Optimal Wastewater Treatment Design by Using Genetic Algorithm

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Abstract

Integrated advanced wastewater treatment provides important fundamental solutions to problems associated with water scarcity prevailing in arid and semi-arid climatic regions.

This was accomplished through treated water with specific specification and characteristics suitable to be used for agricultural, domestic, and industrial purposes. This study is concerned with the use of genetic algorithm procedure for the optimum design of integrated advance wastewater treatment units, with their various types and characteristics. The aim of optimum wastewater treatment units design is to attain optimum values of certain pre-defined objective function.

The objective function is to satisfy certain constraints and achieve minimum capital, maintenance, and operation costs. Chemical clarification treatment unit was used in this study.

This study includes development of computer program for advances wastewater treatment plants design adopting genetic algorithm. The program was developed using Matlab software.

The results obtained from this study include the finding of optimum design criteria for advanced wastewater treatment plants. The obtained design criteria are satisfying the required water quality with minimum treatment cost.

الخلاصة

توفر المعالجات المتقدمة المتكاملة لمياه الصرف الصحي حلولا جذرية ومهمة لمشاكل شحة المياه السائدة في العديد من البلدان ذات النظم المناخية الجافه وشبه الجافه ، ويتم ذلك من خلال الحصول على مياه معالجة ذات مواصفات محددة بالإمكان استخدامها لمختلف الأغراض الزراعية والمنزلية والصناعية.

يتركز موضوع هذه الدراسة على استخدام طريقة الخوارزميات الجينية في التصميم الأمثل لوحدات المعالجة المتقدمة وبمختلف أنواعها ومواصفاتها. تهدف مسألة التصميم الأمثل لوحدات المعالجة المتطورة إلى الوصول إلى قيم معايير التصميم المختلفة والتي تعطي اقل قيمة لدالة الهدف وتحقق في الوقت ذاته متغيرات المسألة . وتمثلت دالة الهدف في كلفة وحدات المعالجة بعناصرها المختلفة إضافة لكلفة الصيانة والتشغيل.

تمت دراسة المعالجة المتقدمة لمياه الصرف الصحي وتحديد متغيرات التصميم باعتماد وحدة المعالجة الكيميائية

استخدمت مياه الصرف الصحي الخارجه من محطة المعالجة الثانوية المركزية في منطقة حمدان. استخدم برنامج baltaM والبرامجيات الاخرى المرتبطه في تطوير برنامج الخوارزميات الجينية الذي استخدم في الدراسة لإغراض الحصول على المحددات أعلاه .

احتوت المخرجات في هذه الدراسه على مجموعه المعايير التصميميه المثلى للمعالجه المتقدمه بحيث تحقق هذه المعايير النوعيه المطلوبه للمياه المعالجه وباقل كلفه.

Introduction

Two main objectives of wastewater treatment plants are to maximize the efficiency and minimize the cost. As these two objectives are conflicting, optimization research must be conducted by accessing a specified requirement that restricts the size of the process units to maximum efficiency or minimize cost. The most frequently observed objective is to minimize cost with specified insured efficiency. Different optimization approaches are available and genetic algorithm (GA) is one of them.

The genetic algorithm (GA) approach was found to be useful optimization tool, capable of providing optimal design estimate while incorporating design and effluent quality constraints [1]. Some of the advantages of a GA include [2]:

• It optimizes with continuous or discrete variables.

• It doesn't require derivative information.

• It, simultaneously, searches from a wide sampling of the cost surface.

• It deals with a large number of variables.

• It optimizes variables with extremely complex cost.

• It provides a list of optimum variables, not just a single solution.

• It may encode the variables so that the optimization is done with the encoded variables.

• It works with numerically generated data, experimental data, or analytical functions.

The aim of this study is to develop GA approach for optimum design of different alternatives of advanced wastewater treatment (AWT) plant. The optimum design includes establishing combinations of design criteria for the incorporated treatment units. To fulfill this aim, the study objectives include:

1. Developing and building a pilot plant of water treatment system to establish mathematical expressions to be used in relating the design criteria of flocculation and sedimentation units (which are mostly applied in AWT plants).

