Combining GIS Spatial Analysis and PRA Concepts to Support Advanced Reactor Siting Decisions

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Abstract:

Siting multiple advanced reactors within a region introduces decision-making challenges that differ from traditional large light-water reactor (LWR) siting, including (i) the temporal and spatial dynamics of siting multiple reactors sequentially within a specific region, where earlier selections affect later ones and correlations across sites are not explicitly modeled, and (ii) interdependencies among siting criteria, where a single factor can cause compound influence on other criteria. This paper presents an ongoing study to investigate how concepts and techniques from probabilistic risk assessment (PRA) for nuclear power plants can be adapted to enhance siting decision-making for advanced reactors.

The paper presents the proposed computational framework and reports on progress in three key modules. First, a literature review is conducted to identify decision criteria relevant to advanced reactor siting. These decision criteria are organized into four main categories: health and safety, environmental, land use and socioeconomics, and engineering and cost considerations. A geospatial decision-support platform is then developed in ArcGIS to evaluate candidate sites across the Western Pennsylvania region, incorporating siting criteria such as population density, protected lands, seismic and landslide hazards, hazardous facilities, wetlands, and slope. These decision criteria are aggregated through a weighted overlay to generate composite suitability scores. A sensitivity analysis approach leveraging PRA importance measures is also proposed to assess how uncertainty in the relative weights of decision criteria affects site suitability rankings, which can provide decision-makers with insight into the uncertainty and robustness of decision analysis outcomes.

1. INTRODUCTION

In recent years, advanced nuclear reactors, including small modular reactors (SMRs) and microreactors, have emerged as a promising approach to improving the safety, operational flexibility, and cost-effectiveness of nuclear energy. One of the primary distinctions between these advanced reactors and conventional large light water reactors (LWRs) is scale. Traditional reactors typically generate over 1,000 MWe, whereas SMRs and microreactors are limited to approximately 70-350 MWe and 1-20 MWe per unit, respectively. To offset the loss of economies of scale, advanced reactors introduce modularity and mass manufacturing, which allow components, or in the case of microreactors, complete units, to be produced in centralized factories and transported to the site for installation. These design differences enable SMRs and microreactors to offer greater deployment scalability and suitability for non-conventional or remote locations. Beyond design, advanced reactors also differ in operating conditions and target applications. For instance, their ability to operate at higher temperatures makes them better suited for industrial process heat and other high-temperature applications.

These unique characteristics necessitate different siting considerations compared to conventional LWRs. The decision problem addressed in this study focuses on the siting of advanced nuclear reactors, specifically SMRs and microreactors, across a geographic region. Due to their smaller power output and integration with individual loads, multiple reactors (potentially dozens to hundreds) may need to be distributed within a given region. Unlike conventional siting studies focused on a single large nuclear power plant, this is a portfolio decision problem: identifying which locations within the region are suitable candidates and how the combination of selected sites can meet regional deployment objectives.

A literature review has been conducted focusing on publications that performed siting analysis for nuclear power plants (regardless of reactor type or design) and employed the Geographic Information System (GIS) as a core analytical tool. In total, this review includes 15 references, some of which are cited later in this paper when siting decision criteria are identified. The review has identified three research gaps. First, existing siting decision frameworks treat site selection as a one-time assessment, with no study incorporating temporal dynamics or the sequential deployment of multiple reactors over time. Second, when multiple sites are evaluated jointly, the spatial and operational correlations among those selections were largely unaddressed. Third, at the decision-criterion level, most studies treated siting factors as independent inputs while not accounting for compound effects due to their interdependence. Population distribution, for instance, can have a common-cause influence on multiple decision criteria, such as transportation infrastructure, labor availability, public acceptance, and social vulnerability; however, such dependency structures have not been captured in existing frameworks.

