# A GENETIC ALGORITHM APPROACH TO THE OPTIMIZATION OF A RADIOACTIVE WASTE TREATMENT SYSTEM

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## ABSTRACT

This study is concerned with the applications of goal programming and genetic algorithm techniques to the analysis of management and operational problems in the radioactive waste treatment system (RWTS). A typical RWTS is modeled and solved by goal program and genetic algorithm to study and resolve the effects of conflicting objectives such as cost, limitation of released radioactivity to the environment, equipment utilization and total treatable radioactive waste volume before discharge and disposal. The developed model is validated and verified using actual data obtained from the RWTS at Kyoto University in Japan. The solution by goal programming and genetic algorithm would show the optimal operation point which is to maximize the total treatable radioactive waste volume and minimize the released radioactivity of liquid waste even under the restricted resources. The comparison of two methods shows very similar results.

## INTRODUCTION

The world's increasing demand for the electric power is tending to exhaust natural resources. Although the importance of nuclear power plants has been emphasized because of the efficiency of resources utilization, their construction and operation are sometimes avoided and limited by the problems of safety and generated radioactive waste. With these restricted conditions, existing nuclear power plants have to generate more electric power in order to meet this demand, consequently resulting in the more generation of the radioactive waste. Because the radioactive waste volume treatable by the RWTS is limited by the capacity and restricted resources (cost, water consumption, storage area limitations etc.) the planning and maintaining of the optimal operation condition of RWTS with multi-objectives has been the one of the major issues during the last several decades. The actual optimization in the field of nuclear power implies an economic evaluation based ona cost benefit analysis. But the system has multiple and conflicting objectives. To deal with these complex problems, we used the goal programming and genetic algorithm and their results are compared. The goal programming establishes goals for each objective and minimizes the deviation from its goals. Therefore, it could find the optimal operation point to make the best use of the restricted resources. An important aspect of goal programming is that it seeks a best solution with respect to a number of conflicting and incompatible objectives which are achievable at the expense of one another.

Genetic Algorithm (GA) is a stochastic search algorithm introduced by J. Holland during the 1970s based on ideas and techniques from genetic and evolutionary theories (Holland 1975)[1]. Such GA has been theoretically and empirically proven to provide a robust search in complex spaces. GA requires the variable set of the optimization problem to be coded as a finite length string. GA operates at the string level to exploit similarities among high performance strings, where conventional methods usually deal with

[1] Holland, J. H. Adaptation in natural and artificial systems Ann Arbor: The University of Michigan Press; 1975

cost functions and variables directly. This makes GA computationally simple yet powerful in the search for improvements (Goldberg 1988)[2]. The most striking characteristic of GA is the large flexibility allowed in the formulation of the optimal problem and the search process for the optimal solution.

This paper presents a GA approach to the radioactive waste treatment system optimization. The GA method is applied to evaluate the performance of a radioactive waste treatment system that has multi-objectives and various constraints. The main purpose of our study is to demonstrate the potential of GA in the optimization of such problems and to present guidelines for the application. And as a result of this study, we expect that the method will generate the optimal condition of operation which is to maximize the total treatable radioactive waste volume, to minimize the released radioactivity of radioactive liquid wastes and to minimize the radioactive solid wastes.

## GENETIC ALGORITHM

Genetic Algorithm is a random search technique that mimics processes observed in natural evolution. It combines survival of the fittest (or best) among string structures (solutions) with a structured yet randomized information exchange. Genetic algorithms differ from traditional optimization techniques in many aspects. They work with an encoding of the variables (typically bit string) rather than the variables themselves, and use probabilistic transition rules to move from one population of solutions to another rather than a single solution to another. The most important and interesting characteristic of genetic algorithms is that they use only objective function evaluations. That is, they does not use any information on differentiability, convexity or other auxiliary characteristics. This property makes genetic algorithms easy to use and implement for a wide variety of optimization problems.

