“Siting of Hazardous Facilities”

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Chapter 11

Siting of Hazardous Facilities

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While OR methodologies ranging from risk assessment to decision analysis have helped to improve our understanding of the siting process, finding homes for hazardous facilities has remained a controversial area of public policy analysis. This chapter first describes the features of the siting problem which have made it difficult to find a home for noxious facilities and then proposes a set of guidelines for improving the process. In our view methodologies which are designed to improve siting outcomes must be coordinated carefully with a broader process view of siting. The remainder of the chapter summarizes recent research on the nature of the hazardous facility siting problem and related transportation problems with a focus on route-mode selection issues, facility location models and decision analysis for choosing between predetermined sites. This chapter concludes by raising open questions for future research.

1. Introduction

Rachel Carson’s book Silent Spring [1962] first made the general public aware of environmental hazards by depicting the sudden and eerie disappearance of living creatures on earth as a result of toxic chemicals which poisoned the air, water, and soil. People’s fears have been further honed by heavily publicized ‘catastrophes’ with the dumping of carcinogens at Love Canal and Times Beach, the nuclear power plant accidents at Three Mile Island and Chernobyl, and the chemical disasters at Seveso, Italy and Bhopal, India.¹

This new climate of concern has consistently attached itself to waste-disposal facilities. Indeed, because of intense public opposition, it has become exceedingly difficult for government agencies and private developers to site landfills, incinerators, repositories, and other facilities that dispose of solid, hazardous or radioactive waste. For example, 28 of the 34 solid waste incinerators proposed for

¹ See Kleindorfer & Kunreuther [1987] for a review of these catastrophes and the public policy debate to which they gave rise.
California were either canceled or postponed in the late 1980s. Likewise, although the Environmental Protection Agency (EPA) has estimated that between 50 and 125 new sites would be needed for storing hazardous waste, no facilities were sited by 1986 and very few since then [Whitehead, 1991]. This inability to find successful sites for new waste facilities is part of a larger trend that extends to many other facilities that benefit society as a whole, but have undesirable impacts on the local community (e.g., AIDS treatment centers, halfway houses for parolees, and recycling plants to name a few). [Lake, 1987].

This chapter addresses these issues from two perspectives: descriptive and prescriptive. The next section provides an overview of characteristics of the siting process and describes examples of recent problems in finding acceptable locations for nuclear power plants, hazardous, and radioactive waste disposal facilities. We argue that, to be effective, OR methodologies which are designed to improve siting outcomes must be coordinated carefully with a broader process view of siting. By focusing on both process and outcome considerations a set of prescriptive guidelines for siting are presented in Section 3.

The remainder of the paper reviews the operations research methodologies for improving the siting process. Section 4 provides a formal statement of the siting problem. Section 5 reviews OR approaches for analyzing hazardous materials transportation problems. Sections 6 and 7 summarize the relevant OR literature on location theory and decision analysis as it relates to the siting of hazardous facilities. The chapter concludes by discussing several open questions and areas for future research.

2. Descriptive characteristics of hazardous facility siting

Hazardous facility siting involves a number of competing, interacting features. This section describes these features and illustrates them by examples as a prelude to our discussion of operations research methodologies for improving the siting process.

2.1. The problem: global benefits and local costs

Consider the siting problem for waste disposal. Society faces a dilemma in finding homes for different types of trash and waste. On the one hand, people demand the goods and services whose production yields waste as by-products. There appears to be widespread agreement by the public on the need for properly designed and managed disposal facilities, since, in the aggregate, their presence would yield benefits in excess of their risks and costs. On the other hand, opposition is vehement when mention is made of locating a trash disposal or hazardous waste facility at a specific site (i.e., in someone's backyard). A 1980 national opinion poll found that over 95% of respondents would actively protest against siting a hazardous materials facility near their home [U.S. Council on Environmental Quality, 1980]. Today we expect that opposition to be the same or
even greater. This is a typical feature of hazardous facility siting: societal benefits from such facilities may be large, but the risks and costs to a host community are also perceived to be large.

2.2. Relevant interested parties

In any siting controversy there are a set of interested parties, each of whom has their own values and goals. There are those groups who would like to see the facility built because it yields sufficient benefits to them; others are likely to have serious concerns about the facility.

Some of the interested parties may feel the same way about the facility but for different reasons. For example, an environmental group may oppose the construction of a high-level nuclear waste repository primarily because they would like to end the use of nuclear power and recognize that this will happen if there is no place to store the waste. Citizens groups may oppose the facility due to strong fears of an accident either to themselves or future generations.

When one lines up all the different interested parties on a particular siting question there is likely to be considerable conflict on whether the facility is needed and, if so, where it should be placed. The fact that different groups may have the same attitude toward a proposed facility but for very different reasons suggests that it is important to understand the nature of the controversy before making policy recommendations. A closer look at the stakeholders who are involved in a given siting situation provides strong insights into why such controversies are likely to exist.

2.2.1. Applicant

The initiator of the siting effort is the applicant – the firm, agency, or other organization that is interested in seeing that a certain type of facility is built (or more generally, that a specific problem is solved). In siting problems related to solid or hazardous waste, the applicant is typically either a private corporation or the state.

For private firms to enter into the siting fray, they must first perceive that their economic benefits from the proposed facility (e.g., a new landfill for municipal waste or a hazardous waste incinerator) will be greater than the construction costs and operating expenses associated with the facility, as well as the transaction costs associated with convincing the community and regulatory agencies to grant a permit.

Governmental agencies have also been applicants, frequently out of necessity. For example, states bear ultimate responsibility for finding a means of disposal of low-level radioactive waste. Similarly for high-level radioactive waste, national legislation has established responsibility for oversight and siting of a repository with several federal agencies. The federal government assumed this role as a result of (a) the accumulation of high-level nuclear waste at its own weapons installations, and (b) legislation that explicitly transferred responsibility for civilian waste from the generators (i.e., public utilities) onto itself. Direct responsibility for
the management of high-level nuclear waste has been assigned to the Department of Energy (DOE). DOE in turn has been active in evaluating sites such as the Yucca Mountain Nevada site for a geologic repository. We discuss this case in more detail below.

Whether the applicant is from the private or the public sector, there will be certain common concerns. The first concern, obviously, is to find some site where it is possible to build the facility. If the applicant is a private firm, this objective is accompanied by the need to find a site where the facility can be run in a cost-effective manner. All applicants must show some concern with protecting the public’s health and safety, although this responsibility is generally made more explicit when the applicant is a government agency.

2.2.2. Affected constituency

This term refers to the individuals, groups and agencies directly impacted by the proposed facility. These residents and their political representatives often have a strong say over whether a facility can be built at the proposed site. Solid waste problems normally involve municipalities which must find a community willing to take their trash. At the other extreme is the high-level nuclear waste (HLNW) repository problem where the federal government must find a site where it is legally and politically able to license and construct the facility.

2.2.3. Public interest groups

In recent years, citizens groups and environmental groups have become increasingly active in siting debates. These organizations generally represent the interests and preferences of certain sectors of the public. For example, the Sierra Club and Natural Resources Defense Council are concerned with the short- and long-term effects that a proposed waste disposal facility will have on the environment. Local citizens groups are normally concerned with the health and safety of the local residents as well as with the impact that the facility will have on property values.

2.2.4. Regulatory bodies

Government agencies normally have well specified formal responsibilities in the siting process. Their roles are defined by legislation, the nature of the facility, and the type of applicant who plans to develop the facility. One of the key areas of interest in current siting debates is how the general public perceives these governmental bodies. For example, what values and goals do Nevadans assign to the Department of Energy in its attempt to study Yucca Mountain as a site for the HLNW repository?

2.3. Disagreements about facts and values

Different stakeholders may disagree about the merits of a proposed facility for a number of reasons. The most obvious cause of disagreement stems from differences in vested interests. For example, residents of an area in the proximity of an incinerator or landfill may be concerned with the impact on future property
values should they wish to sell their property. The business community may be concerned with the potential negative impact that a waste repository may have on tourism or convention activity, but neither the regulatory agency nor the applicant may have this as a primary consideration. The regulatory agency is concerned primarily with ensuring that the applicable laws and regulations are likely to be satisfied, while the developer hopes to run a cost-effective operation that meets the letter of the law.

Even when stakeholders are talking about the same impact, they may disagree on the extent of what it will be. Disagreement is especially common with facilities that handle hazardous or radioactive material. Part of this disagreement results from complexities in the causal chain of events. Kasparsen, Renn, Slovic, Brown, Emel, Gobel, Kasparsen & Ratiok [1988] have pointed out that the consequences of risk events go far beyond direct harms to include many of the indirect impacts such as loss of confidence in institutions and the perceived fairness of the risk management process. They point to the accident at Three Mile Island which did not kill any individual but wrought enormous social consequences in the form of stricter regulations, greater opposition to nuclear power and an increased concern with other complex technologies such as chemical plants and genetic engineering. This potential social amplification of risk needs to be taken into account when designing the decision process and strategies for siting and managing new facilities.

Because of the wide range of potential impacts that might be considered, as well as the extensive uncertainty involved in predicting any specific impact, the evidence gathering process tends to be decentralized and conflictual. Each stakeholder group collects data on the facility in order to defend its position, satisfy its objectives and meet its responsibilities. To a large extent these data pertain to the issue of risk (either to health or the environment), although the different groups may vary significantly with respect to the nature of information they collect. At the most elementary level, different definitions of risk may be utilized. For example, one group may define risk in terms of the consequences of the worst-case scenario, while another stakeholder may disregard any possible event where the probability of its occurrence falls below a specific threshold.

Even if risk is defined in the same way by all the stakeholders, there are likely to be significant discrepancies in estimates. For new technologies there are limited statistical data on how well the facility is likely to perform in practice. In the case of the proposed HLNW repository, one has to rely entirely on theoretical or prototype analyses since there is no historical record to consult. Scientists may disagree on the assumptions on which their analysis is based, and thus come up with very different estimates of probabilities and consequences.

