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Application of Game Theory in solving the nuclear waste treatment conflict between countries using ε-MOEA

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ABSTRACT

BACKGROUND AND OBJECTIVES: The management of high-level nuclear waste is a pressing global challenge, with over 400,000 metric tons in temporary storage worldwide. International disputes frequently arise due to disagreements over site selection, cost allocation, environmental risks, and long-term liability, often leading to negotiation deadlocks. Existing governance frameworks lack structured mech-anisms to balance the competing objectives of multiple stakeholders, including waste-producing (“Disposer”) nations and potentially affected (“Affected”) nations. This paper aims to resolve these transboundary nuclear waste treatment conflicts by developing a hybrid analyti-cal model that integrates Game Theory to model strategic interactions and the ε-Multi-Objective Evolutionary Algorithm (ε-MOEA) to find optimal solutions that balance competing goals such as cost, environmental safety, and economic benefits.

METHODS: This manuscript employs a combined Game Theory and computational algorithm approach to resolve international nuclear waste disputes. Game Theory models the conflict between two player types: disposer countries (waste producers) and affected countries (those impacted by disposal). Each player has specific goals, strategies, and costs, with the model seeking a Nash Equilibrium-a stable agreement where no country can unilaterally improve its outcome. Due to the problem’s high complexity with multiple competing objectives, the study utilizes the ε-MOEA optimization algorithm. This algorithm efficiently explores millions of possible strategy combinations to identify optimal compromises, balancing outcomes to ensure fair and practi-cal solutions for all involved countries.

FINDINGS: Computational experiments compared ε-MOEA against other multi-objective algorithms (NSGA-II, NSGA-III, PESA2, VEGA). The key finding was that all algorithms converged to the same optimal fitness value (-5280.33), demonstrating the model’s robustness in identifying a stable equilibrium. However, ε-MOEA achieved this result with the shortest and most stable runtime (approximately 5.00 seconds per iteration), significantly outperforming other algo-rithms in computational efficiency. This indicates that ε-MOEA is particularly well-suited for solving this complex, high-dimensional problem efficiently, providing a diverse set of Pareto-optimal solutions for policymakers to evaluate trade-offs.

CONCLUSION: A hybrid Game theory and ε-MOEA framework effectively resolves international nuclear waste conflicts by modeling strategic interactions and optimizing for multiple objectives. This scalable approach identifies stable, fair agreements that balance the interests of both producing and af-fected nations, supporting sustainable international governance. Future work should focus on improving computational efficiency for larger numbers of players.

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INTRODUCTION

Managing high-level nuclear waste remains one of the most pressing and unresolved challenges in global energy and environmental policy. Despite decades of research and international regulation, no universally accepted, large-scale, long-term solution exists, leaving over 400,000 metric tons of spent nuclear fuel in temporary storage as of 2023 (Sjoberg & Sjoberg, 2009). The central challenge lies less in technical feasibility than in the political, economic, and ethical barriers to implementation. Countries differ in geological conditions, technological capacity, and public acceptance, leading to divergent national policies and regulatory approaches. Domestic disposal may be infeasible for nations with limited territory or unstable geology, pushing the issue into the international arena. However, proposals for shared or transboundary repositories often trigger fierce resistance from potential host countries and neighboring regions, due to concerns about sovereignty, environmental justice, and long-term liability (World Nuclear Association, n.d.; International Atomic Energy Agency, 2019). This persistent deadlock-illustrated by the European Union's failure to establish a joint deep geological repository despite technical readiness-underscores the systemic gap: the absence of transparent frameworks to balance competing stakeholder interests. The long-term structure of the IAEA Safety Standards Series is illustrated in Figure 1. The asymmetric distribution of benefits and risks further exacerbates these disagreements. Waste-producing countries may seek cost-efficient disposal abroad, while host countries demand compensation, security guarantees, and environmental safeguards. As a result, international negotiations frequently stall, leaving waste stockpiled in interim storage facilities that were never designed for multi-decade use (Yue *et al*., 2017). A notable example is the decades-long deadlock in the European Union over a shared deep geological repository, where competing interests have blocked progress despite clear technical feasibility (Li & Wang, 2023). Similar conflicts have emerged in East Asia and North America, highlighting a systemic gap in current governance frameworks: the absence of structured, transparent mechanisms to balance competing stakeholder objectives.