2. Writing a computer program using Matlab software to formulate the problem and perform the best design of AWT plant.

OPTIMIZATION MODEL FORMULATION

The primary objective of the wastewater treatment plant design is to determine design and operating parameters of the process such that the total cost is minimal and effluent quality meets the set standards. In this study an optimization model has been developed, which combines the GA.

The genetic algorithm is an optimization and search technique based on the principles of genetics and natural selection. A genetic algorithm allows a population composed of many individuals to evolve under specified selection rules to a state that maximizes the “fitness” (i.e., minimizes the cost function) [6]. The genetic algorithm is best illustrated by the simple flow diagram in Fig.(1). The population of strings is randomly initialized giving a diverse range of possible solution. Each of these solutions is evaluated and given a fitness score. At this point the population is examined to see if a suitable solution has been found. This could be obtained when a given goal has been reached or a certain level of improvement has not been achieved over a fixed number of generations. If the stopping criteria have been reached the GA enters loop involving three stages. The first stage is to select a new population based on fitness. This is, in Darwinian terms, performing a 'survival of the fittest' operation on the population. The selected population, which is usually the same size as the initial population, then forms the basis of a mating pool and enters the second stage of the loop. In the second stage, two genetic operations are applied to the mating pool crossover and mutation. The final stage of the loop re-evaluates the evolved population and then the loop return to the start where the stopping criteria are examined. If they are not met the population re-enters the loop, otherwise, the GA exits and the best solution found from the search is chosen [3, 4].

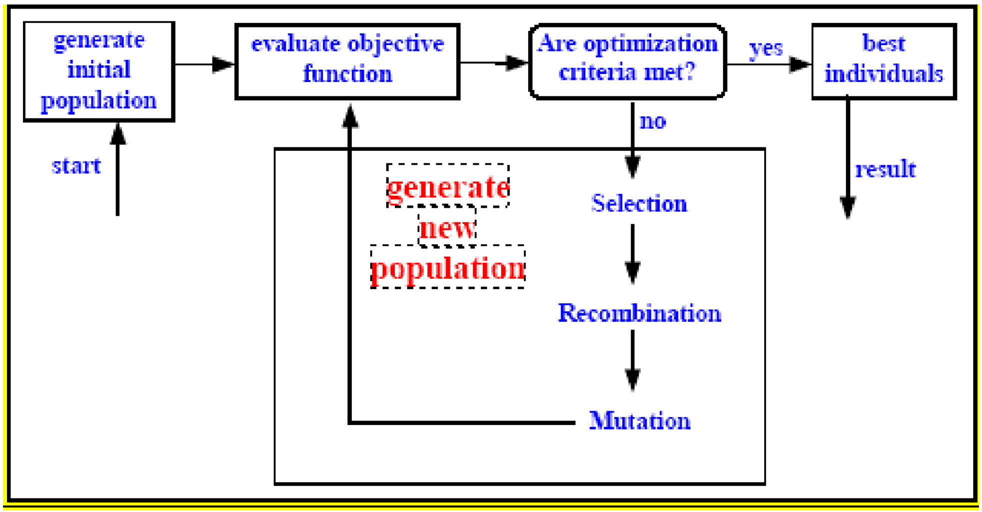

Fig.(1) Structure of genetic algorithm [5].

The basic steps of genetic algorithms development are namely:

1) Selection of model parameters (optimization variables),
2) Parameters encoding,
3) Generation of the initial population,
4) Evaluation of the string,
5) Selection of the (chromosomes) strings for reproduction [6],
6) Crossover of the selected strings, and
7) Mutation of the strings.

The adoption of these steps is dependent on type of GA application, which in this studies the design of AWT plant.

In this study, for combination of processes used to treat wastewater. This is particularly true for advanced treatment technologies capable of treating wastewater to a degree of quality appropriate for a specific reuse, making the selection of the most suitable sequence of processes for any potential reuse situation more complex. Chemical clarification unit is used.

Selection of Optimization Variables

Generally, optimization variables are divided into two sets; decision (independent) variables and state (dependent) variables. In designing an AWT plant, the decision variables include the design criteria of all the treatment units plant, while, the effluent quality and treatment cost are the state variables. The GA optimization determines the optimal values for all decision variables which are represented by the chromosomes. For the optimum design of AWT train using GA, the optimization variables depend on type of AWT plants. The design variables for chemical clarification unit are;

[t_{ra}, G_{ra}, No_{ra}, t_f, G_f, No_f, t_s, SOR, No_s]

t_{ra}, G_{ra}, and No_{ra} = detention time, velocity gradient, and number of rapid mix tanks, respectively.

t_f, G_f,.and No_f = detention time, velocity gradient, and number of flocculation tanks, respectively.

t_s, SOR, and No_s = detention time, surface overflow rate, and number of sedimentation tanks, respectively.