In many siting controversies, there arise issues where the available data are insufficient to determine whether a certain scientific statement is true or false. In fact, as many philosophers have argued, it is only possible to prove that a scientific statement may be false, not that it is correct. In the case of low probability events, there is inherently insufficient information to prove that a given risk estimate is incorrect due to the limited data on accidents. For this reason Weinberg [1972]
proposed the term ‘transscientific’ to describe these risks. In other words, there is no practical basis for estimating the statistical chances and consequences of the occurrence of certain types of accidents. For such risks, risk assessment is an art rather than a science.

As a result of this indeterminacy, each stakeholder is likely to be able to find some expert to defend a particular point of view. It is often difficult to dispute or confirm this position with solid scientific evidence. For example, a private contractor or government agency anxious to site a waste facility will be able to identify scientific experts who claim the facility poses little risk to health and safety. Citizen groups can find other experts who paint a very different picture, claiming that the facility poses great hazards. To date, there have been no forums or science courts for examining the reasons for these differences but even if such institutions were established, there may be legitimate differences that are not reconcilable based on existing data.2

Even if there were general agreement on the size of the facility’s risk (or other factual issues), the different interested parties are likely to disagree on values. This point has been clearly brought home by Von Winterfeldt & Edwards [1984] in a study of technological conflicts and disputes about risky technologies. By studying 162 different cases they developed a taxonomy for classifying different disputes based on conflicts over facts and values. They point out that in the case of siting new facilities, some disputes will arise over facts (as indicated above), but the debate between relevant stakeholders will revolve primarily around values and moral issues on which legitimate differences exist. For example, questions arise as to whether society should develop technologies that we cannot fully control and whether we should expose future generations to potential long-term risks which are not fully understood. These issues turn out to be of great concern to the public and affected constituencies when judging the attractiveness of a HLNW repository for long-term storage, but typically have not been considered as critical issues by the applicant.

Disagreements over both facts and values are more likely to occur in siting cases where the applicant has failed to cultivate the trust of the affected constituency. Firms and government agencies that have poor track records managing existing facilities, or that put forth a demeanor of arrogance or secretiveness in their dealings with the public, have an extremely difficult time gaining the confidence of local residents. In these cases, the motives, the data, and the conclusions of the applicant are likely to be met with a special breed of skepticism. This has in fact been the nature of the relationship between the Department of Energy and the states that have been identified as having potential HLNW repository sites, particularly Nevada [see Kunreuther, Easterling, Desvousges & Slovic, 1990; Siovic, Layman and Flynn, 1991].

2 See Kunreuther & Linzerooth [1982] for a detailed case study of the siting of a liquified natural gas terminal showing the wide variety of risk assessments utilized by different stakeholder groups in the siting process.
2.4. Institutional arrangements

Understanding a siting case also requires an appreciation of the institutional arrangements. It is important to identify which parties have an interest in seeing that a facility is built, which parties have regulatory or statutory authority over the siting decision, and the overlap between these two sets. An especially key factor concerns the degree of control that the local ‘community’ can exert over the siting decision; in some cases, the decision must be approved by the town council or the zoning commission, while in other cases, the state preempts local authority.

It is interesting to compare the siting of a high-level radioactive waste facility to the low-level radioactive waste siting challenges in terms of the institutional arrangements facing individual states. In the high-level case, each state is represented in the forum that dictates siting policy (i.e., U.S. Congress), but the ultimate decision making authority rests at the federal level. Candidate states are assigned some special authority (e.g., oversight), but in general, they are subject to the discretion of a higher-order applicant. In contrast, for the low-level radioactive waste case, each state has the responsibility to find a suitable means of disposal. Hence, the state is the applicant.

2.5. Siting processes

The decision-making process associated with any particular siting problem depends to a large extent on the nature of the institutional arrangements between the different stakeholders. Legislation, regulation and cultural considerations all play a role in determining what type of process is likely to be put in place. Three illustrative approaches are described below.

2.5.1. Decide Announce Defend (DAD) approach

The traditional approach to siting, at least up until 1980, was the DAD approach. It is normally characterized by three sequential stages. In Stage 1 the applicant, normally the developer or contractor, makes a series of technological choices based on engineering analyses regarding the need for a facility, the type of facility to build, and where to locate it. These decisions are not discussed with the other concerned stakeholders, such as the local government or residents living near the proposed facility. In Stage 2, the developer publicly announces the proposed technological and siting package. Then in Stage 3 the developer defends his position amidst much conflict and opposition [O'Hare, Bacow & Sanderson, 1983].

This process has not worked in practice because it alienates many of the stakeholder groups, including those who have veto power over the siting decision. It also fosters an adversarial relationship between the developer and the local community. In effect, a DAD proposal constitutes a challenge for the affected groups to find fault with the proposal. O'Hare, Bacow & Sanderson [1983] provide several case studies illustrating the failure of the DAD procedure in practice.
2.5.2. Legislated siting processes

Due to the failure of the DAD process, there have been developments at both the state, regional, and federal levels to specify the siting process within legislation. These legislated processes generally call for formal negotiations between the various parties with a direct interest in a proposed facility.

For example, the Massachusetts Hazardous Waste Siting Act of 1980 is a state-initiated effort designed to stimulate negotiation between a developer and a host community. Several communities in Massachusetts have expressed an interest in hosting a waste disposal facility, but no siting agreements have been reached to date. In each case where it appeared that a facility might be sited, groups have raised the claim that the facility would pose an undue economic or psychological burden on local residents, and hence pose a special risk. In these situations, the Massachusetts legislation enables the community to exclude these waste facilities.

Legislated siting procedures have also been worked out at the regional level. The Low Level Radioactive Waste (LLRW) Policy Act of 1980 required that each state take responsibility for the LLRW generated within its borders, but also recommended that groups of states form compacts to deal with their disposal problems more efficiently. As of mid 1991, regional compacts have been formed for Appalachian, Central Interstate, Central Midwest, Midwest, Northwest, Rocky Mountain, Southeast, and Southwestern regions.

Those states that are selected to host a repository (or who elect to go on their own) must then find a suitable site for the facility. In many cases, the procedure for selecting this site is also specified through legislation. However, this does not necessarily guarantee that the procedure will play out according to plan.

In the high-level nuclear waste case, a legislated siting strategy was invoked at the federal level. In formulating the Nuclear Waste Policy Act of 1982, Congress recognized the need to find a site that would be both technically and politically acceptable. Thus, an intricate (and some might add fragile) arrangement which acknowledged the concerns of different stakeholders was negotiated. Under the act, strict safety standards would be employed, all potential sites would be considered, the site selection procedure would be systematic and fair, regional equity would be sought, and candidate states would have some degree of control over the decision making process. However, as discussed in Kunreuther, Easterling, Desvouges & Siovic [1990], many of the agreed upon provisions have unravelled in practice due to the problems noted above of value conflicts, scientific uncertainties, and related public perceptions of the risks of radioactive waste.

2.5.3. Voluntary siting agreements

The legislated process requires the host community to prove that the facility should not be built as proposed. Under voluntary siting, the objective is to construct a facility proposal that appears attractive enough to cause communities to consider becoming a partner in the effort to site it.

Communities will not even consider entering into a voluntary siting process unless they are assured that the facility will operate safely. Second, the need for the proposed facility must be widely recognized by demonstrating that the
current or future costs associated with the status quo are unacceptable. Third, the applicant must construct a package of benefits that makes potential host communities feel that they are better off with the facility than without it.

Ideally, the potential benefits will be attractive enough that several communities will each make offers for the facility. The resultant competition is beneficial both in terms of economic efficiency and in generating a balanced debate regarding the actual risks and impacts associated with the facility. The ultimate goal of the voluntary siting process is to change the commonly observed NIMBY (Not In My Backyard) response to YIMBY (Yes in My Backyard).

2.6. Process and outcome considerations

The concepts of procedural and substantive rationality developed by Simon [1978] for structuring choice under uncertainty are useful for formulating prescriptive guidelines for siting a noxious facility. Procedural rationality refers to the decision processes utilized by the different interested parties concerned with a particular problem given inherent human limitations in collecting and processing information. Substantive rationality refers to the way an outcome(s) is chosen from a set of alternatives. It focuses on the types of benefit-cost criteria that are utilized and how specific policy tools can facilitate the final outcome.

A large literature has emerged that recognizes the importance of both these types of rationality in formulating siting strategies. The importance of process considerations has been emphasized by a number of social scientists given the failure of the traditional Decide Announce Defend (DAD) approach to siting which was common through the 1970s [Kunreuther & Linnerooth, 1982; Morell & Magorian, 1982; O’Hare, Bacow & Sanderson, 1983; Portney, 1991; Susskind & Cruikshank, 1987]. This research points out that the DAD process has not worked in practice because it alienates many of the interested parties, including those who have veto power over the siting decision. There is general agreement across all these studies that one needs to involve the interested parties in siting discussions even if this requires more time and effort than the DAD approach.

Outcome-based approaches to siting have also been developed which involve the use of multi-attribute utility models to choose between alternative sites [Keeney, 1980] and examine how compensation can play a role in encouraging communities or regions to accept a facility [Kunreuther, Easterling, Desvousges & Slovic, 1987; O’Hare, Bacow & Sanderson, 1983]. Today compensation or benefit-sharing is considered a legitimate policy tool for siting facilities. There is general agreement, however, that it should only be introduced as a part of the process after the affected public is convinced that appropriate mitigation and control measures will be in place so that the risk associated with the facility is considered to be acceptable [Carnes, Copenhaver, Sorensen, Soderstrom, Reed, Bjornstad & Peelle, 1983; Peelle, 1987; Gregory, Kunreuther, Easterling & Richards, 1991].
3. Improving the siting process

The siting process involves global benefits and local costs and, typically, considerable uncertainties. Potential host communities for hazardous facilities have therefore been very reluctant to site such facilities unless they expect to share in the benefits (e.g., through employment or tax relief), and only if they feel a sense of trust toward the applicant and developer and a sense that the siting process is equitable.

