along the axis. To generate convexity in the cost function, γ decreases from 0 to -1.

Figure 1: Efficient supermajorities with convex costs.

7 Conclusion

This paper has outlined a comprehensive framework for investigating the inefficiency of majority-rule decision related to siting noxious facilities and demonstrated its prevalence. While there are certainly other factors that help determine the location of a noxious facility, the inefficiency driven by skewed costs among voters spread across the spatial landscape could have a considerable effect on siting outcomes.

Through a robust model that can accurately capture the population distribution within a locality as well as the costs they incur from a proposed facility, we have shown that a supermajority rule is required to overcome the inherent inefficiency in simple majority rule



Excess costs are reported using the measure of under-compensation. Counties are arranged in order of increasing excess costs with a linear disamenity cost function.

Figure 2: Excess costs with majority rule siting.

decisions. Although, the exact value of this supermajority varies with the spatial distribution of the population and with the relationship between costs and proximity to the facility. In general, the necessary supermajority increases as populations concentrate farther away from the facility, as well as when the disamenity cost function becomes (more) convex in distance. Both of these effects relate directly to the fundamental driver of the inefficiency: an individual decision based entirely on whether the outcome is positive or negative, combined with an evaluation of efficiency that depends on the magnitude of the outcome.

As discussed in the paper, the interaction of two factors, population distribution across the locality and the disamenity imposed by the facility, emerges to a complex aggregate cost function. However, our model incorporates these factors into a simple function that is easy to work with and consequently enables us to perform a general analysis of the siting problem and obtain important insight. Moreover, our model also provides simple guidance for policy-makers to ensure efficient siting decisions. Using available census data, the locality can capture the distance distribution of its residents. Next, given the specifics of the proposed facility, its cost parameters, γ and δ, can be incorporated to complete the aggregate cost function. As in Tables 1 and 2, the efficient supermajority is easily identified based on these cost function parameters.

References

Aitken, M. (2010). Wind power and community benefits: Challenges and opportunities. *Energy Policy*, 38(10):6066–6075.

Arrow, K. J. (1951). *Social Choice and Individual Values*. London: Chapman and Hall.

Berman, O. and Wang, Q. (2008). Locating a semi-obnoxious facility with expropriation. *Computers and Operations Research*, 35:392–403.

Cass, N., Walker, G., and Devine-Wright, P. (2010). Good neighbours, public relations and bribes: The politics and perceptions of community benefit provision in renewable energy development in the uk. *Journal of Environmental Policy and Planning*, 12(3):255–275.

Castle, G. (1993). Hazardous waste facility siting in manitoba. case study of a success. *Air and Waste*, 43(7):963–969.

Church, R. L. and Drezner, Z. (2022). Review of obnoxious facilities location problems. *Computers and Operations Research*, 138.

Coutinho-Rodrigues, J., Tralhao, L., and Alcada-Almeida, L. (2012). A bi-objective modeling approach applied to an urban semi-desirable facility location problem. *European Journal of Operational Research*, 223:203–213.

Dasgupta, P. and Maskin, E. (2008). On the robustness of majority rule. *Journal of the European Economic Association*, 6:949–973.

de Borda, J.-C. (1781). Mémoire sur les élections au scrutin. *Mémoires de l'Académie Royale des Sciences année*, pages 657–665.

de Condorcet, M. (1785). *Essai sur l'application de l'analyse à la probabilité des decisions rendues à la pluralité des voix*. Paris: L'imprimerie Royale.

Demesouka, O. E., Anagnostopoulos, K. P., and Siskos, E. (2019). Spatial multicriteria decision support for robust land-use suitability: The case of landfill site selection in Northern Greece. *European Journal of Operational Research*, 272:574–586.

Eiselt, H. and Marianov, V. (2014). A bi-objective model for the location of landfills for municipal solid waste. *European Journal of Operational Research*, 235:187–194.

Erkut, E. and Neuman, S. (1989). Analytical models for locating undesirable facilities. *European Journal of Operational Research*, 40:275–291.

Farber, S. (1998). Undesirable facilities and property values: A summary of empirical studies. *Ecological Economics*, 24(1):1–14.

Fernandez, J., Fernandez, P., and Pelegrin, B. (2000). A continuous location model for siting a non-noxious undesirable facility within a geographical region. *European Journal of Operational Research*, 121:259–274.