A simple genetic algorithm works by randomly generating an initial population of solutions (a generation), then moves from one generation to another by breeding new solutions. The traditional breeding process involves objective function evaluation and three operators. The first operator is reproduction where strings (solutions) are copied to the next generation with some probability based on their objective function value. The second operator is crossover where randomly selected pairs of strings are mated, creating new strings. The third operator, mutation, is the occasional random alteration of the value at a string position. It plays a secondary role in genetic algorithms since, in practice, it is performed with a very small probability (on the order 1/1000). Mutation diversifies the search space and protects from loss of genetic material that can be caused by reproduction and crossover (Figure 1).

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[2] Goldberg, D. E. Genetic algorithms in search, optimization and machine learning. Reading,Massachusetts: Addison-Wesley; 1985

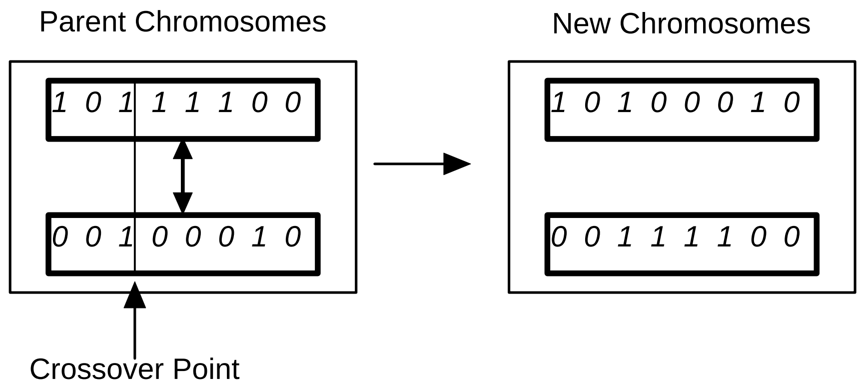


**Figure 1** Crossover operator

## SYSTEM MODELING AND OPTIMIZATION PROCESS

In order to carry out the optimization a feasible region must be determined, based on the system identification. In this study, system identification is based on the radioactive waste treatment system (Figure 2) of KUR (Kyoto University Research Reactor in Japan).