Given the relatively few hazardous facilities that have been sited in recent years there is a need to improve the process. The proposed procedure recognizes the importance of process and outcome considerations and is an outgrowth of a National Workshop on Facility Siting that brought practitioners and siting experts together to address the facility siting dilemma. The Facility Siting Credo was the principal product developed from this workshop. Some of the key steps for developing a workable siting process are summarized below.³

3.1. Step 1: Get agreement that the status quo is unacceptable

Unless the key stakeholders are convinced that maintaining the current situation is worse on key dimensions (e.g., cost, risk) than one of the other options it is highly unlikely that a new site will be chosen. By developing a set of objectives and performance measures one can examine the status quo in relation to the proposed alternatives.

One of the principal ways that the status quo will be shown to be unacceptable is if there is legislation passed requiring new facilities by prespecified dates. As pointed out in the introduction legislated siting procedures such as the Low Level Radioactive Waste Policy Act of 1980 have forced states to either find a site for their own waste or form a compact with other states.

3.2. Step 2: Guarantee stringent safety standards

No community should be asked or will want to trade off health or safety for economic benefits. All potentially hazardous facilities must be required to meet all legally established health and safety standards. The host site will want to have data assuring them that the organizations responsible for satisfying the safety standards of the facility have a proven track record. Candidates for a facility should also have an opportunity to specify any additional health, safety, and environmental standards that could be met through mitigation, such as changes in facility design, substitute technologies, operational modifications, and training of operators.

Swallow, Opaluch & Weaver [1992] suggest a procedure for screening all sites for technical suitability that meet a set of constraints associated with health, safety and environmental effects. For example, landfill sites must satisfy hydrologic and geologic constraints so that it is highly unlikely that pollutants will migrate off-site.

³For more details on the nature of the Facility Siting Credo and an empirical test of its principles see Kunreuther, Fitzgerald & Aarts [1993].
Gregory, Kunreuther, Easterling & Richards [1991] stress the importance of mitigation as a way of ensuring the public that a facility will be safe in the future. The public demands that the best available technology be utilized if there are health and environmental risks associated with the facility. U.S. Ecology learned this lesson with respect to a low-level radioactive waste facility, deciding to forego the extra protection offered by a double-walled barrier. The public, who had generally supported the facility, reacted very negatively to this decision.

Monitoring and control procedures are the key to minimizing risks, maintaining standards and reducing fears of the public regarding the operation of the facility. A written agreement should stipulate conditions for a facility's operation and the type of monitoring procedures that will be followed. For example, maximum thresholds for the facility (e.g., amount of waste, number of admittants) should be established.

Plans and restrictions for the use of the facility should be specified (e.g., restrict who is eligible to ship waste to a facility) and the community should be provided with the right to shut down the facility if certain conditions and standards are not met.

3.3. Step 3: Make the host community better off

A package of benefits should be put together by the applicant so that the proposed host community feels that it is better off with the facility than without it. There should be a way of 'taxing' the gainers from the facility to obtain these funds for reimbursing the potential losers.

A negotiated schedule of contingent compensation payments for any harmful effects should be described in a written siting agreement. Property value guarantees, as well as assessment of future liability to the relevant party (e.g., developer, waste disposers, government) in case of an accident need to be explicitly stated.

Specific property value guarantees need to be established so that residents who sell their homes can obtain a fair price. An illustrative example of this type of arrangement is the program established by Champion International Corp., when it established a landfill in an agricultural area 25 miles north of Cincinnati. Property owners received two appraisals of their property prior to the landfill being sited and used the sale prices of property in other parts of the county to determine any changes in value. If a sale price falls short of the latest countywide value figure, Champion makes up the difference [Ewing, 1990].

An explicit agreement needs to be specified in writing at the time the facility is sited as to who is responsible for the recovery costs following an accident. The nature of the liability payments from any environmental pollution should also be clearly delineated.

3.4. Step 4: Seek acceptable sites through a volunteer process

Avoid naming a 'technically best' site since siting criteria are subjective enough that it is impossible to rank sites with such precision. Look for volunteer sites that would meet minimal technical criteria.
Encourage communities, regions, or states to volunteer sites indicating that this is not an irreversible commitment and that there are potential benefits packages (e.g., new revenues, employment, tax reductions) that come with the facility.

By undertaking preliminary risk assessments one can determine whether the proposed location is feasible for a particular facility. These costs should be borne by the developer or relevant federal agency.

Start-up funds should be provided for potential host communities or states to evaluate their own needs in relation to the siting option. The public should be encouraged to participate in the process to determine the concerns of different groups and whether they can be addressed.

A voluntary approach has been developed in Canada [Rabe, 1991; Zeiss, 1991] and is now being applied in the United States [Rennick & Greyell, 1990; Ruckelshaus, 1989]. Under this siting approach, the developer does not unilaterally select a site, but rather invites all communities with technically suitable sites to enter into negotiations. The developer and community representatives together construct a mutually acceptable facility proposal (which includes benefits).

The key feature is that discretion over the siting decision rests with the communities rather than the developer. The facility will not be sited within a community that has qualms, because only volunteer communities are considered. The emphasis on community control is maintained throughout the entire siting process; a community that initially expresses interest is free to withdraw at any point along the way.

In addition, the strategy strives for a cooperative arrangement in which communities are asked to become partners in the development of the facility. The terms of the partnership are negotiated between community representatives and the developer. These terms may include such factors as the design and operation of the facility and the amount of revenue.

3.5. Step 5: Consider a competitive siting process

Assuming that multiple technically acceptable volunteer sites are found, facility sponsors should consider a competitive process of site selection. Potential host communities should have a chance to propose compensation or incentive packages for later consideration. The final choice of a facility will be a complicated one based on technical criteria, the nature of the benefits package, and a comparison of costs and risks across sites. The advantage of having more than one site compete for the facility is that a particular region does not feel that it is singled out to house a facility that no one else wants.

If there is more than one site in contention then there are several different procedures that might be followed in choosing a final site. One could institute a lottery between the sites in contention and agree to pay the 'winner' a prespecified sum $S$. After the 'winner' is announced any of the other sites have the option of bidding for the site by offering a lower amount than $S$. This bidding could take the form of a sealed bid auction with each candidate specifying the minimum amount they would require to take the facility [Kunreuther & Portney, 1991]. It could
also take the form of an open bidding system with the monetary offer continuing
to drop until only one site remained. Alternatively, one could begin the bidding
process with a low amount and raise it until one community agreed to host the
facility. This reverse Dutch auction process has been proposed by Inhaber [1990].

An alternative procedure would be to ask each site to specify the benefits
package it would require and then let the developer or government agency decide
which location should be declared the ‘winner’. The criteria for determining the
host site would be based not only on the amount of compensation required but
also risk, costs, and other economic factors.

These approaches are designed to encourage regions to think positively about
the possibility of hosting a facility. In fact, by giving them an opportunity to specify
a benefits package each candidate may think about how much they would lose
if they were not chosen to host the facility – a strange reversal of the normal
NIMBY reaction.

4. Operations research and hazardous facility siting

The methodologies on siting developed in the operations research literature are
designed to find an optimal outcome (e.g., a site, set of transportation routes)
based on a well-specified objective function and a set of constraints. The next four
sections review some of these formal approaches and provide a general guide to
the literature on the topic. A more comprehensive bibliography on any of these
topics can be found in the papers referenced in this review. Our purpose in this
paper is to summarize the principal questions addressed in the OR literature and
specify the models utilized to answer them.

After providing a general statement of the siting problem below, we review the
literature on transportation of hazardous materials (Section 5) and extensions of
traditional facility location models to hazardous facilities (Section 6). In Section 7
we first explore decision analytic approaches to the evaluation of alternative sites
and then illustrate the importance of process issues in determining an acceptable
outcome. The challenges in finding a site for the first high-level nuclear waste
repository in the United States offers a concrete example of the need to address
procedural as well as substantive rationality questions when addressing the facility
siting question.

It is useful to begin with a general statement of the siting problem. Let \( X \)
be the set of feasible siting options, where each \( x \in X \) represents a specific set
of site locations, facility types at each location, technologies used, transportation
routes used, and any other characteristics important to the costs and benefits of
operations or to the perceived risks of the facilities to be sited. In the simplest
problem of locating a single facility of specific size and technology within a region,
\( X \) could just represent the coordinates of feasible locations for the facility.

Let the relevant stakeholders in the facility siting problem be denoted by \( \Theta \),
where the typical \( \theta \in \Theta \) might be a household generating waste or a household in
the host community near \( x \).
Let $Y$ be the set of risk reduction and mitigation measures, where each $y \in Y$ represents a vector of individual and collective actions which might reduce the probability of an accident or mitigate the consequences of accidents if they occur. Such actions would include special safety equipment, monitoring and control procedures, insurance, investments in emergency response capability and so forth.

Let $Z$ be a set of states of the world, with some distribution function $F(z)$ describing their relative likelihood of occurrence. For the moment, we will assume that all stakeholders agree on a common-knowledge distribution function $F(z)$.