Addressing this gap requires tools that can model conflict, cooperation, and trade-offs simultaneously. Research into sustainable alternatives, such as transmutation, waste reuse, and deep geological repositories, must be balanced with interim storage in strategic approaches to nuclear waste management (International Atomic Energy Agency, 2019). Game Theory (GT) provides a foundation for analyzing strategic interactions, fostering collaboration, and stabilizing international agreements (Köksalan *et al*., 2011; Yu *et al*., 2020). It assists in reducing conflicts and coordinating national incentives by encouraging stable agreements (Ho *et al*., 2022). A fundamental idea in GT, the Nash equilibrium allows stakeholders to make logical decisions (Finus & Rundshagen, 2015). Yet, Game theory alone cannot account for the multiple conflicting objectives-cost, safety, environmental impact-that define nuclear waste man-

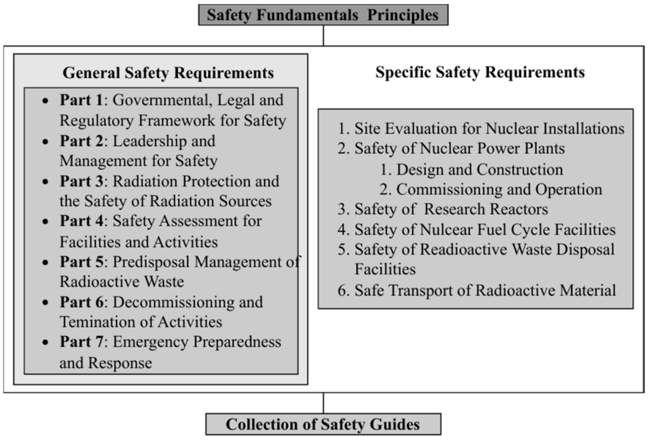


Fig.1: The long-term structure of the IAEA Safety Standards Series (International Atomic Energy Agency, 2019)

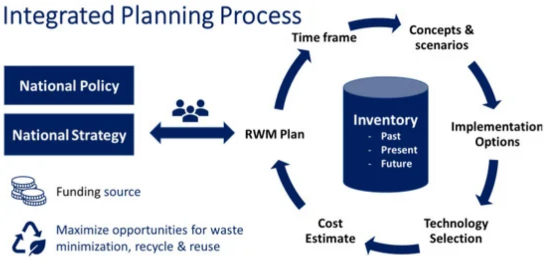


Fig. 2: Flow sheet diagram of an integrated planning process (Zoran *et al*., 2022).

agement. To address this, this study integrates Game theory with the ε-MOEA. ε-MOEA is designed to generate diverse Pareto-optimal solutions through ε-dominance, enabling decision-makers to explore trade-offs efficiently (Wong *et al*., 2017). Its capacity to maintain various solutions appropriate for multiple national agendas accounts for its efficacy in resolving nuclear waste issues (Yang & Xu, 2021). The algorithm employed in this study, ε-MOEA (Epsilon Multi-Objective Evolutionary Algorithm), is a type of Multi-Objective Evolutionary Algorithm (MOEA) that uses ε-dominance to maintain a diverse set of Pareto-optimal solutions. According to (Wong *et al*., 2017), the Pareto front generated by MOEAs allows decision-makers to explore trade-offs and make informed decisions based on stakeholder preferences. ε-MOEA is an optimization technique that considers multiple conflicting objectives simultaneously, utilizing Pareto front solutions, constraints, and ε-dominance to define acceptable trade-offs. A study by Yang & Xu (2021) demonstrated that ε-MOEA outperformed other interactive MOEAs due to its efficient handling of ε-dominance. This algorithm is particularly beneficial in nuclear waste treatment disputes, where it is crucial to balance cost, safety, and environmental impacts among the increasing number of involved countries. In a multi-stakeholder context, ε-MOEA retains a wide range of solutions tailored to the diverse strategies and preferences of different nations. Fig. 2 depicts the flow sheet diagram of an integrated planning process.

Addressing the conflict related to nuclear waste treatment among countries involves several critical inquiries and challenges:

(i) How can MOEAs balance competing goals and optimize the distribution of nuclear waste sites?

(ii) In what ways can Game Theory support the creation of just and effective waste management plans?

(iii) In international negotiations, what function does strategic interaction modeling serve?