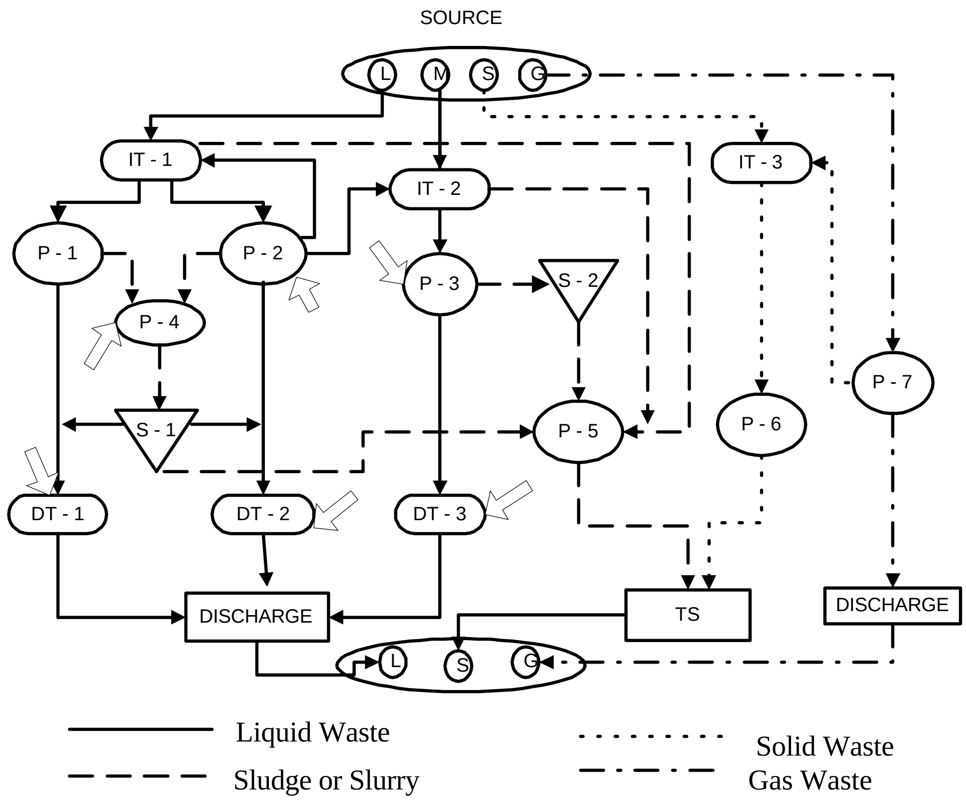


Figure 2. Reference System

### *System Criteria*

The priority order was temporarily set and the sensitivity analysis was carried out for priority rearrangement, variation of target values and adding or deleting the goal constraints.

· *Cost Restriction*

Treatment cost, $C_t$, the disposal cost as a consignment fee for the temporarily stored wastes cost, $C_d$, and the cost of water, $C_w$, are assumed to change proportional to their respective amount.

$$(C_T + C_D + C_W) + d_1^- - d_1^+ \leq 10^7 \left( \text{Yen}/\text{yr} \right)$$

Therefore, the objective function can include the following.

$$\text{Minimize} \quad P_1(d_1^-)$$

$$\begin{aligned} &P_i \; : \text{i-th priority} \\ &d_i^- : \text{under achievement of the i-th goal} \\ &d_i^+ : \text{over achievement of the i-th goal} \end{aligned}$$

· *Water Consumption*

Water is consumed for cooling at P-3, and P-4 and back washing at P-2, while the cooling water is recycled at P-3. It is spent without reuse at P-4. Water is also used for dilution at DT-1, DT-2, DT-3 so as to meet the release criteria (below $10^{-1}$ *m*Ci/m$^3$ or $20^{-1}$*m*Ci/m$^3$).

$$X_{P2W} + X_{P3W} + X_{P4W} + X_7 + X_8 + X_9 + d_2^- - d_2^+ \leq 5000 \left( m^3/\text{yr} \right)$$

$$\begin{aligned} &X_{PiW} = \text{Water volume at the P-i} \;\; (i = 2,3,4) \\ &X_i = \text{Water volume at the i component} \;\; (i = 7,8,9) \end{aligned}$$

Therefore, the objective function can include the following:

$$\text{Minimize} \quad P_2(d_2^-)$$

· *Total Operation DaysLimit*

This equation includes the operation days, monitoring, and regeneration days.

$$Y_1 + Y_2 + Y_3 + Y_4 + Y_{MON} + Y_{REG} + d_3^- - d_3^+ \leq 200 \;\; (\text{day/yr})$$

$$\begin{aligned} &Y_1 = \text{Annual operation days of P-1} \\ &Y_2 = \text{Annual operation days of P-2} \\ &Y_3 = \text{Annual operation days of P-3} \\ &Y_4 = \text{Annual operation days of P-4} \\ &Y_{MON} = \text{Annual operation days for monitoring} \\ &Y_{REG} = \text{Annual operation days for regeration} \end{aligned}$$

Monitoring days is 2 times the evacuation frequency of each inlet tank because monitoring is required before and after released from the inlet tank.