Grislain-Letremy, C. and Katossky, A. (2014). The impact of hazardous industrial facilities on housing prices: A comparison of parametric and semiparametric hedonic price models. *Regional Science and Urban Economics*, 49:93–107.

Hardin, G. (1968). The tragedy of the commons. *Science*, 162:1243–1248.

Hardin, R. (1995). *One for All: The Logic of Group Conflict*. Princeton University Press.

Harris, W. (1994). Siting a hazardous waste facility: A success story in retrospect.

Ingberman, D. E. (1995). Siting noxious facilities: Are markets efficient? *Journal of Environmental Economics and Management*, 29(3):S20–S33.

Kaya, I. A. and Erol, N. K. (2016). Conflicts over locally unwanted land uses (LULUs): Reasons and solutions for case studies in Izmir (Turkey). *Land Use Policy*, 58:83–94.

Kim, T.-H. and Kim, H.-K. (2014). The spatial politics of siting a radioactive waste facility in Korea: A mixed methods approach. *Applied Geography*, 47:1–9.

Kraft, M. E. (2007). *Democratic Dialogue and Acceptable Risks: The Politics of High-Level Nuclear Waste Disposal in the United States*, chapter 3. Georgetown University Press.

Krinsky, I. and Robb, A. L. (1986). On approximating the statistical properties of elasticities. *The Review of Economics and Statistics*, 68(4):715–719.

Kumaraswamy, P. (1980). Generalized probability density-function for double-bounded randomprocesses. *Journal of Hydrology*, 46:79–88.

Kunreuther, H., Kleindorfer, P., Knez, P. J., and Yaksick, R. (1987). A compensation mechanism for siting noxious facilities: Theory and experimental design. *Journal of Environmental Economics and Management*, 14:371–383.

Kunreuther, H. and Kleindorfer, P. R. (1986). A sealed-bid auction mechanism for siting noxious facilities. *American Economic Review Papers and Proceedings*, 76(2):295–299.

Laurent-Lucchetti, J. and Leroux, J. (2009). Axiomatic foundation for lindahl pricing in the NIMBY context. *Munich Personal RePEc Archive Working Paper.*

Loomis, J. (2011). What's to know about hypothetical bias in stated preference valuation studies? *Journal of Economic Surveys*, 25(2):363–370.

May, K. O. (1952). A set of independent necessary and sufficient conditions for simple majority decision. *Econometrica*, 20:680–684.

McCluskey, J. J. and Rausser, G. C. (2003). Hazardous waste sites and housing appreciation rates. *Journal of Environmental Economics and Management*, 45:166–176.

McKelvey, R. D. (1979). General conditions for global intransitivities in formal voting models. *Econometrica*, 47:1085–1112.

Minehart, D. and Neeman, Z. (2002). Effective siting of waste treatment facilities. *Journal of Environmental Economics and Management*, 43(2):303–324.

Mitchell, R. C. and Carson, R. T. (1986). Property rights, protest, and the siting of hazardous waste facilities. *The American Economic Review*, 76(2):285–290.

Mueller, D. (2017). Grid extension in German backyards: A game-theory rationale. *Journal of Environmental Planning and Management*, 60(3):437–461.

Oates, W. E. and Schwab, R. M. (1988). Economic competition among jurisdictions: Efficiency enhancing or distortion inducing? *Journal of Public Economics*, 35:333–354.

O'Hare, M., Bacow, L., and Sanderson, D. (1983). *Facility Siting and Public Opposition*. Van Nostrand Reinhold.

Olson, M. (1965). *The Logic of Collective Action: Public Goods and the Theory of Groups*. Harvard University Press.

O'Sullivan, A. (1993). Voluntary auctions for noxious facilities: Incentives to participate and the efficiency of siting decisions. *Journal of Environmental Economics and Management*, 25:s12 – s26.

Pelekasi, T., Menegaki, M., and Damigos, D. (2012). Externalities, NIMBY syndrome and marble quarrying activity. *Journal of Environmental Planning and Management*, 5(9):1192–1205.

Perez-Castrillo, D. and Wettstein, D. (2002). Choosing wisely: A multibidding approach. *The American Economic Review*, 92(5):1577–1587.

Rossi-Hansberg, E., Sarte, P.-D., and III, R. O. (2010). Housing externalities. *Journal of Political Economy*, 118(3):485–535.

Saari, D. G. (1997). The generic existence of a core for q-rules. *Economic Theory*, 9:219–260.

Samuelson, P. A. (1954). The pure theory of public expenditures. *The Review of Economics and Statistics*, 36:387–389.