Specification of Objective Function

The objective function of AWT plant in the current population is taken as the sum of the annual costs, which is to be minimized. A general form of the applied objective function is;

$$Minimize\ f(x) = \sum_{1}^{N} C_i \quad \ldots(1)$$

where:

f (x) = objective function in terms of the total costs.

C_i = annual cost of individual unit that includes capital and operation and maintenance costs.

N = number of treatment units in each AWT unit.

x = decision variables

Formulation of Cost Function

The annual cost of water treatment includes the annualized capital cost, annual operation and maintenance cost, and land requirement cost."Capital costs" refers to the investment required to construct and begin the operation of the plant, principally materials, labor, and interest. Operation and maintenance costs include the costs associated with the labor, material, and energy required to operate and maintain the treatment plant [7]. The annual cost function for treatment unit-i can be written as:

$$C = ACC + LC + OMC \qquad ...(2)$$

where:

ACC = annualized capital cost of treatment unit, $

LC = land cost of treatment unit, $

OMC = annual operation and maintenance cost of treatment unit, $.

The annualized capital cost can be determined by spreading out the capital cost over a given number of years at a specific interest rate, and is defined as [8];

$$ACC = CC \times CRF \qquad ...(3)$$

$$CRF = \frac{m(1+m)^n}{[(1+m)^n - 1]} \qquad ...(4)$$

where CC is the capital cost of treatment unit, CRF is capital recovery factor, m is the interest rate per year, and n is the number of years over which the cost will be spread. In this study, all the capital costs shall be spread over a period of 20 years at a 8 percent annual rate of interest.

<u>Chemical Clarification Unit</u>

Chemical clarification process which is composed of three treatment units; rapid mix, flocculation, and sedimentation. For this treatment plant, Eq.(1) is rewritten as;

$$Minimize\ f(x_j) = \sum_1^3 C \qquad ...(5)$$

where; j = 9, $x_j \epsilon$ {t_{ra}, G_{ra}, No_{ra}, t_f, G_f, No_f, t_s, SOR, No_s}, and i= 1, 2, and 3 for rapid mix, flocculation, and sedimentation units, respectively.

For this treatment unit, the annual cost function (Eq. 2) is rewritten as;

$$C_i = ACC_i + LC_i + OMC_i \qquad ...(6)$$

<u>Specification of Design Variables Constraints</u>

The objective functions given above were subjected to a set of design and behavioral constraints. These constraints define the physical boundaries of the decision variables and are written in the form of equality or inequality functions, and as shown below:

The constraints of the chemical clarification unit refers as g can be stated as follows :

a) The power of mixing in rapid mix unit vary over the range (2-5) kW/m^3 per min. [9];

$$g_1: 2 \leq {G_{ra}}^2 \times \mu / t_{ra} \leq 5 \qquad \ldots(7)$$

b) The product of velocity gradient and detention time of flocculation unit varies over the range (10^4-10^5). [10];

$$g_2: 10^4 \leq G_f \times t_f \leq 10^5 \qquad \ldots(8)$$

c)The diameter of settling tank is not exceeding 60m [7];

$$g_3: \left(\frac{4Q}{\pi \; SOR \; NO_S}\right)^{0.5} \leq 60 \qquad \ldots(9)$$

d) The weir loading rate in settling tank is not greater than 250m^3/day/m [9];

$$g_4: \frac{Q}{\pi \left(\frac{4Q}{\pi \; SOR \; NO_S}\right)^{0.5}} \leq 250 \qquad \ldots(10)$$

e) The depth of the settling tank varies over the range (3- 4) m [7];

$$g_5: 3 \leq SOR \times t \leq 4 \qquad \ldots(11)$$

f) The concentration of effluent suspended solids is not greater than SS_{max},. where SS_{max} varies over the rang (5-10) mg/l [1];