By addressing these questions, the study contributes a hybrid analytical framework that combines optimization and strategic modeling, with the potential to guide international institutions, like the IAEA, toward more sustainable and cooperative solutions. As the summary is illustrated in Table 1, conflicts over nuclear waste treatment have been extensively studied, with research providing insights into mitigation strategies. This section reviews key contributions, highlights unresolved challenges, and demonstrates how our approach addresses existing gaps. Game theory has emerged as a critical tool in analyzing international cooperation on nuclear waste management, mitigating non-cooperative behavior while identifying incentives for collaboration (Grimes-Casey *et al*., 2007). (Kaushal & Nema, 2013) examined its role in optimizing disposal strategies, emphasizing leadership dynamics in transboundary waste governance. Other studies have explored cooperation mechanisms: (Phathanapirom *et al*., 2020) analyzed optimal collaboration levels in the nuclear fuel cycle, while (Finus & Rundshagen, 2015) assessed the stability of scientific agreements. Additionally, strategic decision models offer alternative conflict-resolution approaches. Beyond cooperative modeling, strategic decision frameworks provide alternative perspectives on conflict resolution (Xu *et al*., 2022), modified the Prisoner's Dilemma to optimize national benefits, and Phathanapirom *et al*. (2020) developed a financial model balancing national interests. (López-Cabarcos *et al*., 2024) underscored the role of trust and reputation in sustaining long-term agreements. However, these approaches remain largely single-dimensional, focusing on either political cooperation or economic trade-offs, without simultaneously accounting for

Table 1: Summary of recent related research papers by approaches and algorithms.

Method	Year	Problem
GT	2017	Analyze the effect of international law (Schwenk-Ferrero & Andrianov, 2017)
GT	2021	Solve the problem of the spent nuclear fuel treatment process (He *et al.,* 2021)
GT, GMCR	2022	International cooperation in nuclear waste disposal (Yang & Xu, 2021)
GT	2022	Optimize nuclear waste, minimizing potential harm to the environment and humanity, and achieving sustainable development (Xixi *et al.,* 2022)
GT, NE	2021	Develop equitable solutions when bargaining over nuclear waste treatment (Darda *et al*., 2021)
GT	2020	Optimizing nuclear fuel cycle transitions that incorporate (Eryganov *et al.,* 2020).
GT	2022	Optimize international cooperation for ensuring safety, security, and non-proliferation (Kaushal & Nema, 2013)
GT, NE	2021	Policy about marine environments under the current situation (Qu *et al.,* 2018)
GT	2020	Developed to assess the costs and advantages of ultimate repository protection (Ju *et al.,* 2020)
GT	2022	Help countries maximize benefits from NWM while minimizing costs (Xu *et al.,* 2022)
GT	2020	International cooperation in nuclear waste disposal (International Atomic Energy Agency, 2020)
GT	2019	Find efficient NWM (Handl, 1981)
GT, NE	2019	Solve nuclear disposal conflicts in the construction contract (Montonen *et al.,* 2019)
GT	2019	Find the balance point of the stakeholder's benefits (Li & Wang, 2023)
GT	2020	Investigate and resolve the uncertainty on nuclear waste disposal costs (Finus & Rundshagen, 2015)

environmental risks, geopolitical tensions, and long-term sustainability. recent studies (e.g., Xu *et al.,* 2022; lópez-cabarcos *et al.,* 2024) have introduced more realistic elements such as dynamic strategy adjustments and trust mechanisms, yet these still lack robust multi-objective optimization frameworks. In contrast, our study differentiates itself by integrating the ε-moea algorithm into a game-theoretic framework. this combination allows the simultaneous optimization of political, economic, and environmental factors, creating a more holistic approach to resolving international nuclear waste conflicts. Despite these advancements, existing models often lack multi-objective optimization frameworks that address political, environmental, and economic factors concurrently. By integrating the ε-MOEA algorithm into a game-theoretic framework, our study bridges this gap, providing a more comprehensive approach to resolving international nuclear waste conflicts.

With an emphasis on safety and security, the method improves repository design and operation while taking cultural, political, and economic concerns into consideration. By considering factors like long-term health hazards, environmental harm, and intergenerational equality, the GT model ensures that stakeholders make balanced decisions. Stakeholder issues are addressed by optimizing nuclear waste disposal using a combination of Game theory and the MOEA framework. The ε-MOEA model balances environmental effects, transportation costs, and safety to determine the best storage places. Offering insights on fair and effective methods for disposing of radioactive waste aids in studying international policy. Through effective policymaking and collaborative tactics, the platform seeks to support international efforts to reduce the hazards associated with nuclear waste.

MATERIALS AND METHODS

The management of Nuclear Waste Treatment (NWT) is a complex issue influenced by conflicts of interest and cost reduction. The distribution of resources and waste treatment technology significantly impacts outcomes and goals. A Game-theoretic framework is needed to analyze strategic interactions and negotiation dynamics in international agreements. Therefore, our topic can be a model. Assuming that we have $\in N *, n > 2)$players, all of which are countries from around the world. These players can be categorized into 2 specific types of players: $m\ (m \in N *, n > m > 1)$players that are type d represents Disposer countries and

$l\,(l \in N*, n > l > 1)$ players whose type is a represents the affected countries. For instance, we consider three countries: the USA, Russia, and China, all facing the complex challenge of disposing of their nuclear waste. Each country has a set of core objectives, with minimizing. $environmental\,impact(E)$, reducing $cost$, maximizing $preferences(P)$, and minimizing $risk(R)$ being at the forefront. To illustrate, let's assume a dataset with specific values for each country's objectives as per Table 2.

