Factors Evaluation of Particle Swarm Optimization in Para-Tank Model using Gray Decision Making Method

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Abstract - Gray situation decision making is an important component in Gray system theory. It is capable of making satisfactory decisions from among multiple cases, strategies, and objectives. This study investigates three factors of the acceleration equation, i.e. acceleration constants c_1 and c_2 and inertia weight w, which are then used as events in particle swarm optimization of parameters in the para-tank model (PTM) during rainfall–runoff simulation. The values of 0.2, 0.5, and 0.8 are respectively used to create 27 groups of situation sets using the indices of the three decision-making objectives, root mean squared error, coefficient of efficiency, and percent error of total volume, in order to analyze the systematic effectiveness. After comparing the comprehensive effect measures, an optimal decision is reached when the combined effectiveness is at the highest when $c_1 = 0.8$, $c_2 = 0.2$, and $w = 0.5$ and become the optimal parameter values for the PTM.

Keywords - Para-tank model, particle swarm optimization, gray system theory, gray situation decision making.

I. INTRODUCTION

The original concepts of the para-tank model (PTM) and its simplified logical structure were used to demonstrate the properties of the hydrology system in a specific region. Both the above and below surface runoff mechanisms were used to simulate the regional rainfall–runoff relationship, and subsequently, a new hydrology model known as PTM was developed using particle swarm optimization (PSO) for optimizing variables in the model. PSO will be used to optimize parameters within the flood PTM [1]. However, when searching for model parameters using PSO, the acceleration constants c_1 and c_2 and inertia weight w are inherent in the acceleration equation. The existence of these factors indirectly affects the accuracy and simulation speed of the PTM. Therefore, gray decision making from gray system theory will be used to analyze the three factors in order to find the optimal combination.

PSO was developed in 1995 by Kennedy et al. [2] when studying the hunting behavior of bird. In 1998, Shi et al. [3] introduced inertia weight to improve convergence, which has thereafter become the standard version of PSO. The standard PSO is a simulation model of a simplified community and is based on a method of finding the optimal global solution for individual particles subject to their adaptability of the community environment when moved into a desirable region. This study analyzes the simultaneous variations in c_1, c_2, and w and forms three groups of set value mutual pairings. Gray system theory was proposed by Deng Julong [4] in 1982 and has gradually refined over the years. Most studies of related theories and applications of grey prediction and grey relational analysis have found few applications in gray situation decision making. Xue (2000) used gray system theory on explosion design and analysis. As there were multiple factors and objectives in his study, a multi-objective gray situation decision-making model was established from the numerical relationships among the data to show the rules of connections and restrictions. This model helps to find the optimal solution in finite explosion testing in a scientific manner [5]. Cao et al. (2006) used gray situation decision-making theory on the selection of sites for waste and sanitary landfill [6]. Zhang et al. (2009) used data from 1998 to 2007 to establish a gray situation decision-making model to help investors make the best decisions in real estate and the stock market [7]. Wu (2011) applied the multi-objective decision situation to evaluate access control security systems and established a gray relational decision-making system for each product, thus providing a reference to the consumer that is different from the one before, when most evaluations were made by experts via inspection of the systems [8]. Wong (2015) applied gray situation decision making to select industrial factory design proposals using the calculated comprehensive effect measure in size to choose the optimal design. His study presents a relatively scientific approach for choice evaluations in civil engineering [9].

This study will investigate the change in the three factors in the acceleration equation, i.e., acceleration constants c_1 and c_2 and inertia weight w, in PSO when finding optimizing the parameters in the PTM during rainfall–runoff simulation and their impact on accuracy and simulation speed. Three objective decision-making indices, root mean squared error (RMSE), coefficient of efficiency (CE), and percent error of total volume (VER), are used in the analysis to find the combined effectiveness when c_1, c_2, and w are optimal.

II. GRAY SITUATION DECISION-MAKING ANALYSIS

Decision making is applied when making decisions on the operation behavior based on certain defined overall objectives using the optimal comprehensive effect. The underlying premise of gray decision making is to find, from a multitude of strategies in an event, the optimal choice in terms of "comprehensive effects" in response to the occurrence of such an event. Types of gray decision making includes gray situation, gray relational, gray clustering, gray statistical, gray interval, gray planned, gray layer, and gray line capacity planning.