SS_{ef} = 5,6,7,8,9,10 in the first run, second run , third run and so on.

$$g_6: SS_{ef} \leq SS_{max} \qquad \ldots(12)$$

Normalization of the Constraints

The constraints have to be normalized so that each one of them varies between: 1and 0 only. This is essential to get a good convergence rate during optimization process [11]. This can be made by transformation of the constraints to the following form:

$$\breve{g}_j(x) = y_j(x) - 1 \qquad \ldots(13)$$

where; $\breve{g}_j$ is normalized value of constraint g_j , $y_j(x)$ is a function of design variables, and j is the number of the constraints. The normalized values of the adopted constraints are given in Table (1).

Bounds of the Design Criteria

The bounds (or boundary limits) of any problem are the minimum and maximum values of all decision variables, which are in this study, the design criteria of AWT unit. The boundary limits of the problem under consideration were chosen to be the most frequent applied criteria. These limits are presented in Table (2).

Table (1) Normalized values of constraints

j	Normalized value ($\breve{g}_j$)
1	$-1 + 2 \times t_{ra}/{G_{ra}}^2 \times \mu \le 0$; for p≥ 2kW/m^3 per min
	$1 - 5 \times t_{ra}/{G_{ra}}^2 \times \mu \le 0$; for p ≤ 5 kW/m^3 per min
2	$-1 + 10^4/(G_f \times t_f) \le 0$; for $(G_f \times t_f) \ge 10^4$
	$1 - 10^5/(G_f \times t_f) \le 0$; for $(G_f \times t_f) \le 10^5$
3	$1 - \frac{60 \times \sqrt{\pi \times SOR \times NO_s}}{\sqrt{4 \times Q}} \le 0$
4	$1 - \frac{250 \times \pi \times \sqrt{4Q}}{Q\sqrt{\pi \times No_s \times SOR}} \le 0$
5	$-1 + \frac{3}{(t_s \times SOR)} \le 0$; for water depth ≥ 3m
	$1 - 4/(SOR \times t_s) \le 0$; for water depth $\le 5m$
6	$1 - \frac{SS_{max}}{SS_{in} - SS_{in} \times (\frac{86.00\left(\frac{t_s}{t_f}\right)^{0.075}}{100})} \le 0$; for alum dose= 10mg/l

	$1-\frac{SS_{max}}{SS_{in}-SS_{in}\times(\frac{77.64(\frac{t_s}{t_f})^{0.063}}{100})}\leq 0$; for alum dose= 20mg/l
	$1-\frac{SS_{max}}{SS_{in}-SS_{in}\times(\frac{54.55(\frac{t_s}{t_f})^{0.265}}{100})}\leq 0$; for alum dose= 30mg/l
	$1-\frac{SS_{max}}{SS_{in}-SS_{in}\times(\frac{66.20(\frac{t_s}{t_f})^{0.133}}{100})}\leq 0$; for alum dose= 40mg/l
	$1-\frac{SS_{max}}{SS_{in}-SS_{in}\times(\frac{70.17(\frac{t_s}{t_f})^{0.052}}{100})}\leq 0$; for alum dose= 50mg/l

Table (2) The boundary limits of design criteria

Design criteria	Minimum value	Maximum value
t_{ra}	15	60
G_{ra}	500	1500
No_{ra}	2	10
t_f	600	1800
G_f	20	200
No_f	2	10
t_s	3600	14400
SOR	21	75
No_s	2	10

Computation of Penalty Functions

In optimization techniques, external penalty functions are used to convert a constrained problem into an unconstrained problem. This is to be done in order to penalize infeasible solution to feasible solution. The optimum design of AWT plant is considered, the goal of optimization problem is to find the values of the design variables (t_{ra},, G_{ra}, No_{ra}, t_f, G_f, No_f, SOR, t_s, No_s) which minimize the cost function (C_1) under the six constraints (g_1 to g_6) stated above.