The example data presented in Table 2 are hypothetical values constructed for illustrative purposes rather than direct measurements from real-world nuclear waste disposal projects. They are intended to demonstrate how the proposed game-theoretic and ε-MOEA framework can be applied to compare countries with different characteristics. By clarifying these assumptions, we emphasize that the table serves as a conceptual illustration to explain the mechanics of the unified game model. In future empirical applications, the framework can incorporate real-world data such as nuclear policy indicators, economic costs, and environmental risk assessments. In the problem of solving conflicts between countries, our research aimed at two types of players with different characteristics: nuclear waste-disposing countries and affected countries. The two kinds of players share some similar characteristics, such as economic benefits (Finus & Rundshagen, 2015), environmental benefits, environmental damage (Yue *et al.*, 2017), and economic cost for solving the problem (Finus & Rundshagen, 2015). In addition, influenced countries have one more characteristic: health benefits when reducing nuclear waste impact (Li & Wang, 2023). For nuclear waste-producing countries, key variables include the daily discharged wastewater volume (m^3/day), disposal duration (days), human and environmental benefits ($/day), and disposal costs ($/day). For affected countries, relevant factors are the received wastewater volume (m^3/day), duration (days), compensation received ($/day), and risk mitigation costs ($/day). About the strategies, we consider 4 general strategies for both types of players: The impact of nuclear waste discharge on the environment, the cost per nuclear waste discharge event, the impact of nuclear waste discharge on health, and the last one is the risks associated with nuclear waste discharge. The flowchart of the solution for the NWT problem using ε-MOEA is illustrated in Fig. 3. The characteristics of players and strategies are shown in Table 3.

The study explored safe nuclear waste disposal by considering stakeholders' interests, including waste-producing countries, neighboring countries, international organizations, and residents. Solutions include domestic treatment, environmental release, acceptance by neighbors, and setting fees. A stable equilibrium point is crucial, and concerns can be resolved through negotiation. International organizations set requirements for radioactive substance concentrations. Game theory helps understand trade-

Table 2: Summary of data on amending nuclear waste disposal [32]

Country	E (1-10)	C (USD)	P (1-10)	R (1-10)
America	4	1,200	6	2
Russia	5	1,300	5	3
China	3	1,000	8	1

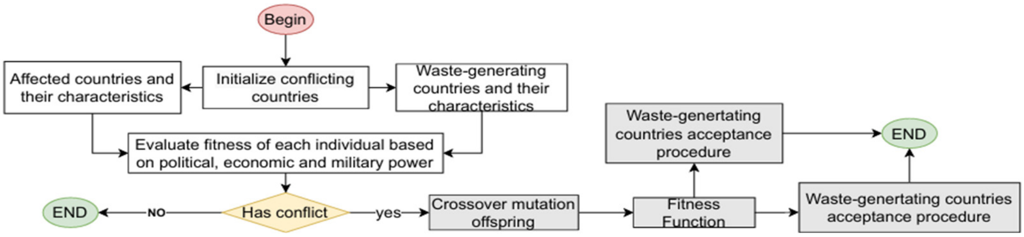


Fig. 3: Flowchart of the solution for the NWT problem using ε-MOEA

Table 3: Characteristics of players and strategies.

Types of players	Characteristics of a Player	Characteristics of Strategies
Disposer d	q^d: Quantity of nuclear waste t^d: Discharge period m: Total number of players d	BH^{da}: Benefits for humans BE^{da}: Benefits for the environment C^{da}: Cost has to pay
Affected a	q^a: Quantity of nuclear waste received t^a: Waste reception period l: Total number of players a	MR^{ad}: Money received RP^{ad}: Potential Risk

offs and potential conflicts. The unified game-based model (Trinh *et al.*, 2019) is a framework that integrates game elements to design a generic model for many sorts of Game theory. Solving conflicts in NWT is a class of conflict problems that belongs to the type of cooperative game with non-zero-sum and imperfect information. Therefore, the Unified Game-based model (Trinh *et al.*, 2019) is necessary and possible to provide efficient solutions or strategies for the above-mentioned problems.