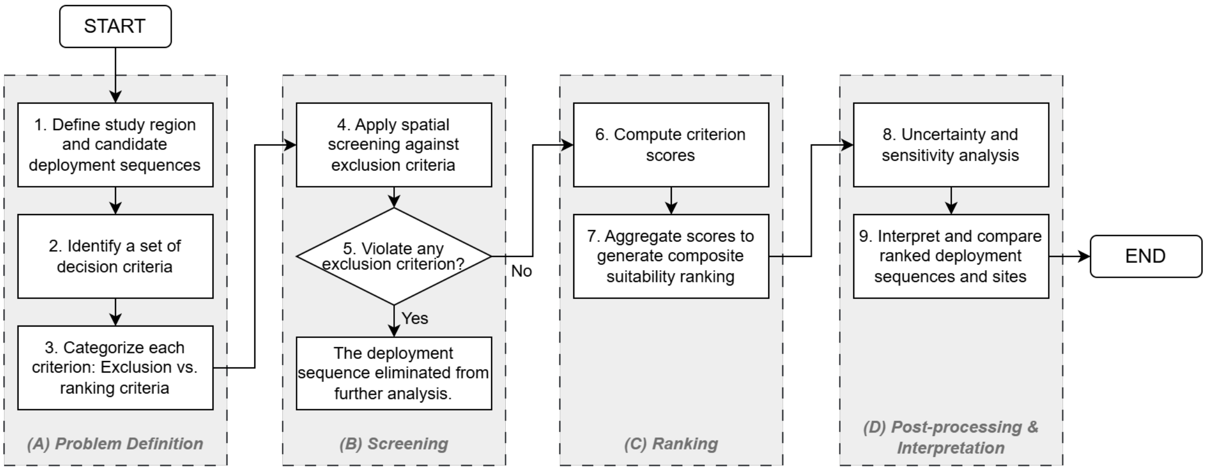
The contribution of this research is to develop a computational framework for advanced reactor siting decision analysis that can address the three research gaps identified above. The framework leverages concepts and techniques from probabilistic risk assessment (PRA) for nuclear power plants, motivated by structural analogies between the identified research gaps and typical nuclear PRA problems; specifically, the treatment of dynamic scenarios and dependencies among failure events and underlying causal factors. These PRA-derived concepts are adapted, rather than directly applied, to the advanced reactor siting context. Within the scope of this paper, the overarching structure of the computational framework is described, followed by reports on key modules under development, including decision criteria identification, spatial analysis, and multi-criteria decision analysis (MCDA) implemented in ArcGIS, and sensitivity analysis.

The remainder of this paper is organized as follows. Section 2 presents the overall structure of the computational framework. The subsequent sections present the development of a few key modules of the computational framework. Section 3 describes the identification of decision criteria for siting advanced reactors. Section 4 reports on the development of the Geographic Information System (GIS) tool for spatial suitability analysis and MCDA. Section 5 presents a new sensitivity analysis approach, developed by adapting concepts of risk importance measures from PRA, to assess the influence of uncertainty in the relative weights of decision criteria. Section 6 provides concluding remarks.

2. METHODOLOGICAL FRAMEWORK

The general workflow aligns with typical decision analysis steps: identification of the decision space, specification of evaluation criteria, assignment of criterion weights, aggregation into composite scores, and interpretation of results. In this study, the decision space consists not of individual locations but of candidate deployment sequences, namely, ordered combinations of sites at which multiple reactors would be sited, where criteria scores and weights may change conditionally depending on the preceding locations selected. The decision analysis workflow adopted in this study follows a four-stage structure, as illustrated in Figure 1.

Figure 1: Decision Analysis Workflow for Advanced Reactor Site Selection.