Samuelson, P. A. (1955). The diagrammatic exposition of a theory of public expenditure. *The Review of Economics and Statistics*, 37:350–356.

Schively, C. (2007). Understanding the NIMBY and LULU phenomena: Reassessing our knowledge base and informing future research. *Journal of Planning Literature*, 21(3):255–266.

Schofield, N. (1983). Generic instability of majority rule. *Review of Economic Studies*, 50:695–705.

Simon, R. (1990). Yes, in my backyard. *Forbes*, 146(5):72.

Sorensen, J. H., Soderstrom, J., and Carnes, S. A. (1984). Sweet for the sour: Incentives in environmental mediation. *Environmental Management*, 8:287–294.

Stevenson, M. (2019). Gas-fired power plant wins voter approval in mexico. *Yahoo Finance*.

Sullivan, A. M. (1990). Victim compensation revisited: Efficiency versus equity in the siting of noxious facilities. *Journal of Public Economics*, 41(2):211 – 225.

ter Mors, E., Terwel, B. W., and Daamen, D. D. (2012). The potential of host community compensation in facility siting. *International Journal of Greenhouse Gas Control*, 11s:S130–S138.

The Economist (2018). Letting passengers pilot the plane. *The Economist*, 429:47–48.

Tsolova, T. (2013). Bulgarian vote for nuclear plant challenges government. *Reuters*.

Ullman-Margalit, E. (1977). *The Emergence of Norms*. Oxford University Press.

Appendix A Propositions 1 and 2

A.1 Proof of Proposition 1

First we claim that the facility is located on a border, by showing that moving away from the border is not optimal for the firm. Consider a facility located on the border and a circle with radius d_m around it. The length of d_m is determined such that the intersection of the circle and the locality includes 50% of the area of the locality. The median voter is located along the perimeter of this circle. Given a convex-shaped locality, moving the facility away from the border location generates an identical circle with radius d_m around its new location, which will encompass greater than 50% of the population. This implies that the median voter would be located closer than d_m, which would increase the required host fee. Therefore, the firm's optimal decision is to locate on the border.

The median distance arc with radius d_m away from the facility divides the locality such that half of the population is within distance d_m from the facility and the other half is beyond. Denote the set of all points beyond the median arc as $\mathbb{B}$ and the set of all points within the median arc as $\mathbb{A}$. Let $f(x, y)$ denote the bivariate distribution of geographic coordinates x and y of household locations. Then define the function $\alpha(z)$ that gives the density function of population at distance z from the median arc within $\mathbb{A}$. This function is a line integral of $f(x, y)$ over an arc concentric to the median arc,

$$\alpha(z) = \int_{\mathcal{L}} f(x, y) \mathrm{d}\ell, \tag{A.1}$$

where $\mathcal{L}$ is the arc with radius $d_m - z$ stretching across the locality's borders. Similarly, we define the function $\beta(z)$ that gives the density function of population at distance z from the median arc within $\mathbb{B}$.

Next, we establish that the median arc will intersect the locality's borders at a point at which the width of the locality is increasing as distance from the facility increases. By contradiction, suppose that the median arc is at a point at which the width of the locality is *decreasing* as distance from the facility increases. Since we have restricted the locality to a convex set, the point of maximum width must be located in $\mathbb{A}$ or at the median arc. Convexity also implies that $\beta(z)$ is decreasing and concave, while $\alpha(z)$ is concave and increases from $x = 0$ over some interval, since these functions simplify to the length of the arc $\mathcal{L}$ at z with a spatially uniform population distribution. Note that $a(z) = b(z)$ at $z = 0$. If the point of maximum width is not located at the median arc there exists some distance, $z = z_1$, at which $\alpha(z)$ is at its maximum. Therefore, the integral of $\beta(z)$ must be strictly less than the integral of $\alpha(z)$ from $z = 0$ to $z = z_1$. However, the integral of $\alpha(z) = 0.5$ must be equal to the integral of $\beta(z) = 0.5$ over the entire locality, since these areas are defined by the median arc. Based on the concavity and monotonicity properties of $\alpha(z)$ and $\beta(z)$, combined with the equality of integrals over the entire distance, the maximum distance in $\mathbb{B}$, i.e. the point at which $\beta(z) = 0$, must be greater than the maximum distance d_m in $\mathbb{A}$. This, of course, cannot hold, as the firm would then optimally locate in $\mathbb{B}$. Therefore, the firm will always locate at a point so that the median arc intersects the locality's border at a point of increasing width away from the facility.