$$G = \langle \{P^d, P^a\}, \{S^d, S^a\}, \{u^d, u^a\}, R^C \rangle \tag{1}$$

Let G represent the unified game model. The set $P^d = \{p_1^d, \dots, p_m^d\}$ denotes the nuclear waste-disposing countries, while $P^a = \{p_1^a, \dots, p_l^a\}$ denotes the countries that are affected by waste disposal. Each country in these sets is considered as an individual player with its own characteristics (e.g., resources, political priorities, and environmental sensitivities). The strategy spaces for the t groups are given by $S^d = \{S_1^d, \dots, S_x^d\}$ for the disposing countries and $S^a = \{S_1^a, \dots, S_y^a\}$ for the affected countries. In practical terms, these strategies might represent options such as choosing a disposal method, negotiating for compensation, or forming alliances. The payoff functions $u^d : S^d \to \mathbb{R}$ and $u^a : S^a \to \mathbb{R}$ measure the outcomes for each player. For example, disposing countries may maximize cost efficiency or political leverage, while affected countries may focus on minimizing environmental risk or maximizing compensation. Finally, let R^C be a vector space representing the conflict set C. A nonempty vector $v_{\rightarrow} \in R^C$ represents the conflicts among n players ($1 \le n \le N$), expressed in the normal (strategic) form of the game. This formulation captures the interplay of competing interests, where each player's choice directly influences both cooperation and conflict in international nuclear waste management.

The payoff function of Disposer can be calculated by the following:

$$u^d = \sum_{i=1,\, j=1}^{m,l} q_i^d t_i^d \left(BH_{ij}^{da} + BE_{ij}^{da} \right) - \sum_{i=1,\, j=1}^{m,l} q_j^a t_j^a C_{ij}^{da} \tag{2}$$

Where u^d represents the payoff function of Disposer d. i, j respectively represent the ordinal number of each player. m,l indicate the total number of Disposer *d* and the total number of Affected a respectively. q_i^d, q_j^a illustrate the quantity of nuclear waste from d and the quantity of nuclear waste received from d of a. t_i^d, t_j^a represent the discharge period of d and the wte reception period of a calcuated by day. $BH_{ij}^{da}, BE_{ij}^{da}$ describe the benefits for humans and the environment during the disposal of a quantity q per time t of Disposer d to Affected a. Finally, C_{ij}^{da} is the Cost that d has to pay to a during the disposal of quantity q per time t. The payoff function of the Affected can be calculated by the following:

$$u^a = \sum_{i=1,\, j=1}^{m,l} t_j^a q_j^a MR_{ji}^{ad} - \sum_{i=1,\, j=1}^{m,l} RP_{ji}^{ad} q_i^d t_i^d \tag{3}$$

Where u^a represents the payoff function of Affected a. i, j respectively represent the ordinal number of each player. m,l indicate the total number of Disposers d and the total number of a respectively. q_i^d, q_j^a illustrate the quantity of nuclear waste from d and the quantity of nuclear waste received from d of a. t_j^a, t_i^d represent the discharge period of d and the waste reception period of a calculated by day. MR_{ji}^{ad} refers to the amount of money a received from d countries to process quantity q of nuclear

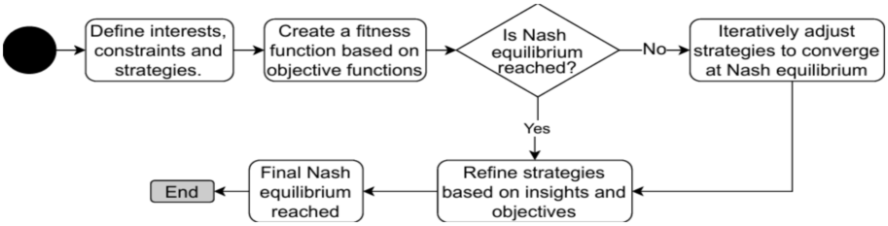


Fig.4: Flowchart of solving the unified Game-based model

waste per time t. Finally, RP_{ji}^{ad} are the potential risks or costs a incurred from relying on d countries for waste disposal. A special framework for comprehending and maximizing interactions among stakeholders in nuclear waste across nations is provided by the Game theory model. Thus, specifically considering each stakeholder's strategic decision-making, possible collaboration, and conflict. By using the NE formula, the discharging country can determine the strategic discharge amount to maximize profits based on other factors such as radioactive dilution and compensation if problems occur. To address NWT problems between countries, the Unified Game-based model can be applied by outlining how the algorithm could be implemented. Determining the parties' goals, limitations, and tactics is the first step. It also recommends developing a fitness function based on two objective functions: u^a and u^d. The model looks for an NE where all parties' aggregate utility is maximized. Strategies are refined iteratively until they converge to a balanced state where no player can increase their payout unilaterally. Figure 4 shows the flowchart for solving the Unified Game-based model.