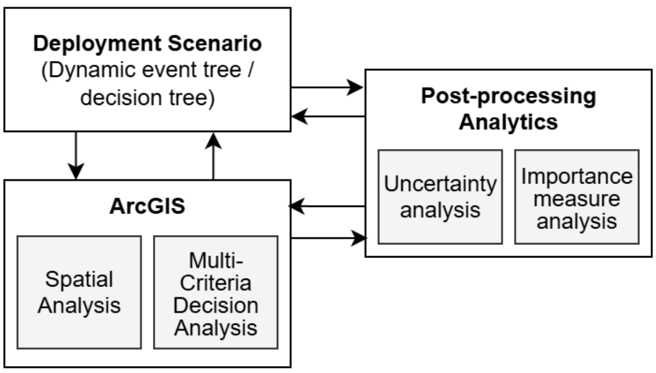
Stage A establishes a decision problem by identifying candidate deployment sequences in the study region and specifying a complete set of decision criteria. Each criterion is then categorized as either an exclusion criterion or a ranking criterion. Exclusion criteria are used for screening in Stage B by applying binary thresholds, while ranking criteria are assigned relative weights for site-suitability scoring in Stage C.

Stage B applies the exclusion criteria spatially and removes any candidate deployment sequence that includes locations violating at least one threshold from further analysis. The retained candidate set then enters Stage C, where individual criterion scores are computed and aggregated into a composite suitability ranking for multi-criteria evaluation. This ranking is not intended as a final recommendation but provided to decision-makers as a systematic basis for informing site selection decisions.

Stage D investigates the details of these ranking outputs through uncertainty and sensitivity analysis, for instance, to identify which criteria significantly drive the ranking results and assess the robustness of the rankings across varying analytical assumptions.

Figure 2 shows the computational framework for implementing the workflow shown in Figure 1.

Figure 2: Overarching Structure of the Computational Platform.



The Deployment Scenario module generates candidate deployment sequences, iteratively executes the ArcGIS model, and updates geospatial input data based on prior siting decisions to capture the conditional dependencies among successive reactor placements. This module is currently under development as part of ongoing work by leveraging dynamic PRA methods.

The Spatial Analysis module, developed using ArcGIS, manages the geographic representation of candidate locations, applies exclusion criteria through spatial overlay operations, and computes criterion scores from geospatial data layers. The Multi-Criteria Decision Analysis (MCDA) module aggregates criterion scores into composite suitability rankings using structured weighting schemes, with the option to define scenario-specific weight configurations reflecting different stakeholder priorities.

The Post-processing Analytics module conducts an uncertainty analysis by propagating parameter and model uncertainties through the ranking results and runs an importance measure analysis to identify which criteria significantly drive ranking outcomes. Outputs from this module inform decision-makers about the robustness of rankings and the relative influence of individual criteria under different analytical assumptions.

The remainder of this paper reports on the development of some of the modules in Figure 2. Section 3 describes the identification of siting decision criteria considered in this study, which serves as the basis for the MCDA module. Section 4 reports on the progress of the GIS tool development for the Spatial Analysis module. Section 5 presents the status of the Importance Measure Analysis submodule, which is being developed by leveraging concepts of risk importance measures from PRA.

3. IDENTIFICATION OF SITING DECISION CRITERIA

This section summarizes the key findings from a literature review to identify relevant decision criteria for siting advanced reactors. These decision criteria form the basis for the MCDA module in the computational framework (Figure 2).

A systematic literature search has been conducted using Google Scholar and ScienceDirect. This review focuses on existing studies published between 2019 and 2025. Table 1 presents the siting decision criteria relevant to SMRs and microreactors, as identified in the literature review. As listed in the first column, four main categories of decision criteria are identified: health and safety; environment; land use and socioeconomics; and engineering and cost-related criteria. Each category includes multiple subcategories, as listed in the second column of Table 1.