To make matters transparent, we assume that risk preferences of stakeholders are representable by a utility function of the quasi-linear form

$$U(x, y, z; \theta) = V(x, y, z; \theta) + M,$$

where $V(x, y, z; \theta)$ is stakeholder $\theta$'s willingness-to-pay (which may be negative) for facility option $x$, when risk mitigation measures $y$ are undertaken and state $z$ occurs, and where $M$ represents 'money' available to spend on other goods; $M$ may incorporate compensation payments to stakeholder $\theta$ to assure that $\theta$ remains at or above some status quo utility level. We have assumed for simplicity here that income or wealth is separable in each stakeholder's preference function. Given this quasi-linear form of preferences, $V(x, y, z; \theta)$ is referred to as willingness-to-pay, since (from (1)) stakeholder $\theta$ would be indifferent between the option $(x, y, z$) and the compensation payment $M = V(x, y, z; \theta)$. In this sense, stakeholder $\theta$ should be willing to pay exactly $V(x, y, z; \theta)$ for $(x, y, z)$. If this payment must be made before the state of the world $z$ is known, then under the expected utility axioms, e.g., of Savage, stakeholder $\theta$ should be willing to pay exactly $E_z[V(x, y, z; \theta)]$ for the option $(x, y)$. If $E_z[V(x, y, z; \theta)]$ is negative, then we interpret $-E_z[V(x, y, z; \theta)]$ as the necessary compensation to stakeholder $\theta$ to make $\theta$ just indifferent between implementing $(x, y)$ and not doing so. Thus, if the expected value $E_z[V(x, y, z; \theta)]$ is negative, then stakeholder $\theta$ is 'inconvenienced' by the siting option $(x, y)$, and some compensation might be required (i.e., $M$ would have to be increased by a transfer payment to stakeholder $\theta$) in order to make up for this inconvenience.

Denote by $C(x, y, z)$ the total out-of-pocket cost associated with option $x$, when $y$ is chosen, and $z$ occurs. $C$ would include the costs of the facility, additional transportation infrastructure, risk mitigation measures and so forth. $C$ would also include the costs of accidents in some states of the world $z$.

The siting problem which we consider is to determine the option $(x, y)$ which maximizes total expected social benefits, i.e.:

$$\max_{x \in X, y \in Y} \quad \mathbb{E}_z \left\{ \sum_{\theta \in \Theta} V(x, y, z; \theta) - C(x, y, z) \right\}$$

subject to

$$\mathbb{E}_z[V(x, y, z; \theta)] + T(\theta) \geq V_0(\theta), \quad \forall x, y, \theta,$$

with

$$\mathbb{E}_z[V(x, y, z; \theta)] + T(\theta) \geq V_0(\theta), \quad \forall x, y, \theta.$$
\[ \sum_{\theta \in \Theta} T(\theta) = -E_z[C(x, y, z)] \forall x, y, \]

where \(E_z\) is expectation w.r.t. \(F(z)\), where \(T(\theta)\) is the transfer payment to stakeholder \(\theta\), and where \(V_0(\theta)\) represents status quo utility for \(\theta\). If \(T(\theta) < 0\), then stakeholder \(\theta\) contributes \(-T(\theta)\) to pay for the facility. If \(T(\theta) \geq 0\), then \(\theta\) receives \(T(\theta)\) in compensation.

Expression (2) is the traditional efficiency criterion of maximizing total net benefits; i.e., the socially optimal choice of \((x, y)\) is that which maximizes the ex ante expected total benefits, represented as the aggregate willingness-to-pay by stakeholders (the first term in (2)), minus the expected social cost of the option \((x, y)\).\(^4\) Equation (3) states that all stakeholders must be compensated at such a level to at least maintain their status quo utility level \(V_0\). Equation (4) states that sufficient monies are collected to pay for the expected cost of the facility. We express this in ex ante terms, which would be appropriate if all risks from the facility were insurable, with insurance costs incorporated in \(C(x, y, z)\).\(^5\)

It is straightforward to characterize a formal solution to the siting problem, Equations (2)–(4). In effect, this problem embodies two separable problems. First is the problem of determining a net benefit maximizing option \((x, y)\) which solves (2). Given the solution \((x, y)\) to this problem, the optimal \(T(\theta)\) are derived which solve (3) and (4) and perhaps other criteria relating to equity. There may be many feasible sets of transfer payments \((T(\theta): \theta \in \Theta)\), especially if the aggregate net benefits at the optimal \((x, y)\) solving (2) are large. Alternative sets of transfer payments \(T(\theta)\) will give rise to alternative Pareto solutions to the siting problem. By summing both sides of (3) and using (4), it can be seen that if there is no solution satisfying (3)–(4) at the optimal solution to (2), then none of the available options dominate the status quo. In that case, of course, no facility should be sited.

The formal approach just described for solving (2)–(4) does not indicate how the siting process should be managed nor how negotiations with various stakeholders should take place to ensure successful implementation. These process management issues are very important as noted in Section 3 above and as we will discuss further below. However, the formulation of the siting problem (2)–(4) does contain important insights on the overall siting problem:

(i) The socially optimal solution solving Equation (2) implies minimizing expected cost for a given level of risk as measured by aggregate willingness-to-pay (WTP). In particular, if it is assumed that \(V(x, y, z; \theta)\) depends on \((x, y, z)\) only through some facility parameter such as expected (or, alternatively, worst case) risk to stakeholder \(\theta\), then the solution to (2) can be represented as

\(^4\) For a more detailed analysis of the foundations and implications of this kind of applied welfare analysis, see Crew & Kleindorfer [1986, Chapter 2]. There it is noted that the quasi-linear preferences assumed here (i.e., the willingness-to-pay form of preferences (1)) are a good approximation to more general preferences under fairly weak assumptions. For a general analysis of location problems in the context of spatial games, see Laing & Slootz [1994].

\(^5\) It is easy to represent governmental subsidies in this framework, e.g., to cover the costs or in the form of indemnity guarantees. One simply defines the government as a stakeholder with ex ante willingness-to-pay \(V_0 = S\), where \(S\) is the maximum subsidy available.
minimizing expected cost subject to risk exposure constraints for each stakeholder \( \theta \) and across all stakeholders. Transfer/compensation payments at the associated solution to this problem would then assure that (3) and (4) were satisfied. The OR literature we review below provides a framework for solving this class of problems. In particular, tracing out the solution to (2) for various individual and social risk levels allows the planner to determine the efficient risk–cost frontier. If aggregate WTP does depend on the assumed risk parameters, this is quite appropriate. Using this approach, the socially optimal solution to (2)–(4) is just the point on the efficient risk–cost frontier at which incremental costs and risks just balance one another, or equivalently at which the aggregate WTP for risk reduction just equals the incremental expected cost of such risk reduction.

(ii) It is important to note that solving Equation (2) explicitly requires that the siting planner understand the various stakeholders’ WTP for various siting and transportation options, and related risk mitigation procedures. Because, as noted in Section 2 above, obtaining such information is difficult, it may be important to use a decentralized approach that allows communities to ‘bid’ for the right to be the host community for a facility having certain risk characteristics. Such decentralized negotiation and bidding processes work best for simple, single-facility siting problems. When multiple facilities or complex transportation problems are involved, the use of value-elicitation and OR-siting techniques to map out efficient solution possibilities along the lines of (i) become imperative, at least to structure the efficient options.

(iii) In Equation (2), we assume implicitly that stakeholders have common beliefs about the likelihood of occurrence of uncertain states of the world \( E_2 \) does not depend on \( \theta \)). This formulation can be generalized to allow heterogeneous beliefs. In practice, the issue of determining stakeholders’ ex ante beliefs and their impact on WTP is difficult, as discussed earlier.

(iv) Finally, it should be clear that (2) represents a first-best solution. Not only is the best facility \( x^* \in X \) selected, but it is also assumed that the optimal risk mitigation option, i.e., the \( y^* \in Y \) solving (2), can be implemented. In reality, this option may depend on individual actions by stakeholders and may not be centrally enforceable.

The above problems make clear why the siting problem, even in theory, is difficult. What is required is a siting process which encourages all stakeholders to understand their preferences and beliefs, together with the siting options available, and to work together to determine a feasible and cost-effective solution to (2), including compensation or transfer payments among stakeholders to ensure that all stakeholders gain from the siting option chosen. In this process, OR models can play an important role by structuring and evaluating the tradeoffs among various risk categories and across stakeholder groups.

In what follows, we consider the contributions of OR to the siting problem under three headings: transportation problems, extensions of facility location problems to deal with risk, and decision analysis methods for evaluating alternative sites. After a review of the contributions of OR modeling in these three areas, we return to process and legitimation issues in the final section of the
chapter. There we examine recent research on coordinating risk analysis and cost reduction methods with negotiation processes for siting. Throughout, we emphasize the importance of OR models and support systems in improving the overall siting process by encouraging informed participation of all stakeholders and by assuring that cost-effective options are considered through use of appropriate OR methodologies to evaluate risk–cost tradeoffs.

5. Transportation of hazardous materials

Hazardous materials transportation problems in the OR literature are concerned with determining the optimal routing and transport modes to minimize several criteria involving expected cost and consequences of accidents. Demands and supplies are usually taken as given, as are the sites of facilities involved (we will relax this last assumption later). The hazardous materials in question can be either dangerous goods (e.g., sulfuric acid or chlorine) or hazardous wastes (e.g., radioactive waste). Two, sometimes overlapping, perspectives are evident in the literature: a profit-maximizing firm’s perspective [Kleindorfer & Vetschera, 1989; List & Mirchandani, 1991] or a regulator’s perspective [Glickman, 1991; Revelle, Cohon & Shobrys, 1991].

The firm’s problem. Which routes and modes should be chosen to minimize the expected costs of transporting the hazardous materials in question subject to observing various regulatory restrictions, e.g., avoiding various routes or transport modes?

Regulator’s problem. Given predicted choices by firms, what are their consequences in terms of property damage, deaths and injuries caused by transportation accidents and which regulatory policies optimize some multi-criteria objective function defined in terms of these aggregate consequences for a given region and given hazardous substance?

Following the literature [e.g., Turnquist & Zografos, 1991], we consider a general problem encompassing both of the above problems. We assume the transport firm is an organization with a multi-criteria objective (which may involve profits, social objectives, equity objectives, risks, etc.) for evaluating its route and mode decisions, and we consider the problem of determining the set of nondominated solutions for this problem.