To solve this constrained optimization problem by genetic algorithm, the penalty function is used to take the constraints into consideration and convert the above constrained problem to an unconstrained one by penalizing infeasible solutions. The new objective function becomes:

$$C(\,x, R_{pj}, r) = f(x) + \sum_{j=1}^{m} R_{pj}\, \langle \breve{g}_{j(x)} \rangle^2 + \sum_{k=1}^{n} r_k [h_k(x)]^2 \qquad \ldots(14)$$

where the parameters R_{pj} and r_k are the penalty parameters for inequality (g_j) and equality (h_k) constraints, respectively. In the current application, there are no equality constraints, while there are six inequality constraints.(i.e., m=6). In terms of design variables of the present application, Eq.(14) can be written as;

$$C(t_{ra}, G_{ra}, No_{ra}, t_f, G_f, No_f, SOR, t_s, No_s, R_p) = f\,(t_{ra}, G_{ra}, No_{ra}, t_f, G_f, No_f, SOR, t_s, No_s) + \sum_{j=1}^{6} R_{pj} \langle \breve{g}_j (t_{ra}, G_{ra}, No_{ra}, t_f, G_f, No_f, SOR, t_s, No_s) \rangle^2 \qquad \ldots(15)$$

For Alum dose= 10mg/l, as an example, Eq.(15) can be written as;

$$C(t_{ra}, G_{ra}, No_{ra}, t_f, G_f, No_f, SOR, t_s, No_s, R_p) = C_1 + Rp \times \Bigg(\langle -1 + \left(2 \times \frac{t_{ra}}{{G_{ra}}^2 \times \mu}\right) \rangle^2 + \langle 1 - \left(5 \times \frac{t_{ra}}{{G_{ra}}^2 \times \mu}\right) \rangle^2 + \langle -1 + \frac{10^4}{(G_f \times t_f)} \rangle^2 \Bigg) + \langle 1 - \frac{10^5}{(G_f \times t_f)} \rangle^2 + \langle 1 - \frac{60 \times \sqrt{\pi SOR\; NO_s}}{\sqrt{4 * Q}} \rangle^2 + \langle 1 - \frac{250 \times \pi \times \sqrt{4\,Q}}{Q\,\sqrt{\pi\, No_s SOR}} \rangle^2 + \langle -1 + \frac{3}{(SOR) \times (t_s)} \rangle^2 + \langle 1 - \frac{5}{SOR \times t_s} \rangle^2 + \langle 1 - \left(\frac{SS_{in} - SS_{ef}}{\frac{SS_{in}}{100} * 100 \left(\frac{t_s}{t_f}\right)^{0.075}} \right) \rangle^2 \qquad \ldots(16)$$

In the above form of cost function, the brackets operate if the constraint is violated (g_j>0), and they become equal to zero otherwise. Reproduction operation is performed with the penalized objective, instead of the original objective function. In this way, the reproduction operator discourages the propagation of the infeasible solutions to future generations.

The parameter R_p can be calculated according to the following expression [12];

$$R_p = 0.1\ to\ 1.0 \times \frac{C(x, R_{pj}, r)}{-\sum_{j=1}^{J} g_j} \qquad \ldots(17)$$

However, it was found that as the values of R_p become large, the optimum solution is reached rapidly. In the present study the value of R_p was taken to be 1.0.

Results and Discussion

According to GA terminology, the search is for a chromosome consists of the nine elements (genes) that minimizes the objective function along with satisfying all the design criteria and effluent quality. During the application of GA in designing AWT unit, the effect of varying the concentrations of influent and effluent suspended solids (SS_{in}, and SS_{ef}) on optimum design criteria was studied. This was done by taking the minimum, average, and maximum values of SS_{in} from the effluent of Hamdan Sewage Treatment Plant located south of Basra (HSTP). This treatment plant serves Basrah city. The sewage is secondary treated in HSTP using conventional activated sludge system. which are 35, 100, and 134 mg/l, respectively, and by considering SS_{ef} of 5, 6, 7, 8, 9, and 10mg/l. The adopted values of SS_{ef} were selected to be within the accepted range of SS in water to be reused for agricultural, domestic, industrial, and groundwater recharge. Also, the effect of varying the alum dose, which affects the relation between t_s and t_f, on the optimum values of design criteria was studied.

The obtained results of GA application for the optimum design of AWT were plotted in term of each design criterion verses SS_{ef} for different SS_{in} at specific value of alum dose and maximum influent flowrate. Table (3) shows the figure numbers with the applied conditions and the obtained optimum values of design criteria.

Table (3) Optimum design criteria of AWT unit for dose 10mg/l.