Gray decision making is a process of elimination that chooses strategies for different events based on the effectiveness of the objectives.

Step 1: First, define the four main factors of gray situation decision making.

1. Case (A): cases that need to be handled. Let case set A = $\{a_i, i = 1, 2,\ldots, n\}$.

2. Strategy (B): plans for handling a certain case. Let strategy set B = $\{b_j, j = 1, 2,\ldots, m\}$.

3. Situation(S) and results (U): the effects of certain strategies on specific cases.

(1) Let the Cartesian product of A and B, $S = A \times B = \{S_{ij} = (a_i \times b_j) \mid a_i \epsilon A, b_j \epsilon B\}$ be the situation set.

(2) Construct an objective decision index set $P = \{p_k, k = 1, 2,\ldots, p\}$ to clearly set the index for consideration of decision making strategy.

(3) Confirm that the resulting sample value $u_{i,j}^p$ is from situation $S_{i,j}$ under the effects of objective p.

(4) Unify effect measure: define function θ: $u_{ij}^p \rightarrow r_{ij}^p \epsilon [0,1]$, where $r_{i,j}^p$ is the effect measure value after unification.

4. Objective (P): Evaluate the index of strategy effectiveness.

(1) Upper effect measure: Reflects the degree of divergence between the result sample value and the maximum result value, defined as Equation (**1**).

$$r_{ij}^p = \frac{u_{ij}^p}{i^{max},j^{max},u_{ij}^p} \tag{1}$$

where i_{max}, j_{max}, and u_{ij}^p are the maximum values of all the sample values related to objective p.

(2) Lower effect measure: Reflects the degree of divergence between the result sample value and the minimum result value, defined as Equation (**2**).

$$r_{ij}^p = \frac{i^{min},j^{min},u_{ij}^p}{u_{ij}^p} \tag{2}$$

where i_{min}, j_{min}, and u_{ij}^p are the minimum values of all the sample values related to objective p.

(3) Medium effect measure: Ideally, this result should be within a certain range of a designated objective, defined as Equation (**3**).

$$r_{ij}^p = \frac{\min(u_{ij}^p, u_0)}{\max(u_{ij}^p, u_0)} \tag{3}$$

where u_0 is the designated moderate value.

Step 2: Evaluate the situation and strategy according to the comprehensive effect measure values.

1. Find the comprehensive effect measure r_{ij}^{Σ} of the situation S_{ij}.

$$r_{ij}^{\Sigma} = \frac{1}{l}\sum_{p=1}^{l} r_{ij}^p \tag{4}$$

2. Evaluate the comprehensive effect measure according to the r_{ij}^{Σ} value found, and then sort and confirm the optimal or satisfactory situation and strategy.

Step 3: Verify results using statistical methods.

1. After sorting the evaluations of the comprehensive effect measure of the r_{ij}^{Σ} values, separate the data into three sections of front, middle, and back.

2. Verify the results of gray situation decision making by evaluating the statistical values of events and strategies in each region.

III. CASE STUDY

A. Summary of the Research Region

Kaohsiung metropolitan region was chosen as the research area. According to the report of "Kaohsiung City flood prevention and drainage plan" [10], on July 11, 2001 at 5pm, a violent south west airflow due to Typhoon Trami caused continuous torrential rain in the Kaohsiung region for 10 h. According to records from Cianjhen and Zuoying weather stations of the weather bureau, the total accumulated rainfall was 525 and 493 mm, respectively. The highest recorded rainfall within 1 h at Zuoying weather station was 126.5 mm, which was close to the 100-year frequency storm rainfall of 130 mm; the rainfall within 3 h peaked at 329 mm, which exceeded the 200-year frequency storm rainfall of 300 mm. Cianjhen weather station recorded the highest rainfall of 119.5 mm in 1 h and 239 mm over 3 h. Both of the above-mentioned rainfall amounts recorded greatly exceeded Kaohsiung City's flood drainage design standards (instant water drainage: 5 years, flood prevention: 20 years). In addition, the tide level at the mouth of the Love River increased dramatically, obstructing the flood. Even though the city's sewage system was at over 90% capacity, the system was seriously overloaded, causing floods of over 1 foot high in low-lying regions of Yancheng District, Benguan and Benhe Village, Baozhugao, Canal No. 2, and Cianjhen District spreading across an area of 300 hectares. In order to compare the results of the PTM, rainfall data of 711 from the Kaohsiung City flood prevention and drainage plan was used, and the average rainfall value of Kaohsiung, Zuoying, and Fengshan was used as the rainfall r(*t*) in the simulation.