A typical methodology is to first model the consequences of a given accident (e.g., as in Kleindorfer & Vetschera [1989] and Institute for Risk Research [1986]) at a given location in the specified region. These models can be very detailed and are useful in investigating for a particular type of accident such issues as plume dispersion, paths of risk exposure, and so forth, together with implications for risk mitigation and emergency response. These location-accident-specific models

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6 This section is based in part on Kleindorfer & Vetschera [1989].
7 As a reviewer points out, many OR models can be used to investigate both the firm’s as well as the regulator’s perspective, by customizing the optimization criterion or by exercising the model suitably.
are also useful as the starting point for modeling aggregate consequences along a route or across a set of routes, modes and locations [e.g., Glickman, 1991; List & Mirchandani, 1991]. Considerable complexity and uncertainty arise at all levels in this evaluation of transport risks because of the current inexact knowledge and available data concerning such risks. Nonetheless, the consequences of various scenarios can be evaluated in sufficient detail to perform useful policy evaluation.

The following major policy areas are related to hazardous materials transportation [cf. Hommel, 1983; O'Hare, 1987]:

- Definition and classification issues (e.g., wastes may be classified as toxic, corrosive, flammable, etc.);
- Routing restrictions (e.g., transport on certain roads may be prohibited);
- Mode restrictions (e.g., transport by truck may be prohibited);
- Packaging regulations;
- Frequency and hours of permitted carriage;
- Liability rules and financial/insurance requirements;
- Restrictions on who may carry the substance in question;
- Labeling procedures and documentation;
- Notification procedures in the event of an accident;
- Emergency response procedures in the event of an accident.

Of the above policy options, the OR literature has been primarily concerned with evaluating alternative routing and mode selection issues to satisfy a scenario where a fixed amount of goods must be supplied to satisfy known demand. The evaluation of regulatory policy options to influence the decision processes of transport firms can then be evaluated in terms of their consequences on firms' route-mode decisions and resulting accident and economic consequences. We will only be concerned here with route-mode selection issues and marginally with liability and insurance.\(^8\)

Route and mode decisions are represented in the following framework. Let \(X\) be a set of feasible transportation alternatives, i.e., various combinations of routes and modes in a given region. \(X\) can be influenced by regulatory policies, which for specific substances rule out one or another route or mode. Given \(X\), one can represent the transport firm's choice process for determining its preferred alternative \(x \in X\) as the solution to the multi-criteria minimization problem:

\[
\text{minimize}_{x \in X} \quad [f_1(x), f_2(x), \ldots, f_n(x)].
\]

We illustrate (5) for the simple case in which the firm is only concerned with minimizing the expected cost of its transport activities, including liability

\(^8\) As noted in Kleindorfer & Vetschera [1989], the other policy areas noted above can be dealt with by evaluating alternative scenarios as data input to routing and mode selection routines. Consider, for example, the area of container safety. Changes in container requirements can be expected to affect significantly the probability that a transport accident will lead to package ruptures and spillage. Impacts of container policy options can thus be represented by modeling the stochastic accident consequences of alternative packaging constraints along feasible route-mode choices. For an example, see Glickman [1991]. For a discussion of liability issues, see Watsabe [1991].
costs from accidents. Let \( L(x, I) \) be the expected net liabilities or monetary damages the firm believes it will incur when required insurance coverage is \( I \) and alternative \( x \) is chosen, and let \( C(x) \) be the out-of-pocket transportation costs for using alternative \( x \). The total expected cost for the carrier is the sum of transportation costs plus expected liabilities, i.e.:

\[
TC(x) = L(x, I) + C(x).
\]  

(6)

The difficulties involved in evaluating hazardous transportation policies arise primarily in the evaluation of \( L(x, I) \), a complex random variable which must be obtained through spatial integration of the consequences of accidents along the route-mode selection \( x \) [cf. Kleindorfer & Vetschera, 1989; List & Mirchandani, 1991]. In the simplest case where an accident can occur along only one segment of a route, say with probability \( P(x) \), we can compute the expected liability of the firm from transport activities as follows:

\[
L(x, I) = P(x) \times (\max[H(x) - I(x), 0]).
\]  

(7)

where \( I(x) \) is the amount of insurance coverage for a carrier serving alternative \( x \), and where \( H(x) \) represents the value imputed by the firm to all economic, environmental and health effects of accidents along the given segment \( x \). These perceived costs may not coincide with actual assessed damages for property and health effects. They simply reflect what the firm believes will be its assessed damages, e.g., based on prevailing court awards for injuries and accidental deaths, if an accident occurs.  

Thus, for the expected cost minimizing transport firm, the following problem results:

\[
\text{minimize}_{x \in X} \quad [L(x, I) + C(x)] = P(x) \times (\max[H(x) - I(x), 0]) + C(x).
\]  

(8)

Note that both the feasible set \( X \) and the perceived liabilities \( L(x, I) \) faced by the firm depend on policy choices. We summarize in Figure 1 the various policy options and the logic by which these are translated into operational route and mode selection decisions. Note that the logic here is to determine the

9 Note that if \( I(x) \geq H(x) \), insurance coverage is sufficient to cover the total damages resulting from the accident and the firm therefore faces no residual liability, i.e., \( L(x, I) = 0 \). Note also that much more complex hazard distributions than our Bernoulli example could be considered [see, e.g., Kleindorfer & Vetschera, 1989], but the logic would be analogous. Note finally that we are treating insurance in this model as a fixed cost of doing business. Insurance decisions could also be treated as a decision variable, and these would likely depend on such matters as the firm's asset base, risk preferences and the existing transport risks as embodied in \( x \) and \( L(x, I) \). For a discussion, see Kleindorfer & Kunreuther [1987] and Watabe [1991].

10 The idea of perceived costs implies that there may be a wide variety of firm decision processes for route/mode selection. On the one extreme, the firm might only consider transport costs \( C(x) \), making its decisions as if it believed \( H(x) \) were identically zero. On the other extreme, a firm might impute very high values to health and environmental damages resulting from its decisions. See Kleindorfer & Kunreuther [1987] for further discussion.
optimal route-mode for a single shipment between a given origin and destination. Aggregating these individual choices across all origin–destination pairs then yields the predicted consequences of the assumed supply–demand scenarios for the regulatory policies under study.

From the above description, we note that there are several levels of analysis related to hazardous materials transportation. These range from detailed location-specific models to aggregate models of the regional or national impacts of transport risks in a particular hazardous materials sector. We now consider a few of the OR contributions at several points along this spectrum.

5.1. Single-location accident evaluation models

At the very micro level of analysis is a description, typically in fault-tree form, of specific consequences of accidents resulting from route-mode choices, at specific locations, and with assumed weather and population exposure conditions (see Figure 2 for an illustration). This detailed level of analysis is especially useful for risk mitigation (e.g., improving emergency response programs or vehicular safety systems). For an introduction to risk management for hazardous materials transportation, see Yagar [1984], Institute for Risk Research [1986], and Saccomanno & Chan [1985].

5.2. Route-mode evaluation and choice models

At the next level of detail, route-mode evaluation models can be used to determine a good (undominated set of) route(s) for a given transport activity,
characterized by the amount and type of substance involved and the fixed points of origin and destination. Typically, such models first generate a set of feasible transportation alternatives in terms of geographical routes, transport modes on sections of the routes and vehicles. A detailed cost and risk analysis is then performed for all alternatives and dominated alternatives are eliminated to arrive at (an appropriate subset of) undominated solutions to Equation (5).

The problem of determining efficient transport alternatives can formally be interpreted as a multi-criteria shortest path problem. Several algorithms were developed in the literature to solve this class of problems [cf. Corley & Moon, 1985; Habenicht, 1982; Hansen, 1980; Martins, 1984]. Generation of all efficient alternatives via these algorithms is, however, usually not practical and various heuristics have been developed. As an example, consider the 3-phase heuristic procedure developed by Kleindorfer & Vetschera [1989] (see Figure 3).

In the first phase, the heuristic generates a set of $K$ alternative candidate paths (for the given origin–destination pair) in the underlying transport network\(^{11}\), where each path is characterized by a route and the modes and vehicles used.

In the second phase of the heuristic, the risk and cost of each path generated in

\(^{11}\) The transport network can be thought of as an undirected graph, consisting of arcs and nodes. Nodes represent geographical locations and points of interchange between arcs. Arcs represent transport possibilities between locations. To obtain a unified structure for analysis, all costs and risks considered are assumed to occur along the arcs. Therefore, arcs are used not only to represent physical transportation between different locations, but also for loading and mode change activities entailing risks or costs.
the first phase is evaluated. This evaluation covers costs of physical transportation, insurance costs and liabilities as described above. The risk analysis evaluates both losses in the form of material damage and health risks to the population through injuries and fatalities. The evaluation covers the stochastic nature of losses (e.g., in terms of expected values, variances, and maximum probable losses) and could be extended to uncertainty analysis as well [e.g., Glickman, 1991].

In the third phase of the heuristic, dominated alternatives are eliminated, using the criteria vector \( f_1(x), f_2(x), \ldots, f_r(x) \) for each alternative generated in the evaluation phase. The result of the third phase is a set of undominated alternatives in terms of risk and cost criteria. A selection can be made directly from this set for a given origin-destination (O–D) pair, e.g., interactively by the decisionmaker. Alternatively, undominated sets for each O–D pair (and substance) can be input into an aggregate planning system for overall regional planning.

5.3. Regional transportation risk evaluation models

In the aggregate mode of analysis we are no longer directly concerned with route and mode selections for each transport activity and O–D pair, but with the aggregation of route-mode selections in a given region or market area, typically for a given hazardous substance. Several levels of complexity are possible here.

At the simplest level, assumptions are made about the volumes to be transported between each O–D pair and what choices transport firms will make from the undominated set of route/mode paths, e.g., minimizing total expected costs subject to regulatory constraints. This yields for each O–D pair and substance a specific route/mode outcome, which can be integrated spatially over all outcomes to yield aggregate outcomes for the region.