Table 1: Siting Decision Criteria Identified in the Literature Review

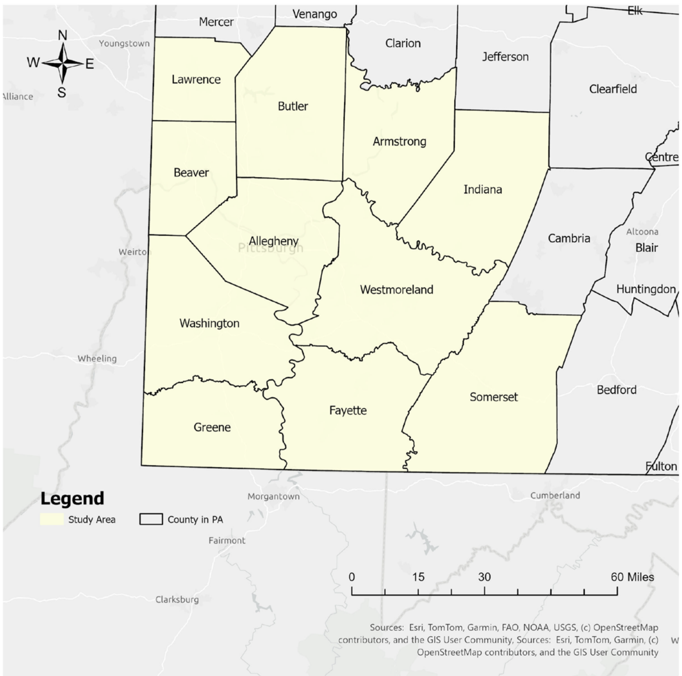
Main Categories	Subcategories
Health and Safety	• Geological and seismological hazards [1, 2] • Nearby hazardous land uses [1, 2] • Accident consequences [1, 3] • Emergency planning [4]
Environmental	• Streamflow / Cooling water availability [1, 2] • Dewatering effects of adjacent wetlands [1, 3] • Environmental sensitivity [5] • Climate change [5]
Land Use and Socioeconomics	• Protected lands [1, 3] • Disruption of important species [3, 5] • Waste management [6] • Social Vulnerability Index [2] • Public acceptance (including nuclear sentiment) [2, 5] • Energy market and operational factors [2, 5]
Engineering and Cost-Related	• Site footprint and land availability [1, 5] • Transportation [3, 5] • Capital costs [5, 7] • Labor rates [2] • Economic applications [2, 7] • Compliance with National/International Regulations [8]

The literature demonstrates a clear trend towards an emphasis on safety when evaluating potential sites for nuclear deployment, with most reviewed studies consistently using health and safety criteria. The socioeconomic criteria, such as the social vulnerability index (SVI), can provide a complementary aspect regarding the communities that are most susceptible to hazards within proximity of the plant [2]. This is relevant for advanced reactors, which may be located closer to higher-density populations than traditional nuclear power plants. Transportation infrastructure also emerged as a critical factor across multiple sources [3, 5]. Because SMRs and microreactors are manufactured in facilities and transported for on-site assembly and deployment, reliable and accessible transportation routes are essential.

4. GIS TOOL DEVELOPMENT

In this section, a baseline ArcGIS model is developed for Spatial Analysis and MCDA in the computational framework. The current model scope covers the Western Pennsylvania region (Figure 3). The model is under development as part of the authors' ongoing efforts, and the results presented here should be considered preliminary.

Figure 3: Study Area in This Paper.



Nuclear power plant siting is inherently a spatial problem, requiring the evaluation of geographic locations against multiple criteria that vary across locations. For the locational evaluation, this study uses a Geographic Information System (GIS), a computer system for capturing, analyzing, and displaying data related to positions on Earth's surface. Among the wide variety of GIS functions, this study conducted a Suitability Analysis using the Raster Calculator, a spatial decision-support method based on multi-criteria evaluation, in ArcGIS Pro 3.6. The GIS software is of an industry standard in the U.S. and has advanced functions with high usability.

The seven criteria, as listed in Table 2, are implemented in the baseline GIS model. These criteria represent the subset of siting decision criteria identified in Section 3. Each criterion maps directly to one or more subcategories in the broader literature-derived taxonomy of decision criteria:

- Wetlands and protected lands are directly included in our GIS model;
- population density is a surrogate parameter that addresses accident consequences and emergency planning considerations;

- seismic hazard, landslide hazard, and slope/terrain address geological and seismological hazards; and
- hazardous generator facilities correspond to nearby hazardous land uses.