In this study, the PTM was primarily used to investigate the effects of torrential rain on urban areas that were relatively more impermeable. We mainly focused on the Love River Basin in Kaohsiung, and according to the distribution of the flooding areas in the 711 flood, the basin was divided into nine catchment sections according to geographical properties, as shown in Fig. (**1**). Residential areas are in catchment section 3; hence, it was chosen as the region in the study.

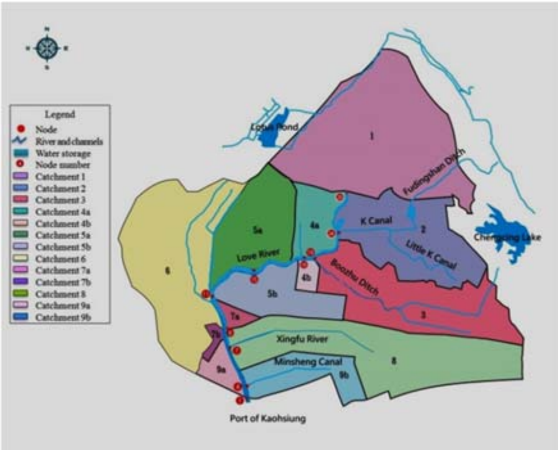

Fig. (1). Catchments in Love River Basin.

B. Analysis Results

Variations in c_1, c_2, and w in the acceleration equation used in PSO are the focus of this study. The gray situation decision-making model is used to analyze the factors, c_1, c_2 and w, in finding the optimal combination. The related information used in the gray situation decision-making model is listed Table 1.

TABLE 1. RELATIONSHIP TABLE OF THE FOUR MAIN FACTORS IN GRAY SITUATION DECISION MAKING.

Gray decision making Four main factors		A = {a_i, i = 1, 2,…, n}			P = {p_k, k = 1, 2,…, p}		
		c_1	**c_2**	**w**	**RMSE**	**CE**	**VER**
B = {b_j, j = 1, 2,…, m}	**0.2**	S = A × B ={$S_{ij} = (a_i \times b_j) \mid a_i \in A, b_j \in B$}			$u_{ij}^p \rightarrow r_{ij}^p \in [0,1]$		
	0.5						
	0.8						

1. Event (A): This study focuses on analysis of c_1, c_2 and w; hence, we define $a_1 = c_1$, $a_2 = c_2$, and a_3 = w.

2. Strategy (B): Events A_1, A_2, and A_3 have values between 0 and 1. To simplify the analysis in terms of the values used, we selected values of 0.2, 0.5, and 0.8 based on the rule of thirds to represent the median value of the three regions of front, middle, and back. Hence, b_1 = 0.2, b_2 = 0.5, and b_3 = 0.8.

3. Objective (P):

(1) Lower effect measure using RMSE to find the minimum value.

(2) Upper effect measure using CE to find the maximum value.

(3) Medium effect measure using VER to find the moderate value.