At the next level of complexity, the problem of minimizing the multi-criteria

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\[ ^{12} \text{See List & Mirchandani [1991] for additional analytic models of integrated path costs and risks.} \]
objective function (5) can be posed for a number of O–D pairs (e.g., the problem of satisfying chlorine demand within a region from a number of production sites, while minimizing a vector or risk–cost attributes).

For either of the above two problems, additional complexities arise in assuring equitable distribution of risks, e.g., minimizing the maximum exposure of any given segment of the population to mortality risks from accidents. This equity balancing might require choosing a number of paths between any given O–D pairs in order to reduce exposure to segments along, say, a major thoroughfare. See Lindner-Dutton, Batta & Karwan [1991].

At the next level of complexity, one can alter regulatory constraints on routing, modes, and other policy variables to mitigate aggregate risks, evaluated at the pattern of choices emerging from the above models. See Kleindorfer & Vetschera [1986].

We have taken siting decisions as fixed in the above discussion. It is clear that an additional level of complexity arises when some flexibility is possible for the sites of sources and sinks of the hazardous materials in question (e.g., when chlorine production sites or radioactive waste disposal sites can be determined as part of the analysis). Even more generally, one would like to integrate these siting and transportation problems to sectoral economic problems, such as solid waste management [e.g., Wilson, 1981]. These problems require at a minimum that we consider the general problem of simultaneous siting and transportation routing decisions.

6. Facility location models for hazardous facilities\textsuperscript{13}

In this section, we review of the facility siting literature for hazardous or noxious facilities, including simultaneous choice of routing and facility choices. The problem of evaluating simultaneous siting and routing decisions is not that much different in principle from that of routing alone, especially in regard to building up from detailed location-specific modeling to more global, aggregate risk–cost tradeoffs. Of course, the simultaneous siting–routing problem can be much more complex, for both computation and ensuing policy analysis, when there are several potential sites for facilities.

Much of this literature on modeling hazardous facility location choices builds on the basic approach of solving multi-objective location models to determine the efficient risk–cost frontier. A policy decision can then be made as to the appropriate tradeoff on this frontier between risk and expected cost. To illustrate, we begin with the ReVelle, Cohon & Shobrys [1991] model for the routing and siting problem and build on this to discuss other contributions.

To make matters transparent, we will consider only two objectives in our formulation, a cost and risk objective. We will also state this problem in the

\textsuperscript{13} This section is based in part on the excellent surveys available in Wilson [1981], Curren, Min & Schilling [1990], and List, Mirchandani, Turnquist & Zografos [1991].
context where most work has been done, namely for hazardous wastes. In this
case, we assume that there are a set of \( n \) possible origins with known locations
and a set of \( m \) possible sites for waste disposal. The multi-objective (hazardous
facility) siting problem can then be stated in the form of the classic warehouse
location problem as follows:

\[
\begin{align*}
\text{minimize} & \quad \sum_{j=1}^{m} \sum_{i=1}^{n} w_{ij} x_{ij} + f_j y_j \\
\text{subject to} & \quad \sum_{j=1}^{m} x_{ij} = 1, \quad \forall i \\
& \quad x_{ij} \leq y_j, \\
& \quad x_{ij} \in \{0, 1\}, \quad y_j \in \{0, 1\}; \quad \forall i, j
\end{align*}
\]

where

\[
i = \text{index of sources/origins; } i = 1, \ldots, n; \\
j = \text{index of eligible destinations; } j = 1, \ldots, m; \\
w_{ij} = \lambda c_{ij} + (1 - \lambda) r_{ij}, \text{ a weighted sum of the cost (} c_{ij} \text{) and risk (} r_{ij} \text{) of using} \\
\text{destination } j \text{ for source } i \text{ wastes, where it is assumed that variable cost of} \\
\text{using } j \text{ for source } i \text{'s wastes are included in } c_{ij}; \\
\lambda = \text{weight between 0 and 1 associated with the cost objective versus the risk} \\
\text{objective; } f_j = \text{fixed cost, on say an annualized basis, for constructing, operating and} \\
\text{maintaining facility } j; \\
x_{ij} = \text{a 0–1 variable: 1 if the destination } j \text{ is used for source } i \text{ and 0 if not; } \\
y_j = \text{a 0–1 variable: 1 if site } j \text{ is selected to construct a facility and 0 if not.}
\]

Let us note a few characteristics of the above problem. First, it is assumed
that the cost \((c_{ij})\) and risk \((r_{ij})\) of a particular origin–destination (O–D) pair
are determined as an input to this optimization problem. This is accomplished by
determining a set of feasible, candidate routes for each O–D pair using the
detailed evaluation models described in Section 5 above [see Kleindorfer &
Veischera, 1989; List & Mirchandani, 1991]. In this sense, combined analysis of
routing and siting builds on the more detailed cost and risk assessment models of
hazardous materials transportation described earlier. Note that as the weighting
constant \(\lambda\) varies from 0 to 1, alternative points on the efficient risk–cost frontier
will be traced out, where risk in this model is assumed to be some additive
measure of siting risk such as expected fatalities or expected number of individuals
exposed to accidents along all routes.\(^{14}\)

\(^{14}\) Non-additive measures of risk such as worst case fatality or exposure risks could also be
included, but these would be represented in minimax form across routes and facilities. Such
non-additive measures are especially important in representing equity issues such as the maximum
exposure or risk of any individual or group [see, e.g., List & Mirchandani, 1991].
Second, it should be noted from Equation (10) that the above model assigns only a single route to each O–D pair. More complex models are possible which would allow waste shipments from a given origin to be split among several disposal sites [e.g., List & Mirchandani, 1991; Wilson, 1981]. In the same spirit, we have suppressed the details of the amount of hazardous materials originating at source \( i \). In the event of split shipments to multiple destinations, these details would have to be represented. This is accomplished in standard transportation model format by representing cost in a per unit fashion, with total cost for a given O–D pair then proportional to the number of tons shipped from \( i \) to \( j \).

Third, the number of facilities \( j \) could also be constrained by appending an appropriate upper bound on the sum of the \( y_j \)'s. In the simplest case, only a single facility might be allowed.

When used in association with an appropriately rich model of transportation risks, this class of models provides interesting insights into cost–risk tradeoffs. These models have been used for a host of planning problems (see Wilson [1981] for a review of the early literature), regional solid waste management models (see Gottlinger [1988]), and for a number of environmental and cost–risk evaluation problems (see Current, Min & Schilling [1990] for a review). In the typical application, e.g., List & Mirchandani [1991], the weighting parameter \( \lambda \) is varied from 0 to 1 to assess the nature of jointly optimal facility siting and routing decisions for the pure cost-based solution (\( \lambda = 1 \)), the minimum risk solution (\( \lambda = 0 \)), and various middle-ground alternatives (\( 0 < \lambda < 1 \)).

The above problem statement is in the context of a single hazardous waste. This is easily extended to deal with multiple waste streams [e.g., Wilson, 1981]. Similarly, transfer stations and resource recovery facilities can be included with slightly more complex objective and constraint structures [e.g., Gottlinger, 1988]. Such transfer facility problems require in particular the introduction of additional 0–1 location variables to represent the choice set for transfer/resource recovery facilities. This problem has been of special interest recently since many municipalities have found themselves short of solid waste disposal capacity and have therefore had to resort to using regional disposal alternatives. In this context, the economics of compaction, bulk transport and resource recovery are, of course, of considerable import.

A final related context worth noting is that of hazardous materials routing–siting problems in which destinations represent market areas (e.g., for chlorine or some other hazardous good) and origins represent supply points (e.g., plants producing chlorine). A very similar version of the above problem would then apply in trading off cost and risk of assigning various market areas to various supply facilities, with associated cost–risk efficient routing between supply and demand points [Batta & Chiu, 1988; List, Mirchandani, Turnquist & Zografos, 1991].

As noted, while risk is included in models such as the above, the assessment of risk (in the form of the \( r_j \) parameters) is actually an input to this formulation. While this is arguably appropriate for aggregate routing and siting evaluation, it should also be clear that it neglects the details of risk perceptions and evaluation of risks across stakeholder groups. Only aggregate expected risk measures can be
7. Siting facilities using decision analysis

Decision analysis (DA) has proven to be a useful approach for structuring the siting problem and has been applied in a number of different contexts (see Keeney & Raiffa [1976] and Keeney [1980] for illustrative examples). DA is a prescriptive approach which suggests a formal procedure for making good siting decisions. It requires the concerned parties to structure the problem so that they can compare a set of alternatives on the basis of a systematic analysis of the impact that the site will have on different performance measures. The DA approach to the problem has a well defined set of steps that are summarized and illustrated below. These steps may be viewed as providing a structured solution to the formal problem (1)–(4) stated above. We will use the notation introduced earlier.

7.1. Step 1. Specify the alternatives

The typical site selection problem involves the selection of a particular location \( x \) from a set \( X \) of different alternatives (including the status quo) using a number of different criteria to choose between them. In determining what alternative to choose, there are many concerns which play a role in the process. As pointed out in Section 2 there are likely to be conflicts between the objectives of the different interested parties which may be difficult to reconcile. Each proposed alternative will be attractive to some groups and is likely to be unattractive to others.

7.2. Step 2. Specify the set of objectives and measures of effectiveness

For the siting of noxious facilities the objectives normally revolve around economic considerations, health and safety features as well as environmental concerns. A growing literature has emerged in recent years as to how one structures objectives into a hierarchy so that one can better understand the key factors which guide the choice process [Keeney, 1992; Von Winterfeldt & Edwards, 1986]. Each objective \( j = 1, \ldots, n \) is then translated into a performance measure that can be measured quantitatively using a specially constructed scale.