Therefore, the objective function can include the following.

$$\text{Minimize} \quad P_3(d_3^-)$$

· *Surface Dose Limit*

*This equation is used at the temporary storage area of solid waste to limit the surface dose.*

$$\frac{1}{2}\left\{\left(\frac{q_{SLG}}{50^2}\right)A\left(\frac{SLG}{TS}\right)+\left(\frac{q_{SLY}}{50^2}\right)A\left(\frac{SLY}{TS}\right)+\left(\frac{q_{SW}}{50^2}\right)A\left(\frac{SW}{TS}\right)\right\}+d_4^- - d_4^+ \le 5 \ \ (mR/yr)$$

$q_i$ : Dose conversion factor $(mR \cdot m^2/\mu Ci \cdot yr)$ $\{i = SLG, SLY, SW\}$
$A_i$ : Activity of the waste
SLG : sludge, SLY : slurry, SW : solid waste, TS : temporary storage

½ means that wastes are taken out to the outside every other six months for disposal. $50^2$ means that radiation dose rate, i.e., surface dose, are measured at the distance of 50 m from the temporary storage area.

*Therefore, the objective function can include the following.*

$$\text{Minimize} \quad P_4(d_4^-)$$

- *Limit of Storage Area*

½ means that wastes are taken out to the outside every other six months for disposal.

$$\left\{\frac{1}{2}\sum_i\left(\frac{a_i}{v_i}\right)\times X_{TS,i}\right\}+d_5^- - d_5^+ \le 90 \ \left(m^2/yr\right), i = (SLG, SLY, COM, IMC, WF)$$

$a_i$ : Occupied area per drum $(m^2)$ $\{i = SLG, SLY, COM, IMC, WF\}$
$v_i$ : Occupied volume per drum $(m^3/drum)$ $\{i = SLG, SLY, COM, IMC, WF\}$
$X_{TS,i}$ : Radwaste volume at temporary storage
COM : Compactible solid wase, IMC : Im - compactible solid waste, WF : Waste filter

Therefore, the objective function can include the following.

$$\text{Minimize} \quad P_5(d_5^-)$$

From the above equations, it is possible to construct the objective function as follows:

$$\text{Minimize} : P_1d_1^- + P_2d_2^- + P_3d_3^- + P_4d_4^- + P_5d_5^-$$

## RESULTS

The results obtained by goal programming, genetic algorithms and RESTEM based on Shimizu's modeling(4) are considerably different from each other. However, after adding material balance constraints for each equipment set and system to Shimizu's modeling, the results obtained by goal programming and genetic algorithm become remarkably similar to that of RESTEM. The sensitivity analysis was done for the modified model used in this paper and this study shows that the modified model can be applied to the various type of system arrangement while Shimizu's was only good for the RWTS of Kyoto University research reactor. However the results of sensitivity analysis can not be fully compared since Shimizu presented only the calculation result, without the supporting data.

### *Validation and Verification of the Model*

In order to carry out the validation and verification of the model, the optimal point was compared with that of Shimizu and the actual value was compared in Tables 1 ~ 5. In Table 1 and Table 2, management cost, water consumption, surface dose, and operation days are close to the design values of $10^7$ Yen/yr, 5000

$m^3$/yr, 5 mR/yr, and 200 days/yr, respectively. This means that the optimal operation point makes the best use of the restricted resources. When the solution was compared with the actual value in Table 1, the total treatable radioactive waste volume was increased to 1.5 times the actual value, and the discharged radioactivity was decreased for the treatable volume, i.e. reduced to 153*m*Ci/$m^3$. In Table 3, dilution water volume was more than that of Shimizu, since the release limit was lowered to $20^{-1}$*m*Ci/$m^3$. Therefore, much water might be required to dilute radioactive liquid waste in order to meet the release limit. In Table 5, slurry and sludge generation rate are all the same, while daily the capacities of P-1, P-2, P-3, and P-4 in column 4 show the lower bound of the design value. With the lower bound, the operating efficiency can be reduced a little bit but it could be one of the best ways when the capacity for input volume is required to be expanded in future and if the life time of the equipment is considered.