Median distance from the facility will be greater than mean distance when mean distance *from the median arc* in $\mathbb{A}$ is greater than in $\mathbb{B}$,

$$\int_0^{A_{Max}} (\alpha(z) - \beta(z))\, z \mathrm{d}z > 0. \tag{A.2}$$

Define the cumulative distribution functions[15] $\Psi(z)$ and $\Omega(z)$ that give the portion of the

[15] Density here is measured relative to the entire population of the locality, so that neither $\alpha(\cdot)$ nor $\beta(\cdot)$ are proper density functions in the context of probability theory. The same is true for the cumulative functions $\Psi(\cdot)$ and $\Omega(\cdot)$.

population in $\mathbb{A}$ and $\mathbb{B}$, respectively, that live within distance z of the median arc,

$$\Psi(z) = \int_0^z \alpha(t)\mathrm{d}t,$$
$$\Omega(z) = \int_0^z \beta(t)\mathrm{d}t.$$

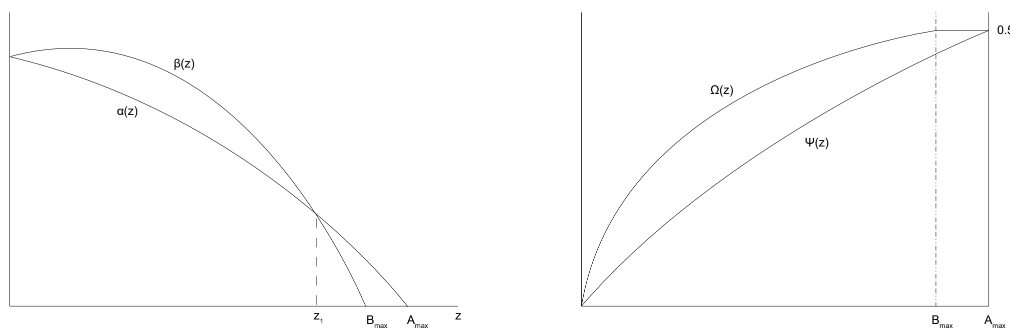
Differentiating by parts, Equation A.2 can be simplified as

$$\int_0^{A_{max}} (\alpha(z) - \beta(z))\, z\mathrm{d}z > 0 \tag{A.3}$$
$$= (\Psi(z) - \Omega(z))\, z|_0^{A_{max}} - \int_0^{A_{max}} (\Psi(z) - \Omega(z))\, \mathrm{d}z > 0 \tag{A.4}$$
$$= - \int_0^{A_{max}} (\Psi(z) - \Omega(z))\, \mathrm{d}z > 0 \tag{A.5}$$

The final simplification of Equation (A.5) comes from function endpoints, $\Psi(A_{max}) = \Omega(A_{max}) = 0.5$ and $\Psi(0) = \Omega(0) = 0$.

We established earlier that $\beta(z)$ is a concave function and can be increasing over its entire domain or only on some interval. The domain of $\beta(z)$ is such that $z \leq A_{Max}$. This restriction follows from the firm's decision to maximize median distance. The function $\alpha(z)$ is concave and decreasing. Therefore, $\beta(z)$ is greater than $\alpha(z)$ over some interval from $z = 0$ to $z = z_1$. The first panel of Figure A.1 illustrates the functions $\alpha(z)$ and $\beta(z)$. In Equation (A.5), recall that $\Psi(z) = \Omega(z)$ at $z = 0$ and at $z = A_{max}$. Combined with properties of $\alpha(z)$ and $\beta(z)$, it is clear that $\Psi(z)$ first-order stochastically dominates $\Omega(z)$. This last point, seen in the second panel of Figure A.1, implies that the integral in Equation (A.5) is negative so that the inequality in Equation (A.2) holds.

Hence, mean distance from the proposed facility, $\bar{d}$, must be less than d_m and if the disamenity cost function $c(d)$ is monotonically decreasing and weakly convex then $c(\bar{d}) > c(d_m)$.