Based on a recently published paper in 2015 on finding parameters in the rainfall–runoff PTM [1], the rainfall amount in the water catchment areas and the flow rate were entered into the PTM analysis. Global area acceleration constants c_1, c_2 and inertia weight w in the region were substituted into the situation set $S_{i,j}$. The following parameters were set: number of particles m = 30, dimensions d = 4, residue height before rain h_0 = 3 mm, accumulated rainfall r_0 = 1 mm, infiltration capacity i(*t*) = 1 mm, and the capacity of the sewage designed q_c was set as the standard design specifications for that region in Taiwan. The section design standard of water drainage was set at 70.9 mm/h, the rainfall intensity of the 5-year storm in Kaohsiung City rainwater sewage system. X_{i1} represents the residue height of the infiltration and depression storage and H_1 was set between 1 and 100, X_{i2} represents the outflow rate of the geographical flood characteristic λ_1 set between 0 and 1, X_{i3} represents the sewage system's residue height H_2 set between 50 and 100, X_{i4} represents the sewage system's outflow rate λ_2 at load capacity set between 0 and 1, and frequency count tmaxwas set at 1000. After calculations, we obtained 27 groups of H_1, λ_1, H_2, and λ_2 as PTM parameters and the objective decision index values of RMSE, CE, and VER. Since VER was negative, correction was needed to change the VER to positive under gray decision making as shown in Table **2**.

TABLE 2. SITUATION SET RESULTS.

Case	PSO factor			PTM parameters				Objective decision index			
	c_1	c_2	w	H_1 (mm)	λ_1 (%)	H_2 (mm)	λ_2 (%)	RMSE	CE	VER	
										Original value	Correction
1	0.2	0.2	0.2	37.3486	59.04	52.1690	24.27	3.6585	0.9996	-0.9026	0.7317
2	0.2	0.2	0.5	37.4537	59.20	52.1626	24.10	3.6581	0.9996	-0.9165	0.7178
3	0.2	0.2	0.8	36.5143	58.52	53.8165	23.96	3.7644	0.9996	-0.7649	0.8694
4	0.2	0.5	0.2	37.4536	59.20	52.1626	24.10	**3.6581**	0.9996	-0.9165	0.7178
5	0.2	0.5	0.5	37.4432	59.18	52.1681	24.12	3.6581	0.9996	-0.9150	0.7193

6	0.2	0.5	0.8	38.1944	57.20	49.4884	24.79	4.2088	0.9995	-1.1458	0.4885
7	0.2	0.8	0.2	37.4536	59.20	52.1626	24.10	3.6581	0.9996	-0.9165	0.7178
8	0.2	0.8	0.5	37.9559	59.81	52.8354	22.97	3.7171	0.9996	-0.9908	0.6435
9	0.2	0.8	0.8	35.1007	57.52	57.7463	26.87	4.1050	0.9995	-0.5410	1.0932
10	0.5	0.2	0.2	37.2949	58.94	52.1412	24.36	3.6592	0.9996	-0.8960	0.7383
11	0.5	0.2	0.5	37.4451	59.19	52.1813	24.11	3.6581	0.9996	-0.9150	0.7193
12	0.5	0.2	0.8	35.4207	53.67	50.5187	31.28	4.4024	0.9994	-0.7890	0.8453
13	0.5	0.5	0.2	37.4534	59.20	52.1628	24.10	3.6581	0.9996	-0.9165	0.7178
14	0.5	0.5	0.5	37.8917	60.17	52.9285	23.12	3.6754	0.9996	-0.9638	0.6704
15	0.5	0.5	0.8	41.4631	60.60	44.4441	23.21	4.3734	0.9994	**-1.6342**	0
16	0.5	0.8	0.2	37.4566	59.20	52.1635	24.10	3.6581	0.9996	-0.9169	0.7174
17	0.5	0.8	0.5	36.3037	58.05	50.8781	23.92	3.8747	0.9996	-0.7400	0.8942
18	0.5	0.8	0.8	35.2222	53.30	53.6074	29.58	4.8889	0.9993	-0.7856	0.8487
19	0.8	0.2	0.2	37.4683	59.22	52.1592	24.08	3.6581	**0.9996**	-0.9185	0.7157
20	0.8	0.2	0.5	36.9238	58.41	52.1357	24.83	3.6690	0.9996	-0.8464	0.7878
21	0.8	0.2	0.8	40.9988	59.94	38.2418	20.89	5.1020	0.9992	-1.5627	0.0716
22	0.8	0.5	0.2	37.4196	59.13	52.1440	24.18	3.6582	0.9996	-0.9126	0.7216
23	0.8	0.5	0.5	36.6787	58.95	51.6804	23.73	3.7633	0.9996	-0.7748	0.8594
24	0.8	0.5	0.8	38.6492	62.02	60.9766	24.58	4.9530	0.9993	-1.0521	0.5821
25	0.8	0.8	0.2	37.1967	58.78	52.1407	24.59	3.6615	0.9996	-0.8837	0.7506
26	0.8	0.8	0.5	37.3942	59.52	54.4564	23.98	3.7245	0.9996	-0.8947	0.7395
27	0.8	0.8	0.8	39.4834	61.45	54.3769	24.67	4.4578	0.9994	-1.2278	0.4065