NP-hard problems are problems that the computer cannot find the exact optimal solution in polynomial time (Montonen *et al*., 2019). NWT is an NP-hard problem with a high-dimensional decision space, intrinsic uncertainty, and a combinatorial character. Long-term consequences are complicated by waste treatment, technology, legislation, and geopolitics. These uncertainties may be modeled with the use of probabilistic techniques and scenario analysis. Resource limitations make the problem worse. ε-MOEA provides a variety of Pareto-optimal results, objective balance, and effective exploration. The ε-MOEA approach is employed to address the multi-objective optimization problem arising from the application of Game theory in resolving conflicts between countries regarding NWT. In this scenario, we can identify the strategies for the nuclear waste-disposing country, the influenced country, and represent them as chromosomes. An example is shown in Fig. 5.

Where the chromosome encodes a string of strategies, where each player's strategy is represented by their respective gene. The value of the gene indicates the specific strategy chosen by the player. Here, the value 0 signifies the absence of a strategy choice, while values 1, 2 denote specific types of strategies selected by the players. Furthermore, it always yields the same result for the same input. It should also be scalable and computable. Here's how we apply the fitness function:

$$F = \left| \frac{\sum_{i=1}^{m} u_i^d}{m} - \frac{\sum_{j=1}^{l} u_j^a}{l} \right| \qquad (4)$$

Where F is the problem's fitness function. i,j respectively represent the ordinal number of each player. m,l indicate the total number of d and the total number of a respectively. Finally, u_i^d, u_j^a respectively indicates the payoff function of d and a. To find a solution with the optimal F, the ε-MOEA algorithm has been proven to be one of the most effective algorithms available. It evaluates various solutions along the Pareto front, balancing environmental impact, economic costs, and resource allocation. Figure 6 illustrates a flow chart of the ε-MOEA Process for NWM decision-making, and Fig. 7 depicts pseudo-code for NWT.

The algorithm starts by creating a large initial population of alternatives for treating radioactive waste, assessing their effects on the environment, legal system, and economy, and grouping people into

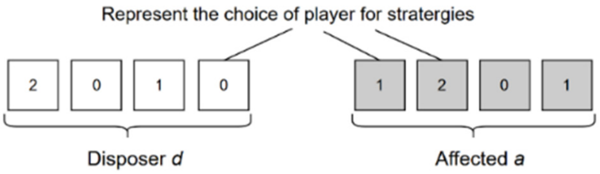


Fig. 5: The process of selecting pairs of chromosomes

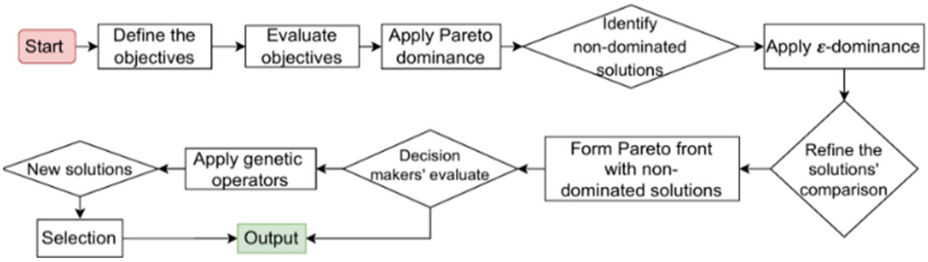
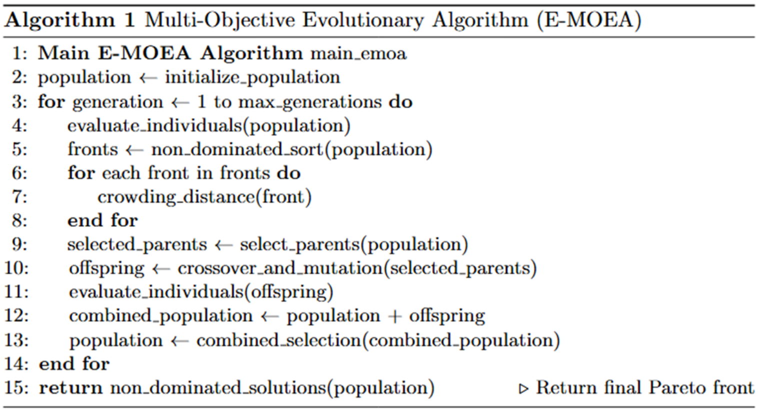


Fig. 6: A flow chart of the ε-MOEA Process for NWM decision-making.