**Table 1 Objectives of Management I**

| | **Treatable Amount ($m^3$/yr)** | **Management Cost ($10^4$Yen/yr)** | **Discharged Radioactivity (μCi/yr)** | **Water Consumption ($m^3$/yr)** |
|---|---|---|---|---|
| Actual | 532 | 600.0 | 126.7 | 2,484.7 |
| SR | 1.5×532 | 900.0 | 190.0 | 3,727.0 |
| SP | 2.0×532 | 1,014.1 | 84.82 | 5,000.0 |
| **YP(I)** | **1.5×532** | **999.9** | **156.4** | **4,999.9** |
| **YP(II)** | **1.5×532** | **999.9** | **153.8** | **4,999.9** |

SR: Solution by RESTEM based on Shimizu's modeling
SP: Solution by goal programming based on Shimizu's modeling
YP(I): Solution by goal programming based on modified modeling with varied objective function
YP(II): Solution by genetic algorithm based on modified modeling with fundamental objective function

**Table 2 Objectives of Management II**

| | **Storage Area ($m^2$)** | **Surface Dose (mR)** | **Water Cost ($10^4$Yen/yr)** | **Treatment Cost ($10^4$Yen/yr)** | **Disposal Cost ($10^4$Yen/yr)** |
|---|---|---|---|---|---|
| SR | 33.21 | 4.51 | 18.635 | 224.3 | 657.02 |
| SP | 22.85 | 5.18 | 24.941 | 155.2 | 840.00 |
| **YP(I)** | **20.65** | **4.91** | **25.000** | **248.9** | **726.01** |
| **YP(II)** | **19.81** | **4.77** | **25.000** | **272.9** | **702.03** |

**Table 3 Specification of Operation Days and Water Consumption**

| | Operation Days (d) | | | | Water Consumption ($m^3$/yr) | | |
|---|---|---|---|---|---|---|---|
| | Operation | Monitoring | Regener-ation | Total | Regener-ation | Dilution | Cooling |
| SR | 100.5 | 91.7 | 7.8 | 200.0 | 109.33 | 1,013.3 | 2,604.3 |
| SP | 94.7 | 59.4 | 4.7 | 158.8 | 66.19 | 1,184.7 | 3,737.2 |
| **YP(I)** | **131.2** | **58.9** | **7.6** | **197.7** | **105.85** | **2,219.6** | **2,674.4** |
| **YP(II)** | **128.6** | **60.1** | **8.7** | **197.3** | **122.11** | **2,146.9** | **2,730.9** |

**Table 4 Radioactive Liquid Waste Management Plan**

| Process | | Volume ($m^3$/yr) | Operating Days (d/yr) | Volume per day ($m^3$/d) | Sludge & Slurry rate (%) |
|---|---|---|---|---|---|
| P-1 | SR | 437.61 | 21.88 | 20.00 | 2.00 |
| | SP | 259.10 | 12.90 | 20.00 | 5.00 |
| | **YP(I)** | **468.06** | **23.40** | **20.00** | **2.00** |
| | **YP(II)** | **424.86** | **21.24** | **20.00** | **2.00** |
| P-2 | SR | 390.48 | 19.52 | 20.00 | 2.00 |
| | SP | 236.40 | 11.80 | 20.00 | 5.00 |
| | **YP(I)** | **378.04** | **18.90** | **20.00** | **2.00** |
| | **YP(II)** | **436.10** | **21.80** | **20.00** | **2.00** |
| P-3 | SR | 63.08 | 17.71 | 3.56 | 2.00 |
| | SP | 16.10 | 8.10 | 2.00 | 2.00 |
| | **YP(I)** | **68.08** | **33.26** | **2.04** | **2.00** |
| | **YP(II)** | **74.00** | **34.03** | **2.18** | **2.00** |
| P-4 | SR | 16.56 | 41.41 | 0.2 | |
| | SP | 24.70 | 61.90 | 0.4 | |
| | **YP(I)** | **9.36** | **55.62** | **0.2** | |
| | **YP(II)** | **8.49** | **51.48** | **0.2** | |