Note: Numbers in bold and highlighted in gray are the extreme (max and min) values.

IV. DISCUSSION OF ANALYSIS RESULTS

A. Comprehensive Effect Measure

After using PSO to find the optimal H_1, λ_1, H_2, and λ_2 in each case, the four parameter values were entered into the PTM calculation using time step to obtain the flow rate Qc(t) and objective flow rate Qo(t). The objective minimum RMSE value, the maximum CE value, and the objective moderate VER value were used for evaluation. Results are shown in Table **3**. Case 20 (when c_1 = 0.8, c_2 = 0.2, and w = 0.5) shows the highest comprehensive effect measure.

TABLE 3. UNIFIED EFFECT MEASURE ANALYSIS TABLE OF GRAY SITUATION DECISION MAKING ON PSO FACTORS.

Case	PSO factor			Objective decision index			Comprehensive effect measure
	C_1	C_2	W	RMSE	CE	VER	
20	**0.8**	**0.2**	**0.5**	0.9970	1.0000	0.4821	**0.8683**
25	**0.8**	0.8	0.2	0.9991	1.0000	0.4593	0.8641
10	0.5	**0.2**	0.2	0.9997	1.0000	0.4517	0.8627
3	0.2	**0.2**	0.8	0.9718	1.0000	0.5320	0.8620
1	0.2	**0.2**	0.2	0.9999	1.0000	0.4477	0.8618
23	**0.8**	0.5	**0.5**	0.9721	1.0000	0.5259	0.8607
22	**0.8**	0.5	0.2	1.0000	1.0000	0.4416	0.8604
5	0.2	0.5	**0.5**	1.0000	1.0000	0.4401	0.8600
11	0.5	**0.2**	**0.5**	1.0000	1.0000	0.4401	0.8600
13	0.5	0.5	0.2	1.0000	1.0000	0.4392	0.8598
4	0.2	0.5	0.2	**1.0000**	1.0000	0.4392	0.8598
7	0.2	0.8	0.2	1.0000	1.0000	0.4392	0.8598
2	0.2	0.2	0.5	1.0000	1.0000	0.4392	0.8598

16	0.5	0.8	0.2	1.0000	1.0000	0.4390	0.8597
19	0.8	0.2	0.2	1.0000	**1.0000**	0.4380	0.8595
26	0.8	0.8	0.5	0.9822	1.0000	0.4525	0.8498
14	0.5	0.5	0.5	0.9953	1.0000	0.4102	0.8490
17	0.5	0.8	0.5	0.9441	1.0000	0.5472	0.8456
9	0.2	0.8	0.8	0.8911	0.9999	**0.6689**	0.8385
8	0.2	0.8	0.5	0.9841	1.0000	0.3937	0.8366
12	0.5	0.2	0.8	0.8309	0.9998	0.5172	0.7596
6	0.2	0.5	0.8	0.8691	0.9999	0.2989	0.7308
18	0.5	0.8	0.8	0.7482	0.9997	0.5193	0.7068
27	0.8	0.8	0.8	0.8206	0.9998	0.2487	0.6856
24	0.8	0.5	0.8	0.7386	0.9997	0.3562	0.6588
15	0.5	0.5	0.8	0.8364	0.9998	0.0000	0.6340
21	0.8	0.2	0.8	0.7170	0.9996	0.0438	0.5686

Note: Unified effect measures are rounded to four decimal places, and values in bold and highlighted in gray are the extreme values (min and max) of the objective decision index.