Algorithm 1 Multi-Objective Evolutionary Algorithm (E-MOEA)

```
Main E-MOEA Algorithm main_emoa
population ← initialize_population
for generation ← 1 to max_generations do
    evaluate_individuals(population)
    fronts ← non_dominated_sort(population)
    for each front in fronts do
        crowding_distance(front)
    end for
    selected_parents ← select_parents(population)
    offspring ← crossover_and_mutation(selected_parents)
    evaluate_individuals(offspring)
    combined_population ← population + offspring
    population ← combined_selection(combined_population)
end for
return non_dominated_solutions(population)          ▷ Return final Pareto front
```

Fig. 7: Pseudo code for NWT

non-dominated fronts. The crowding distance calculation ensures diversity, and the next generation's parents are selected based on their rank and crowding distance.

RESULTS AND FINDINGS

This section presents the results of comprehensive computational experiments evaluating the effectiveness of the proposed Game theory and ε-MOEA model using the experiment parameters listed in Table 4. The system will be written using Java and IntelliJ IDEA for stability and credibility. The experiments will be executed on a robust cloud computing platform supported by Amazon, providing powerful scalability. The server configuration used has a CPU speed of 2.6GHz, 16384 GB RAM, and 300 GB Enterprise SSD storage.

Total number of core objectives that have been applied: 5. Including economic benefit gains for the disposer, financial cost associated with waste disposal for the disposer, environmental cost for the disposer, financial cost of the affected, and environmental cost of the affected. Each player has four crucial collaboration and nuclear waste reduction tactics, and

Table 4: The experiment parameters.

Parameters	ε	Range	Rates	Generations
Description	[0.01, 0.1]	1000	80% / 1%	100

Table 5: Sample data of the core objectives of several 5 players.

Players	Core Objectives				
	$p1$	$p2$	$p3$	$p4$	$p5$
Japan d	5987	1854	679	3748	3687
	6709	1546	617	2585	3865
	5670	1768	568	2874	3594
	5760	1754	896	3785	4987
China a	5789	1768	789	3746	3587
	5708	1647	765	3374	4875
	6098	1876	874	2748	3498
	6745	1978	637	2598	4786

Table 6: Comparison of Fitness value across different algorithms.

	NSGA-II		NSGA-III		ε-MOEA		PESA2		VEGA	
	Fitness value	Run time (s)	Fitness value	Run time (s)	Fitness value	Run time (s)	Fitness value	Run time (s)	Fitness value	Run time (s)
1	5687,38	6,658	6013,88	6,165	5849,84	5,003	5554,54	5,061	5624,12	6,888
2	5322,94	5,936	5595,02	6,821	5845,94	5,017	5378,3	5,138	5215,68	8,053
3	5738,16	6,023	5902,26	6,303	6010,88	5,008	5449,36	5,07	5497,76	8,011
4	5659,92	5,908	5936,64	7,073	5812,74	5,01	5327,9	5,008	5342,02	7,999
5	5659,36	5,812	5721,12	6,137	5717,28	5,016	5144,08	6,724	5429	8,349

there are probably seven essential traits about variables such as: $p1, p2, p3, p4, p5$ which sequentially represent the characteristics that we have mentioned in our payoff function above. Table 5 provides a comprehensive set of data points that describe various dimensions (environmental impact, cost, preferences, risk) associated with nuclear waste disposal for each player. The data likely serves to evaluate and compare the performance and priorities of each country in handling nuclear waste, which is crucial for developing effective algorithms and strategies for international NWM. In continuation, Table 6 further compares the performance evaluation findings of five distinct multi-objective optimization algorithms, namely NSGA-II, NSGA-III, ε-MOEA, PESA2, and VEGA. The primary metrics compared were fitness and runtime.

To compare with the primary algorithm of the study, ε-MOEA, four potential multi-objective evolutionary algorithms are used. This comparison can aid in thoroughly evaluating the performance of ε-MOEA, diversifying solutions, testing stability, and improving ε-MOEA. It will assist in guaranteeing that the solutions developed for the nuclear waste disposal challenge are optimal and best suited to real-world needs and situations. These data indicate that, while all algorithms could find the best answer, their computing efficiency varied greatly, as shown in Fig. 8 below:

The runtimes of the other two algorithms, NSGA-II and NSGA-III, are nearly identical to PESA2, at 14,32% and 12,49%, respectively. The study demonstrates that all algorithms are capable of solving the problem; however, despite variations in performance, ε-MOEA is the most appropriate algorithm because of its optimal fitness value and fast runtimes. The study utilized ε-MOEA, an algorithm designed to solve problems with special properties like legally binding goals or safety and environmental risks. The algorithm generated diverse values and performed well in stable and short runtimes. In the 2nd iteration, it completed processing with a shortest processing time of 5.00 seconds, demonstrating its outstanding capability in solving complex problems, such as nuclear waste disposal conflicts. It is acknowledged that