Alum dose (mg/l)	Design Criteria	Optimum values range*	Reference figures
10	t_{ra}	15-15.25	2
	G_{ra}	500-500.0033	3
	t_f	600-600.015	4
	G_f	20.20.33	5
	t_s	1-1.0027	6
	SOR	75-76	7

- t_{ra} and t_f in sec, G_{ra} and G_f in sec^{-1}, t_s in hr., and SOR in m/day.
- The small difference in the values because of the accuracy of GA.

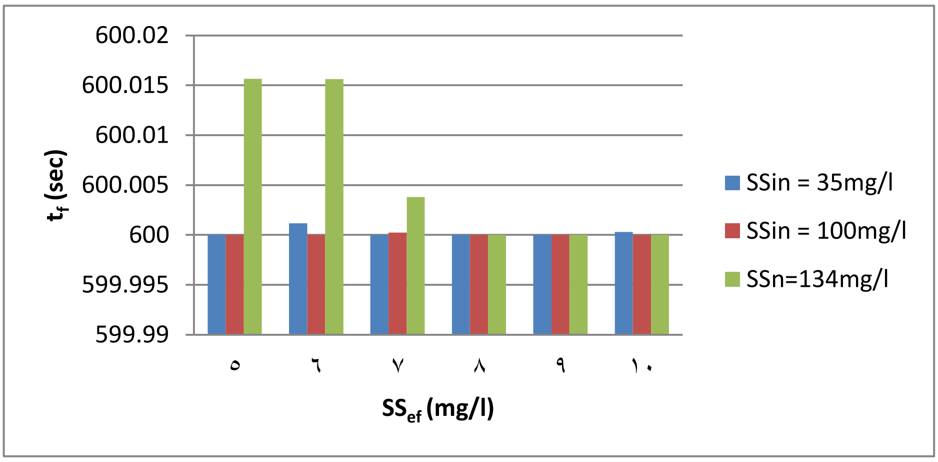

Fig.(2) Effect of SS_{in} and SS_{ef} on t_{ra} for max influent flowrate and alum dose =10mg/l

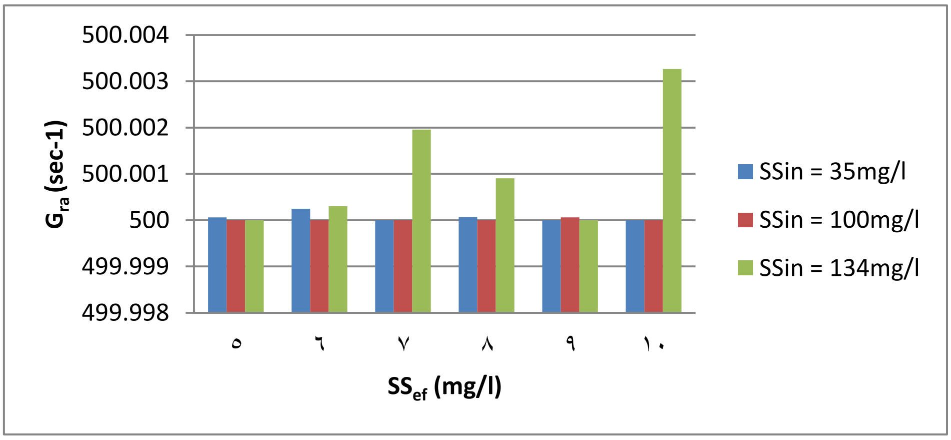

Fig.(3) Effect of SS_{in} and SS_{ef} on G_{ra} for max influent flowrate and alum dose = 10mg/l