Several subcategories identified in Table 1 fall outside our baseline GIS model scope. Additional quantitative data, such as streamflow, cooling water availability, fault proximity, and SVI, are considered for incorporation into future iterations of the GIS model. Qualitative criteria, such as public acceptance, governmental support, waste management, and energy market factors, are not easy to quantify and require integration through decision-support techniques, such as robustness analysis.

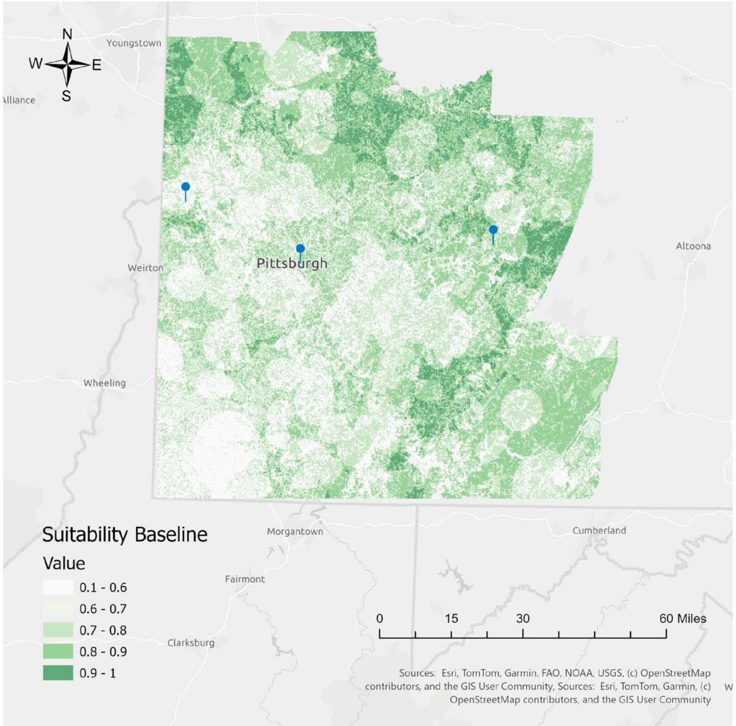
Table 2: Siting Criteria and Data Sources.

Criterion	Description / Threshold	Data Sources	Subcategory in Table 1
Population density	Exclude where ≥ 500 people/mi² within 2 miles	US Census (2023) [9]	Accident consequences; Emergency planning
Protected lands	Exclude all protected areas, such as National Parks, National Forests, Wilderness Areas, state parks, wildlife refuges, and conservation easements	USGS Gap Analysis Project (2024) [10]	Protected lands
Seismic hazard	Exclude more than 4% chance of potentially damaging ground shaking (MMI=VI) in 100 years.	Petersen et al. (2023) [11]	Geological and seismological hazards
Landslide hazard	Exclude moderate or high-risk zones: more than 40 of the 10-m cells exceeded the threshold of the slope-relief within a 90-m grid unit	Belair et al. (2022) [12]	Geological and seismological hazards
Hazardous generator facilities	Exclude cells containing a place that creates hazardous waste	PA DEP (2016) [13]	Nearby hazardous land uses
Wetlands	Exclude wetlands and surface water	U.S. Fish & Wildlife Service (2026) [14]	Dewatering effects of adjacent wetlands; Environmental sensitivity
Slope / terrain	Exclude slopes > 18%	USGS (2024) [15]	Geological and seismological hazards

In ArcGIS, the cell size is standardized to 300 square meters; each criterion value is converted to a Boolean value indicating whether it met the condition (1: suitable, 0: unsuitable); and these seven factors are overlaid. For the ranking analysis of the unscreened locations, we treated each factor as having equal weight and combined them to create a suitability map with sum values ranging from 0 to 1 as the baseline.