Let \( A_j \) represent a vector of performance measures related to objective \( j \). An example of a quantitative performance measure would be the estimated cost of the facility (in dollars). A qualitative performance measure might be the environmental impact of a proposed site using a 0 to 6 scale (where 0 would be no impact and 6 significant damage to certain species). In terms of the problem (1)–(4), this step in DA is concerned with the structure of the WTP preferences in (1) and, in particular, with determining an operational set of measures \( A_j \) such that \( V \) in (1) can be expressed as:

\[
V(x, y, z; \theta) = V[A_1(x, y, z), A_2(x, y, z), \ldots, A_m(x, y, z); \theta]
\]  
(13)
7.3. Step 3: Specify a set of scenarios affecting the performance measures

The states of the world $z$ in (1)-(4) are referred to as 'scenarios' in siting applications of DA. Constructing scenarios which depict a set of events that might occur at a particular site is a highly subjective process. It involves indicating the nature of specific risks that are associated with a particular site and the specification of the probabilities of such risks actually materializing.

Systematic procedures such as fault trees and event trees have been utilized for constructing scenarios for complex events [see Von Winterfeldt & Edwards, 1986]. However, there is often considerable variability across experts in characterizing the probabilities of these scenarios occurring due to the lack of past data and differences in assumptions which guide the analysis. For example, in the analysis of the risks associated with siting liquified natural gas facilities there was considerable discrepancy on the chances of specific accident scenarios by different experts [Kunreuther, Lathrop & Linnerooth, 1982]. There are also likely to be specific biases in estimating probabilities [Kahneman, Slovic & Tversky, 1982] that must be recognized when undertaking these analyses.

Ideally there will be a set of probabilities and outcomes associated with each scenario $z$ for each specific site $x \in X$. These might be the result of consensual agreement if there is sufficient statistical data upon which to base these estimates. Let $P(A_1, \ldots, A_m | x, y, z)$ represent the probability that scenario $z$ will occur at site $x$ when control procedures $y$ are used and yield outcomes $A_1$ on each of the $m$ performance measures associated with evaluating the site. In practice there will be significant differences between the experts for reasons stated above and it may be hard to reconcile these differences. In this situation it may be necessary to analyze the impact of different estimates of $P(A | x, y, z)$ on the performance of alternative sites, where $A = \{A_1, \ldots, A_m\}$.

The nature of the scenarios constructed by any one expert will differ depending on the nature of the siting questions being raised. For example, the key issue may be the uncertainty of the cost of specific siting proposals in which case a set of scenarios will be constructed which focus solely on this performance measure and assign different probabilities to different estimates of the costs for each site $i$. The other performance measures will either not be considered in this portion of the analysis or are set at some arbitrary level (e.g., mean outcome). Other scenarios will focus on the impact of different events that might occur at the site (e.g., an accident, leakage of toxic waste) and its impact on different measures. In this case the cost of facility $i$ may be specified at some level (e.g., best estimate). If the probability of an accident occurring is affected by the cost of the facility then these interactions should be built into the scenario construction [Schoemaker, 1991].

7.4. Step 4: Assessing the values of different stakeholders

The relationship between different performance measures in constructing scenarios depends on the utility function of the different interested parties, i.e., on the structure of $V$ in (13). There is a large literature on the assessment of multi-
attribute utility functions or value functions for siting problems [Keeney, 1980]. Two extreme cases highlight some of the challenges associated with this step in the decision analysis process.

At one end of the spectrum is the case where there is a single stakeholder who has final authority to make a decision and attempts to reflect the concerns of all the relevant stakeholders in constructing a multi-attribute utility function. For example, if the state feels it has the authority to site a facility and can impose its will on the citizenry then one would want to assess the state’s utility function (as represented by a policymaker) in undertaking a decision analysis. The key steps in such a process would be to determine the degree and nature of independence among the different performance measures [Keeney & Raiffa, 1976], assess the utilities for different measures (e.g., health effects, costs) and determining the scaling factors which reflect the relative importance of the different performance measures comprising the utility function.

At the other end of the spectrum is the case where many stakeholders are involved with a particular siting problem. It may then be useful to understand how \( V(x, y, z; \theta) \) varies across stakeholders \( \theta \) by developing utility functions for each important stakeholder group (i.e., for each \( \theta \in \Theta \)). A value tree is the elicitation or construction of a formal value structure by indicating the importance of different objectives and their performance measures. Value trees can be constructed for each individual stakeholder (or for a representative sample of stakeholders) and then combined into a joint value tree based on the concerns of all the parties [Von Winterfeldt, 1987]. At the end of this process there are still likely to be differences in the importance placed on specific performance measures by different stakeholders. This type of information will enable the parties to investigate alternative solutions to the siting problem to see if they can arrive at compromises.

7.5. Step 5: Evaluating alternative sites

In this stage of the process one can evaluate the expected net benefits of different sites. Although each siting problem has its own special characteristics there are two general approaches to the problem of determining the optimal site from a set \( X \) of possible alternatives.

7.5.1. Simultaneous selection process

If there are no fixed costs associated with obtaining detailed data on the site and interacting with the relevant stakeholders then it will always be optimal to consider the \( m \) different sites simultaneously and determine the one which maximizes expected net benefits where net benefits takes into account economic, health, safety, and environmental considerations. Let \( E(B(x)) \) represent expected net benefits of site \( x \), where \( E(B(x)) \) is determined in theory as the solution to (2).\(^5\) Figure 4 depicts a highly simplified decision tree for a siting problem where

\(^{15}\) We neglect here the determination of site-specific mitigation measures \( y(x) \).
there are \( N \) possible sites \( x_1, \ldots, x_N \) so \( X = \{x_1, \ldots, x_N\} \). As before, we assume a set \( Y \) of risk mitigation measures and a set of scenarios (or states of the world) \( Z = \{z_1, \ldots, z_K\} \). We denote by \( P(A \mid x, y, z) \) the probability of occurrence of the outcome vector \( A = \{A_1, \ldots, A_m\} \), given the option \((x, y)\). The resulting outcome on the different performance measures is evaluated using multi-attribute utility functions of the different stakeholders. As shown in Figure 4, if site \( x \) is selected and risk mitigation measures \( y \) are implemented, then the utility outcomes for the different stakeholders under scenario \( z \) are given by (1), that is:

\[
U(x, y, z, M; \theta) = V(x, y, z; \theta) + M,
\]

where \( V \) is given in Equation (13) and \( M \) may be adjusted with compensation payments \( T(\theta) \) as in (3) and (4).

There is limited discussion in standard DA as to how one combines these utility functions if there are significant differences between the stakeholders.\(^{16}\) The use of value tree analysis is one approach for recognizing that the weights associated with different performance measures may differ across stakeholders and proposing compromise options that are attractive to the opposing stakeholders. In the end there may still be conflicts among the parties which may then require other procedures for attempting to resolve. Value trees may diagnose the nature of the conflicts but their usefulness in actual conflict resolution has still to be proven [Von Winterfeldt, 1987].

\(^{16}\) Under the standard assumption of quasi-linear preferences (see (1)), aggregation across stakeholders is straightforward in theory. One needs only sum WTP across stakeholders, using transfer payments as in (3) to assure status quo levels of utility. In practice, of course, a host of complicating factors arise to hinder this process, not least of which is the determination of the WTP for each stakeholder, but also including considerations of equity as discussed above.
7.5.2. Sequential selection process

If there are substantial fixed costs\(^\text{17}\) of characterizing each potential site, then it may be more desirable to sequentially examine the sites. Now one needs to define net benefits for any site before any information is collected on the details of the site. Let this be represented as \(E[B(x_i | 0)]\). After characterization one may learn considerably more about the nature of the problems at this particular site. Cost estimates of the process will be more precise and the political dynamics may be clarified. This new state of knowledge for site \(i\) is represented by \(E[B(x_i | 1)]\).

If \(F\) is the fixed cost associated with initiating the siting process in any location, then a sequential process will initially save \((N - 1)F\) by only looking at one site. Suppose that the sites are ordered by when they will be characterized so that site 1 is initially selected, site 2 would be next in line and site \(N\) last in line. If some potential locations already have more noxious facilities in their vicinity than others then for equity reasons they may be placed towards the end of the line. Other locations which appear to be particularly well suited physically to host the facility may be towards the beginning of the line.

A second site would only be characterized if new information were collected after examining site 1 which indicates that \(E[B(x_2 | 0)] - F > E[B(x_1 | 1)]\). Denote the probability of this occurring was \(q_1\). Site 3 will only be characterized if site 2 is examined and it is determined that \(E[B(x_3 | 0)] - F > E[B(x_2 | 1)]\).

Figure 5 depicts the sequential process and specifies the expected net benefits at each stage of the process. Note there is always some chance that a simultaneous

\[q = \text{Probability that } E[B(x_{n-1} | 0)] > E[B(x_n | 1)] + F\]

Fig. 5. Sequential site characterization.

\(^{17}\) See Keeney [1992] for a discussion of some of the costs of site evaluation. See Kunreuther, Easterling, Desrouges & Slovic [1990] for a detailed discussion of these in the context of the Yucca Mountain site evaluation for a high-level nuclear waste repository.
process will discover a facility with a higher net benefit than if one followed the sequential process. However, if $F$ is sufficiently high, then such a process cannot be justified *ex ante* if one used the criterion maximize expected net benefits. For example, Keeney [1987] has compared sequential and simultaneous procedures to determine which site(s) should be characterized for locating a high-level nuclear waste repository. He recommended a sequential procedure due to the very high costs of characterization ($1$ billion per site).

### 7.6. Process issues in siting facilities

Decision analysis can play an important role in clarifying the objectives of the relevant stakeholders concerned with a particular siting problem, characterizing their similarities and differences as well as evaluating the performance of different sites. At the end of the process it may reveal substantial conflicts between the groups which cannot be resolved through this type of formal analysis.

#### 7.6.1. Siting the high-level nuclear waste repository

A case in point is the selection of a site for the first high-level nuclear waste repository. The search for a permanent means of disposing high-level nuclear waste originated in the mid 1950s when it became apparent to members of the Atomic Energy Commission that the temporary and makeshift methods of disposal were inadequate. The pressure to find a permanent means of disposal of civilian waste intensified in the 1970s and culminated in the passage of the Nuclear Waste Policy Act (NWPA) of 1982.