(a) Density function (b) Cumulative distribution

In (a), the function $\alpha(z)$ denotes the density of distance from the median arc (located at distance d_m) for households within distance d_m of the proposed facility ("no" voters, set A). The function $\beta(z)$ denotes the density of distance from the median arc for households beyond distance d_m of the proposed facility ("yes" voters, set B). In (b), the cumulative distributions of distance from the median arc for households in A and B are expressed as $\Psi(z)$ and $\Omega(z)$, respectively. Note that these are modified density and cumulative functions, respectively, in which values indicate density or probability of distances within a particlar subset (A or B), but relative to the entire locality. Therefore, each density function has area under the curve equal to 0.5 and the cumulative function reaches its maximum at 0.5.

Figure A.1: Population distribution for spatially uniform distribution.

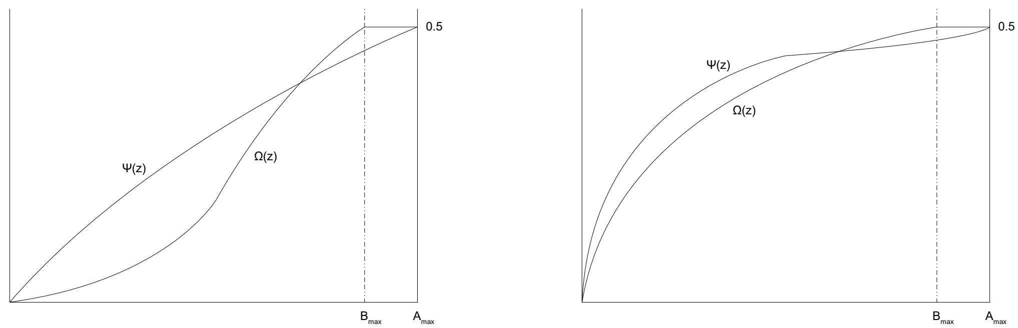
A.2 Proof of Proposition 2

The density function of distance to the facility is the continuous piecewise function equal to $\alpha(z)\ \forall z \in \mathbb{A}$ and equal to $\beta(z)\ \forall z \in \mathbb{B}$, defined above. If this function is concave then $\alpha(z)$ and $\beta(z)$ are also concave functions. Therefore, the proof in A.1 applies.

A.3 Discussion of Alternative Cases

The uniform spatial distribution in Proposition 1 restricts the distance distribution to be entirely dependent on the shape of the locality. Convexity in the shape of the locality is enough to ensure inefficient siting. Without restrictions on the spatial distribution of the population and on the shape of the locality, the functional properties of $\alpha(z)$ and $\beta(z)$ discussed above cease to hold. Still, distributions under which Equation A.2 holds can be seen by analyzing $\Psi(z)$ and $\Omega(z)$. The only condition for an inefficiency is that the area under the curve $\Psi(z)$ is less than the area under the curve $\Omega(z)$.

Whether inefficient siting will arise in equilibrium can be seen as a matter of the relative concentrations of population on either side of the median distance. There are two general mechanisms that will prevent this inefficiency from arising in the siting decision. The first is a large concavity in $\Psi(z)$, as seen in the first panel of Figure A.2. In this situation, there is a concentration of population at distances very close to the median and within $\mathbb{A}$. At the same time, such a concentrated population density must not exist near the median arc in $\mathbb{B}$. Alternatively, the second panel of Figure A.2 illustrates a large convexity in $\Omega(z)$ that prevents an inefficiency from occurring. This corresponds to a high concentration of individuals at far distances. Such a concentration increases mean distance. Note that in both situations, we are considering changes in the spatial distribution of the population that do not impact median distance, so that these population concentrations put downward pressure on aggregate costs.



(a) Concentration near median (b) Concentration at far distance

The functions $\Psi(z)$ and $\Omega(z)$ show the cumulative distributions of distance from the median arc for households in A and B, respectively. Note that these are modified density and cumulative functions, respectively, in which values indicate density or probability of distances within a particlar subset (A or B), but relative to the entire locality. Therefore, each density function has area under the curve equal to 0.5 and the cumulative function reaches its maximum at 0.5.

Figure A.2: Distance distributions that do *not* lead to inefficient siting.

Appendix B Estimated α and β Parameters

	min	max	mean	sd	median	25%	75%
α	1.65	18.54	4.44	2.64	2.32	3.69	7.59
β	0.89	9.56	2.50	1.28	1.28	2.24	4.01
skew	-1.18	-0.01	-0.36	0.18	-0.58	-0.34	-0.16

This tables presents summary statistics of parameter estimates for 116 county population distributions. We omit 2 counties that have positively skewed distributions relative to the optimal facility location. The measure *skew* is directly calculated for each county using the α and β estimates.

Table B.1: Parameter estimates summary