The preliminary result of the screening analysis and suitability ranking is shown in Figure 4. The map visualizes the suitability of advanced reactor site selection based on the aggregated consideration of the criteria listed in Table 2. The more suitable areas are shown in darker green. The blue pins on the map indicate the three illustrative reference sites that are further evaluated in Section 4.

Figure 4: Preliminary Suitability Score.



4. IMPOTANCE MEASURE ANALYSIS

This section presents a sensitivity analysis method developed for the Post-processing Analytics module of the computational platform (Figure 2). The purpose is to identify the relative importance of sources of uncertainty based on their influence on suitability ranking results. Specifically, we examine the impact of uncertainty associated with the relative weights of decision criteria. Assigning a single probability distribution to these weights is not straightforward; hence, typical uncertainty quantification methods, such as Monte Carlo simulation, are not suitable. Instead, this study proposes an importance-measure-like approach, leveraging the concept of risk importance measures from nuclear PRA [16].

In practice, it is unlikely that each decision criterion varies individually or independently. A more practically meaningful situation is a shift in the broader decision context, for instance, a change in regulatory emphasis or stakeholder priorities that can affect the relative importance of multiple criteria simultaneously. To facilitate decisions under such situations, a “contextualized importance measure” analysis is proposed, rather than a traditional one-at-a-time approach. The procedure consists of four steps: (1) identify a set of contextual change scenarios; (2) for each scenario, identify the subset of decision criteria whose relative weights are influenced; (3) for each scenario, construct two sensitivity cases: R+ where the weights of the impacted criteria are increased, and R- where they are decreased; and (4) execute the GIS analysis under each sensitivity case and compute the contextualized importance measures following the same logic as common risk importance measures in PRA.

$$FVL_i = \left(R_0 - R_{i,-}\right)/R_0 \tag{1}$$

$$RAWL_i = \left(R_{i,+} - R_0\right)/R_0 \tag{2}$$

where FVL_i and $RAWL_i$ are the Fussell-Vesely-like and Risk-Achievement-Worth-like contextualized importance measures for scenario i, respectively. R_0 represents the baseline suitability score computed with the baseline criteria weights, while $R_{i,+}$ and $R_{i,-}$ are the suitability scores computed with increased and decreased weights under scenario i, respectively.

Three illustrative scenarios are considered in this study. Each scenario reflects a distinct siting decision-making priority: (1) Safety-Conservative, prioritizing hazard avoidance and accident consequence limitation, (2) Infrastructure/Deployment Driven, prioritizing constructability and resource availability, and (3) Community/Land Use, prioritizing the avoidance of land use conflicts and proximity to energy users. Table 3 summarizes the criteria influenced by each scenario.

Table 3: Criteria Impacted by Each Contextual Change Scenario.

Scenario	Impacted Criteria
Safety-Conservative	Population density, seismic hazard, landslide hazard
Infrastructure/Deployment-Driven	Wetlands, slope
Community/Land Use	Population density, protected lands, wetlands