The NWPA recognized that a repository would not be politically acceptable to a host state unless the state had itself undertaken actions that assured citizens of the safety of the facility and the suitability of the local site [Colglazier & Langum, 1988]. The actual process of site selection has deviated considerably from the objectives of the NWPA. More specifically, the Department of Energy (DOE) developed a set of general guidelines for evaluating possible repository sites which explicitly consider public health and safety, environmental, and socioeconomic considerations.

On the basis of these guidelines DOE selected five sites as suitable for housing a repository. The procedures used by DOE were criticized by a number of groups including a letter from the National Academy of Sciences (NAS) calling their methods ‘unsatisfactory, inadequate, undocumented and biased’ [Merkhofer & Keeney, 1987]. As a result of these concerns, DOE elected to evaluate the five nominated sites based on multi-attribute utility analysis (MUA) in order to rank the top three sites.

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18. In this situation three sites were considered by the Department of Energy to be potential candidates because they appeared to be geologically safe. However, there was considerable uncertainty as to the costs of constructing the facility. Characterization involves construction of an exploratory shaft to the proposed repository area, subsurface excavation and tunneling as well as other activities.
In May 1986 DOE provided a different ranking of the proposed sites than the one suggested by the MUA. Some of the factors which were ignored in the MUA but may have been important to DOE in its consideration of which sites to consider are the degree of local opposition and risk factors such as fear and anxiety, equity concerns and equity considerations [Merkhofer & Keeney, 1987].

The controversy on where to locate the repository took another turn in December 1987 when Congress amended the NWPA of 1982 by selecting Yucca Mountain, Nevada as the site which should be characterized for the repository. In essence Congress changed its position on siting from one of simultaneously characterizing three sites to a process whereby Nevada would be the site for the repository unless geologic flaws were discovered in the more detailed characterization process. If Yucca Mountain was declared unsafe then one of the other two sites would be characterized. Note that this siting process differs from the sequential procedure discussed in the previous section where sites already characterized remain potential candidates for a facility at all stages.

The reaction to the Congressional ruling produced strong opposition to the repository in Nevada. Not only did state officials as well as the citizenry feel that the process was unfair, but they perceived the risks of the repository to be unacceptably high even though DOE claimed that the repository would pose no risk at all [Kunreuther, Easterling, Desvousges & Slovic, 1990]. Scientific evidence supporting the public's concern was provided by one of DOE's staff geologists in Las Vegas, Jerry Szymanski, who has promoted the theory that Yucca Mountain is subject to earthquakes which might create problems of radioactive waste leaking into the groundwater [Marshall, 1991]. This theory has been disputed by much of the scientific community but has fueled considerable opposition to the repository [Easterling & Kunreuther, 1994].

The search for a place for the HLNW repository illustrates the dilemma facing society in siting the entire set of potentially hazardous or noxious facilities ranging from landfills and trash disposal plants to radioactive waste facilities. Even if there is general agreement by scientific experts that a new facility will reduce the aggregate risk over the status quo (e.g., temporarily storing nuclear waste in many different places) this information may have no meaning to the residents of the community or state where the facility is being proposed. From their perspective the risk to them is increased over the status quo and for that reason they would prefer to have the facility located elsewhere.

Preemptive legislation which enables the appropriate legislative body (e.g., Congress, state legislature) to specify a site location does not appear to be an effective strategy for ensuring that objectionable facilities are built. Morell & Magorian [1982] point out that in almost any siting controversy at least one stakeholder group will have some degree of de facto veto power. If a preemptive strategy has succeeded in any state we are unaware of it. In fact, states such as Massachusetts that have considered adopting preemptive strategies for locating hazardous waste facilities have abandoned them because they have recognized the ability of local officials to defeat an unwanted facility [Bacow, 1980]. The recent experience of Clean Harbors trying to locate a hazardous waste incinerator in
Braintree, Massachusetts reveals the power of citizen groups to stop a project which has been viewed by experts as scientifically sound and one that promised to reduce risks over the status quo [Brion, 1991].

The rather extensive literature on siting potentially hazardous facilities that has emerged in recent years has stressed the importance of fear by communities as a principal reason for opposing the siting of facilities. There are two types of fear which need to be distinguished: fear associated with health and environmental effects of the facility to whom personally as well as future generations and fear associated with economic impacts such as a decline in property values or unemployment.

Turning to concerns over health and environmental effects, studies of the public's perception of risks suggest that probabilities and loss magnitudes play a minor role in people's judgment of the severity of risks. Risk severity really depends on subjective features such as the voluntariness of exposure, familiarity, catastrophic potential and dread [Fischhoff, Slovic, Lichtenstein, Read & Combs, 1978; Slovic, 1987].

Nuclear waste repositories and hazardous waste facilities are perceived to be particularly dangerous because the public knows little about them and dreads the health impacts from any accident or leakage from the facility. A national survey of 1201 residents and a Nevada survey of 1001 individuals both revealed that average perceived risk from a HLNW repository is more serious than any of five other risks [Kunreuther, Easterling, Desvouges & Slovic, 1990]. A national sample of 400 citizens throughout the U.S revealed that 1/3 of them were opposed to having a hazardous waste treatment facility in their backyard because they felt it was unsafe and dangerous [Portney, 1991].

With respect to economic impacts citizens in communities selected to host disposal facilities have expressed concern that the facility will lower property values. There is some evidence that these declines have occurred with some noxious facilities [Metz, Morey & Lowry, 1990]. McClelland, Schultz & Hurd [1990] did uncover evidence of depressed property values in the vicinity of an abandoned hazardous waste dump. Greater reductions in property value were observed in areas with a higher perceived risk. Interestingly enough the perceived risk was related to odors which were viewed by the scientific experts to be harmless.

A region may be concerned with the possibility of stigma effects from a proposed facility and hence oppose it on this ground. In the case of hazardous or nuclear waste the region may be concerned with having an image of a 'wasteland' that may discourage new businesses from entering the area or discourage consumers from buying products [Slovic, Layman, Kraus, Chalmers, Gesell & Flynn,

- Respondents were asked to rate the seriousness of the risks to them from six different sources on a scale of 1 (not at all serious) to 10 (very serious). The other 4 risks were home accident, job accident, nuclear power plants and nuclear weapons testing site. On the national level the nearby repository had an average perceived risk of 5.6 and an average rating of 5.2 for exposure to hazardous chemicals. Home accidents (the lowest rating) had a value of 3.9. The Nevada survey yielded perceived seriousness estimates that were slightly high for all risks.
1989]. In the case of a Multiple Retrievable Storage (MRS) facility, Tennessee refused to host the facility at Oak Ridge after considering the potential impact to economic development efforts in the eastern part of the state [Sigmon, 1987]. Agricultural communities in eastern Washington state opposed a nuclear waste repository at Hanford claiming that it would be perceived by the consuming public as contaminating fruits and wines grown in the area and hence cause a decline in the economy [Dunlap & Baxter, 1988]. The stigma and perceived risk of an HLH 66 repository (should it be constructed at Yucca Mountain) was viewed as adversely affecting future convention business [Easterling & Kunreuther, 1994] and tourism [Slovic, Layman & Flynn, 1991] in Las Vegas, 100 miles away from the proposed site.

7.7. Importance of equity and legitimacy

The siting of a noxious facility will have important distributional effects since certain groups and individuals will gain while others will lose. These equity considerations play an important role in selecting the alternative sites as well as in deciding what type of siting process to follow.

In addition to the perceived costs and benefits of a given facility that can be evaluated by a DA framework there are often strong feelings as to whether it is fair to place the facility in my backyard. Morell & Magorian [1982] point out that people do not want to feel that they are being taken advantage of when asked to host a facility. One example which they provide to illustrate this point is the case of Starr County, Texas which refused to accept a hazardous waste landfill even though they agreed that it did not pose any risks. The residents in the community were poor and felt they had been exploited by wealthier areas of the state.

O'Hare, Bacow & Sanderson [1983] have argued that the different parties in the siting debate, in particular the proposed communities, must be convinced that the status quo is unacceptable. Easterling [1992] has suggested that residents of a community, region or state would be inclined to feel that the siting process was fair if they believed that the local site is the safest one available. For the affected public to feel this way, the developer of a facility must have a reputation for assessing risk accurately, for constructing the facility according to rigorous standards and for managing the facility competently. Credibility and trust in the process is particularly relevant for new facilities since there is no past history on which to base relevant estimates.

8. Concluding comments

The above review points to a number of important implications for the use of OR methodologies in support of siting of hazardous facilities. First, our general model of Section 4 points to the interlinking of values and beliefs with siting, transport and risk mitigation options for efficient siting of hazardous facilities. In particular, OR methods are clearly important in evaluating options
for transportation, siting and technology selection and in incorporating these into appropriate decision support systems to allow efficient risk–cost tradeoffs to be determined. Second, compensation (in-kind or monetary) to promote equity and to share benefits across stakeholders may be essential to enable implementation of efficient siting alternatives. Third, risk mitigation and control are central aspects of efficient siting. Finally, the information and equity issues associated with the siting of hazardous facilities make it imperative to understand siting as a process in which OR methods can contribute to determining efficient risk–cost tradeoffs, but in which the central problem is helping stakeholders to determine their values and beliefs relative to the siting options.

In particular, while operations research can contribute significantly to understanding and mitigating the multi-stakeholder risks associated with hazardous transportation and facility siting, it should be clear from the above that OR modeling is but one element of the complex process of assessing costs and risks in support of decision making in the siting process.

In our opinion, the key to the future success of siting problems will be integrating OR methods more closely with host community decision processes, to allow host communities to assess and to understand both the costs and the benefits they would be assuming in hosting a hazardous facility. This is clearly where the challenges for future research lie.

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