**Table 5 Discharged Radioactive Liquid Waste**

| Process | | Discharged Volume ($m^3$/yr) | Radioactivity Limit (μCi/$m^3$) | Discharged Amount (μCi/yr) |
|---|---|---|---|---|
| DT-1 | SR | 1,303.30 | 0.1 | 130.33 |
| | SP | 1,305.00 | 0.05 | 65.25 |
| | **YP(I)** | **2,355.17** | **0.05** | **117.75** |
| | **YP(II)** | **2,137.84** | **0.05** | **106.89** |
| DT-2 | SR | 499.59 | 0.1 | 49.96 |
| | SP | 367.60 | 0.05 | 18.38 |
| | **YP(I)** | **708.90** | **0.05** | **35.44** |
| | **YP(II)** | **817.80** | **0.05** | **40.89** |
| DT-3 | SR | 97.27 | 01 | 9.73 |
| | SP | 23.70 | 0.05 | 1.19 |
| | **YP(I)** | **64.32** | **0.05** | **3.21** |
| | **YP(II)** | **121.67** | **0.05** | **6.08** |

## *Sensitivity Analysis*

The target values of goals were changed, the priority order was rearranged and the goal constraints were added in or deleted from the priority structure for the sensitivity analysis.

The analysis, changing the target values of goal constraints, was conducted to analyze the resource requirements to achieve stated target values of goals or level of goal achievements for the capacity or level of resources available. The total treatable volume was varied from 532 $m^3$/yr to 1064 $m^3$/yr (= $2\times532$ $m^3$/yr) increased by 0.5 times. Its optimal value was 798 $m^3$/yr (= $1.5\times532$ $m^3$/yr). The goal level of cost limit was decreased to $9\times10^6$ Yen/yr, and the release limit of radioactivity from $10^{-1}$ *m*Ci/$m^3$ to $20^{-1}$ *m*Ci/$m^3$. Also other goal values (operation days, surface dose limit, and etc) were varied. The target values of goals must be kept as original design value except the release limit. The design value of release limit was $10^{-1}$ *m*Ci/$m^3$ originally but the optimal point was obtained at $20^{-1}$ *m*Ci/$m^3$. It implies that the design value for the release limit can be lowered.

For the other sensitivity analysis the priority order was rearranged and the goal constraints were added in or deleted from the fundamental objective function which was composed of cost, operation days, and water consumption. Two types of result were obtained and were compared at row YP(I) and YP(II) in Table 1 ~ 5. YP(I) considered the various objective function which was added or deleted goal constraints of the storage area and surface dose limit in the fundamental objective function by goal programming. Despite adding or deleting the goal constraints of surface dose, storage area and the rearrangement of the priority order the result was not affected at all. The results of YP(II) in the tables were calculated when the fundamental objective function was considered and which is obtained by genetic algorithms. And it was found that the priority order was not important also because the result was not affected by the rearrangement of priority order.

## CONCLUSIONS

GA is applied to the optimization problem of radioactive waste treatment system. The most attractive feature of GA is the flexibility allowed in the problem formulation and in the search process. The GA has capabilities to predict the optimal point at any given constraints as aforementioned. Although there are many constraints involved to solve the complex problem, the decision maker has a freedom to calculate the optimal operation point to satisfy its needs.

At the optimal operation point of the reference system, which makes the best use of the restricted resources, the following conclusions are obtained:

Both the P-1 and P-2 are operated at the lowest rate (20 $m^3$/day) with the lowest production of sludge (2%),

P-3 is operated at the lowest rate (2 $m^3$/day) and the lowest production rate of slurry (2%) while the operating days are longer than any other units,

Total treatable radioactive waste volume is 1.5 times as much as nominal value and the release limit of radioactive liquid waste is $20^{-1}\mu Ci/m^3$.

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## KEY WORDS

Multi-objective, Goal programming, Genetic Algorithm, Reproduction, Cross-over.