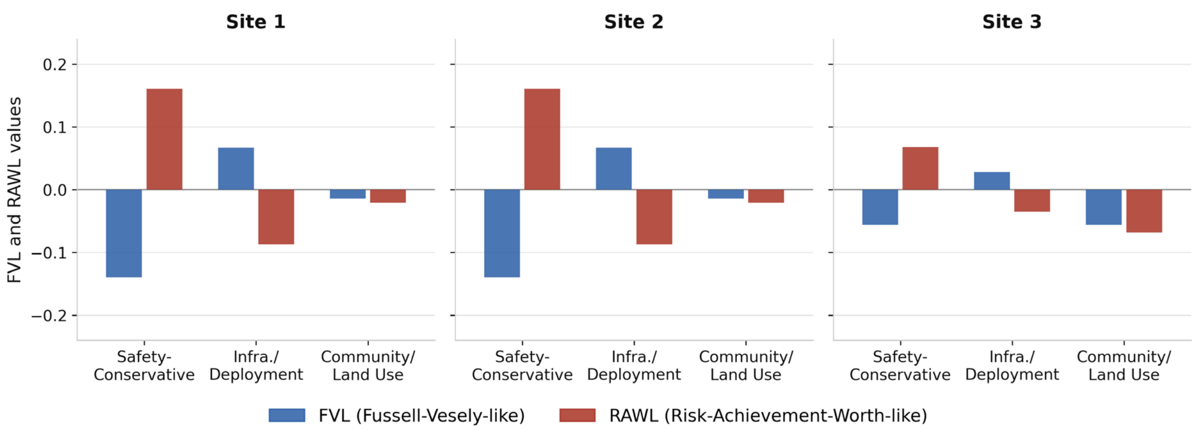
The baseline quantification, R_0, uses equal weights across all seven criteria, corresponding to the results shown in Section 4.2. For the positively changed case, R_+, the criteria impacted by a given scenario are assigned twice the weight of the remaining criteria. For the negatively changed case, R_-, the assignment is reversed, where the remaining criteria receive twice the weight of the scenario-impacted criteria. All weights sum to 1 in every sensitivity case. This setup produces seven ArcGIS runs in total, including one baseline and two sensitivity cases per scenario.

In this illustrative case study, suitability scores are extracted at three representative sites selected solely for demonstration purposes: (1) the University of Pittsburgh Campus, (2) the Beaver Valley nuclear power plant, and (3) the Homer City Energy Campus. It should be noted that the authors do not intend to propose these sites as actual candidates for future reactor siting. Instead, they are selected to illustrate how the tool developed in this study can characterize features across different sites within the studied region.

Figure 5 shows the results of FVL_i (a blue bar) and $RAWL_i$ (a red bar) for each of the representative sites being analyzed for demonstration. The results show that the Safety-Conservative scenario is the dominant sensitivity driver across all three sites, producing the largest FLV and RAWL magnitudes. The Infrastructure/Deployment-Driven and Community/Land Use scenarios show comparatively smaller influence at Sites 1 and 2. In contrast, Site 3 presents a different pattern: the Community/Land Use scenario reaches the same sensitivity magnitude as the Safety-Conservative scenario, likely attributed to Homer City's land-use profile.

Sites 1 and 2 produce identical FLV and RAWL values across all scenarios, indicating that the current criterion set may lack sufficient resolution to distinguish between these two sites. Ongoing iterations of the GIS model, incorporating additional criteria from Table 1, could resolve this degeneracy.

Figure 5: Results of Importance Measure-Like Sensitivity Analysis.



6. CONCLUSION

This paper investigates how concepts and techniques from nuclear plant PRA can be adapted to address decision-making challenges specific to the siting of multiple advanced reactors. Two challenges motivate this work: (i) the temporal and spatial dynamics of sequential siting decisions, where preceding site selections affect later ones, and (ii) the interdependencies among siting criteria, where a single factor can induce compound influence on other criteria.

A new computational framework is proposed to address these challenges, and progress on three key modules is reported in this paper. A structured literature review has identified a set of decision criteria organized into four categories: health and safety, environmental, land use and socioeconomics, and engineering and cost, which provide a systematic basis for decision criterion selection. A GIS-based spatial analysis and MCDA platform is being developed in ArcGIS for the Western Pennsylvania region. A sensitivity analysis approach adapted from PRA importance measures has been introduced to evaluate how uncertainty in criterion weights propagates to site suitability rankings, which can offer decision-makers a structured means of identifying dominant sources of uncertainty and assessing the robustness of site rankings.

Ongoing work focuses on two key aspects of the computational framework. First, the decision criteria included in MCDA are being expanded to incorporate categories not yet included in the current analysis. Second, the Deployment Scenario module is being developed using dynamic event tree methods to explicitly treat time-dependent siting sequences and inter-site dependencies.

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