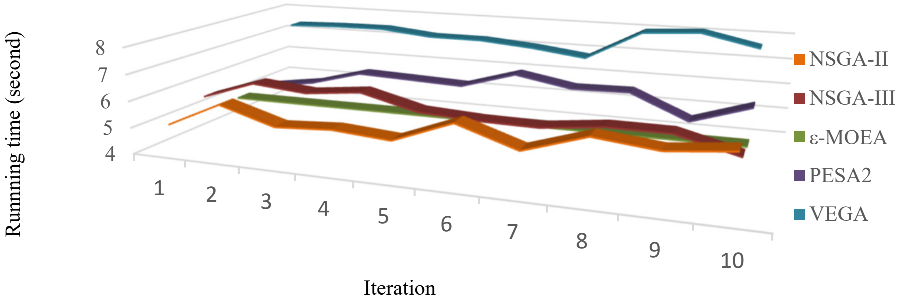


Fig. 8: A comparison of runtimes between different algorithms.

the analysis presented in this study is primarily computational and does not yet incorporate empirical validation through a real-world nuclear waste disposal case study. The purpose of this computational focus was to establish a proof of concept for the proposed ε-MOEA-GT framework, ensuring its feasibility, efficiency, and stability under controlled experimental conditions. While this limitation reduces the immediate practical generalizability of the results, it provides a necessary foundation for subsequent research. Future work will extend the framework by applying it to empirical datasets, such as cross-national nuclear waste policies, disposal cost assessments, and environmental risk indices, to test its robustness in real-world contexts. This progression from computational modeling to empirical application will enhance the practical value of the research and strengthen its policy relevance.

CONCLUSION

Nuclear waste treatment disputes remain a persistent challenge in international relations and environmental governance. This study contributes a novel integration of ε-MOEA with GT, creating a multi-objective framework that simultaneously incorporates political, environmental, and economic dimensions of nuclear waste management. Unlike previous single-dimensional models, this approach demonstrates how multiple conflicting objectives can be balanced in practice. Empirical findings show that the ε-MOEA-GT framework enables more stable cooperative outcomes by reducing incentives for unilateral defection and improving the fairness of burden-sharing among states. Although the algorithm requires longer computation times due to the complexity of handling multiple actors and objectives, the results indicate that these trade-offs yield more equitable and sustainable agreements. Practically, this model offers policymakers a structured tool to evaluate negotiation strategies, anticipate conflict scenarios, and identify agreements that are both efficient and stable. By directly addressing the interplay of strategic behavior and multi-objective optimization, the study provides a pathway for mitigating international disputes over nuclear waste treatment.

AUTHOR CONTRIBUTIONS

The 1st author contributed primarily to the preparation and writing of the manuscript. Do Thi Ngoc Anh participated in developing the research idea, discussing the model jointly with Dong Trung Anh, and carried out the study under the supervision of Trinh Bao Ngoc. Vu Quoc Huy contributed to dataset collection and field validation. Do Thi Phuong Phuong Thao, Pham Thi Huyen, Ngo Van Quyen, and Hoang Thi Thuy Dung provided financial support that enabled the successful completion of this research.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

ε-MOEA	Epsilon Multi-Objective Evolutionary Algorithm
BE	Benefits for the Environment (in payoff function)
BH	Benefits for Humans (in payoff function)
C	Cost (one of the core objectives)
CPU	Central Processing Unit
E	Environmental Impact (one of the core objectives)
F	Fitness Function
GB	Gigabyte
GMCR	Graph Model for Conflict Resolution
GT	Game Theory
IAEA	International Atomic Energy Agency
MOEA	Multi-Objective Evolutionary Algorithm
MR	Money Received (in payoff function)
NE	Nash Equilibrium
NP-hard	Non-deterministic Polynomial-time hard (a class of computational problems)
NSGA-II	Non-dominated Sorting Genetic Algorithm II
NSGA-III	Non-dominated Sorting Genetic Algorithm III
NWM	Nuclear Waste Management
NWT	Nuclear Waste Treatment
P	Preferences (one of the core objectives)
PESA2	Pareto Envelope-based Selection Algorithm II
R	Risk (one of the core objectives)
RAM	Random-Access Memory
RP	Potential Risk (in payoff function)
SSD	Solid-State Drive
USD	United States Dollar
VEGA	Vector Evaluated Genetic Algorithm

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