B. Verification of the Statistical Method

Table **4** was generated after the comprehensive effect measure were sorted and grouped into front, middle, and back sections using the frequency count statistics. In the first nine entries (front section) of the results, $c_1 = 0.8$ occurred four times, $c_2 = 0.2$ occurred five times, and $w = 0.5$ and 0.2 each occurred four times. From the viewpoint of statistics, when $c_1 = 0.8$, $c_2 = 0.2$, and $w = 0.5$, most of the first nine entries after sorting of the comprehensive effect measures were consistent with the results from gray situation decision-making comprehensive effect measures (objective decision indices: RMSE, CE, VER).

TABLE 4. FACTOR'S FREQUENCY OF OCCURRENCE IN ORDERED COMPREHENSIVE EFFECT MEASURE.

Section / Factor	Front		Middle		Back	
	Value	Frequency of occurrenc	Value	Frequency of occurrenc	Value	Frequency of occurrence
c_1	0.2	3	0.2	3	0.2	3
	0.5	2	0.5	4	0.5	3
	0.8	**4**	0.8	2	0.8	3
c_2	**0.2**	**5**	0.2	2	0.2	2
	0.5	3	0.5	3	0.5	3
	0.8	1	0.8	4	0.8	4
w	0.2	4	0.2	5	0.2	0
	0.5	**4**	0.5	4	0.5	1
	0.8	1	0.8	0	0.8	8

C. Discussion

When using PSO to optimize parameters in the PTM, the acceleration constants c_1 and c_2 and inertia weight w exist in the acceleration equation, which indirectly impact the accuracy of parameter optimization and simulation speed. But after adding the gray situation decision making, an optimal comprehensive effect can be achieved by choosing different strategies in different cases through the elimination process according to the objective results.

In our example, there were in total 27 cases and the objective decision indices, RMSE (smaller the better), CE (larger the better), and VER (nominal the best), were used for evaluation. For the objective decision index RMSE, the minimum unified effect measure value occurred in case 4 ($c_1 = 0.2$, $c_2 = 0.5$, $w = 0.2$). For the objective decision index CE, the maximum unified effect measure value occurred in case 19 ($c_1 = 0.8$, $c_2 = 0.2$, $w = 0.2$). For the objective decision index VER, the moderate value of the unified effect measure occurred in case 9 ($c_1 = 0.2$, $c_2 = 0.8$, $w = 0.8$). After evaluation of the comprehensive effect measures, the optimal case was found to be case 20 ($c_1 = 0.8$, $c_2 = 0.2$, $w = 0.5$) with a value of 0.8683, the decision of which could not be made using a single objective decision index, implying that multiple objectives are desirable for the best optimization.

Using statistical methods to verify the results, we found that in the sorted front section, $c_1 = 0.8$ occurred four times, $c_2 = 0.2$ occurred five times, and $w = 0.5$ occurred four times. We can see from the results that the combination of $c_1 = 0.8$, $c_2 = 0.2$, and $w = 0.5$ appears most frequently, which is also the optimal selection of the gray situation decision making. This confirms that gray situation decision making can indeed select a case with the optimal comprehensive effect. This is a simple and easy-to-use application of multi-objective optimization.

V. CONCLUSIONS

This study proposed the application of gray situation decision making for the analysis, comparison, and investigation of factors in the acceleration equation in PSO. After the objective decision index evaluation to the effect measures of RMSE, CE and VER were evaluated in our results; case 20 ($c_1 = 0.8$, $c_2 = 0.2$, $w = 0.5$) with an comprehensive effect measure of 0.8683 was the best out of the 27 cases. The statistics of frequency occurrence of the nine cases in the front section of the ordered data results verified the effectiveness of gray situation decision making. It also confirmed that PSO could generate a set of optimized factors during parameter simulation of the new hydrology model (PTM) that would help to a certain extent in enhancing speed and accuracy in future model simulations.

Using gray situation decision making to solve multiobjective optimization is a good reference with regard to decision making. However, finding out how to establish a more objective and quantitative index factor in the right weight ratios will be the topic for future development.

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