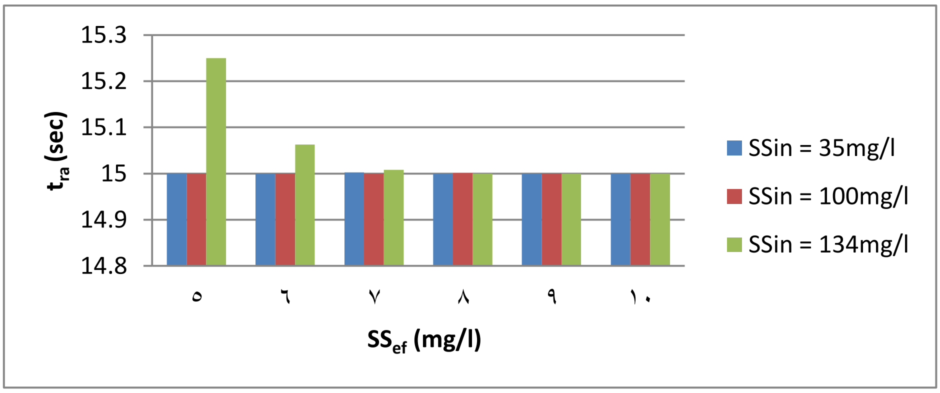

Fig.(4) Effect of SS_{in} and SS_{ef} on t_f for max influent flow rate and alum dose = 10mg/l

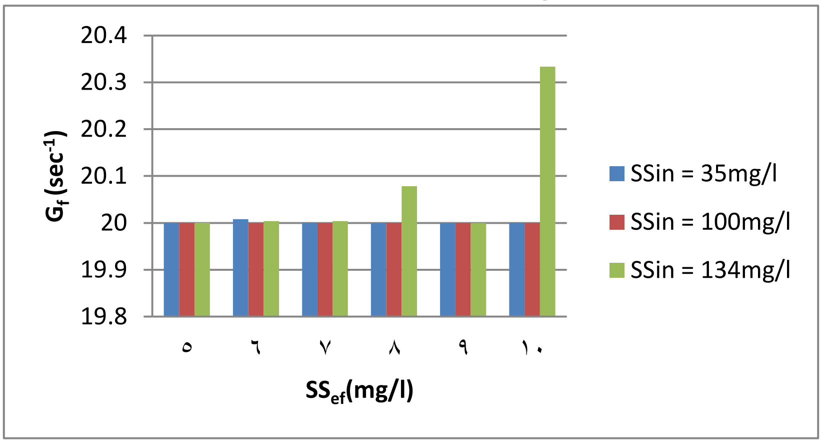

Fig.(5) Effect of SS_{in} and SS_{ef} on G_f for max influent flowrate and alum dose = 10mg/l

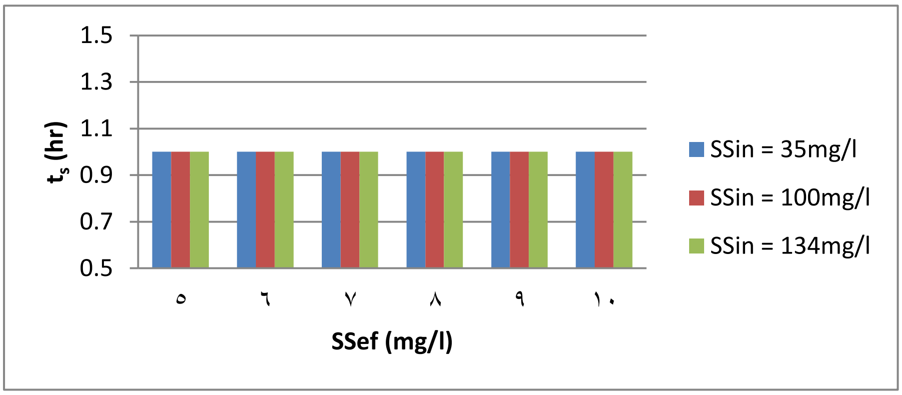

Fig.(6) Effect of SS_{in} and SS_{ef} on t_s for max influent flowrate

and alum dose = 10mg/l

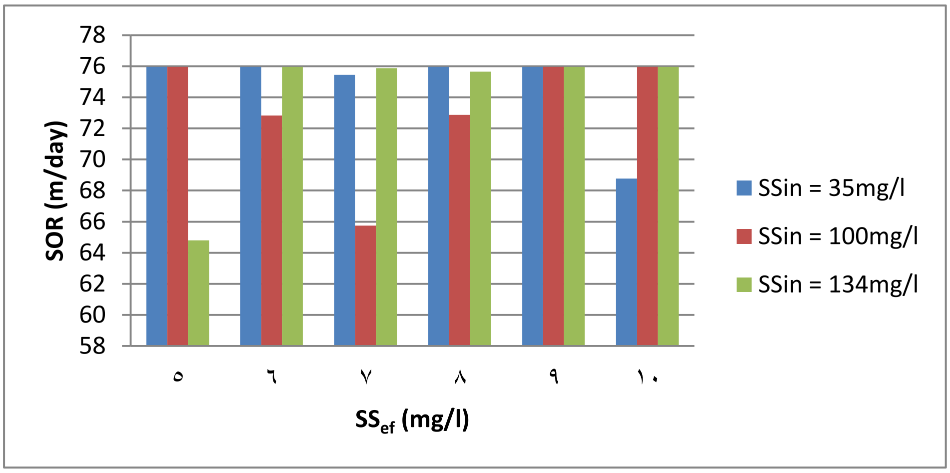

Fig.(7) Effect of SS_{in} and SS_{ef} on SOR for max influent flowrate and alum dose = 10mg/l

From Table (3), the followings can be noticed:

1- The detention time and velocity gradient of rapid mix unit (t_{ra} and G_{ra}) are not influenced by the variations of SS_{in}, SS_{ef}. The obtained optimum values are the minimum and equal to 15sec and 500 sec^{-1}, respectively.

2- The optimum value of t_f is not influenced by the variations of SS_{in}, SS_{ef}, and alum dose and the optimum value is 600 sec.

3- The optimum number of tanks for rapid mix , flocculation , and settling tanks was found to be constant and not changed with the variations of SS_{in}, SS_{ef}.

Cost of AWT unit

For the optimum design of AWT unit, the cost of the unit was plotted verses SS_{ef} for the three considered values of SS_{in} for alum dose of 10 mg/l as shown in Fig. (8).

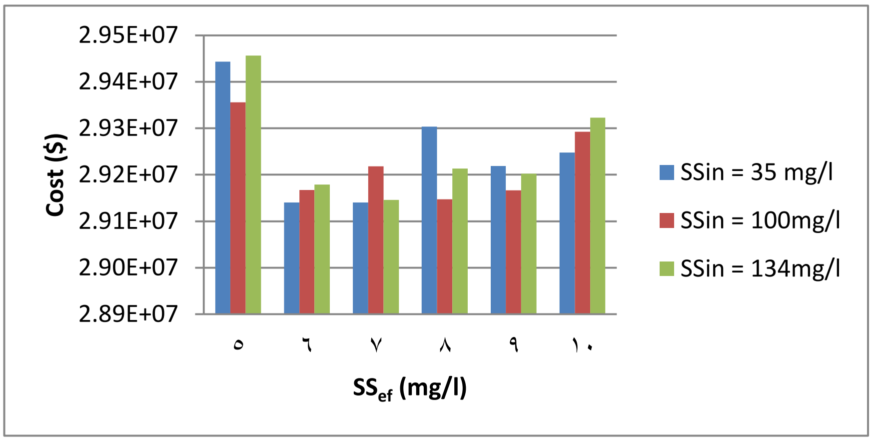

Fig.(8) Effect of SS_{in} and SS_{ef} on treatment cost for max influent flowrate and alum dose = 10mg/l

From fig.(8), it can be shown that:

1- The maximum cost is obtained for minimum SSef which is 5 mg/l and for this value.
2- For specific SS_{ef} value, there is no clear relation between treatment cost and SS_{in}.
3- For specific SS_{in} value, there is no clear relation between treatment cost and SS_{ef}.

Conclusions

From the development and application of advanced wastewater treatment plant, the following conclusions can be drawn within the scope of the present study:

1- Genetic Algorithm was found to be very powerful technique for operating and defining optimum values of the parameters used in design of the advanced wastewater treatment system.
2- A penalty function can be used to find the global optimum design of constrained problems such as of advanced wastewater treatment design and in conjugation with the genetic algorithm developed in this study.

3- The optimum value of design variables in rapid mix unit t_{ra}, and G_{ra} are found to be within minimum value and equal to 15sec, and 500sec^{-1} respectively, and is not influenced by the variations of SS_{in}, SS_{ef}.

4- The optimum value of design variable detention time in the flocculation unit (t_f) is not influenced by the variations of SS_{in}, SS_{ef}, and it is found to be within minimum value of the range of 10min.

5- The chemical clarification cost is found to be increased with maximum value of SS_{in} and minimum SS_{ef}.

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