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Applications of genetic algorithm to aesthetic design of dam structures

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In this paper, an attempt is made to develop a decision-making supporting system for the aesthetic design of dam structures. The present system is based on genetic algorithm and computer graphics. Genetic algorithm is able to produce many design alternatives, whereas computer graphics is useful to prepare their view simulations. In order to evaluate the alternatives, the analytical hierarchy process method is used to reflect the preference of designers. A numerical example of coloring a dam structure is presented to demonstrate the applicability of the system developed here. Copyright © 1996 Civil-Comp Limited and Elsevier Science Limited.

Key words: aesthetic design, analytical hierarchy process method, computer graphics, dam structures, decision making, genetic algorithm.

INTRODUCTION

Recently, the aesthetic design of structures has been focused upon since the need to consider the view of the structures is becoming one of the important design conditions. In the past, perspective and photomontage techniques have been utilized to image the completion of structures at site. However, these techniques required a lot of effort and time even for an image. On the contrary, due to the remarkable developments of computer technology and data processing, the image of structures on a graphic workstation is effective in preparing several alternatives in the design process. In addition, by using the image view of computer graphics, it is possible to choose an adequate configuration from those alternatives without difficulty.[1] Computer graphics can produce a real and three-dimensional view of the structure with rather less load. Moreover, since the view can be superposed on the photograph of the site, it is possible to examine the effect upon or harmony with the environment surrounding the structure.

In this paper, an attempt is made to develop a decision-making supporting system for the aesthetic design of dam structures. The present system is based on genetic algorithm (GA)[2,3] and computer graphics (CG). GA can seek the optimal solution by simulating the evolution process of living beings, because it was invented to mimic some of the processes observed in natural evolution. GA has such advantages that its optimization procedure can be implemented with a very simple algorithm, the possibility of reaching the global optimum is high due to the multiple-point search, discrete variables can be dealt with, and imprecise and vague objective functions can be handled. For these characteristics, it seems that GA is quite suitable for the aesthetic design of structures. While GA is able to produce many design alternatives, CG is useful to prepare their view simulations.

First, the basic concept and architecture of this system are described. Next, some problems faced in the application of GA to the aesthetic design are made clear. In order to reach an optimum design, it is necessary to evaluate the superiority of each alternative. However, the evaluation of aesthetic aspects is not easy because of the variety and complexity of individual preference. The analytical hierarchy process method is introduced to reflect the preference of designers exactly in the evaluation of the fitness function. A numerical example of coloring a dam structure is presented to demonstrate the applicability of the system developed here.

ARCHITECTURE OF THE SYSTEM

The objective of the system is to support a designer to make decisions on the aesthetic design of dam structures, where his/her preference should be reflected exactly. To realize this objective, CG is utilized to make the comparison easier and GA is employed to provide useful

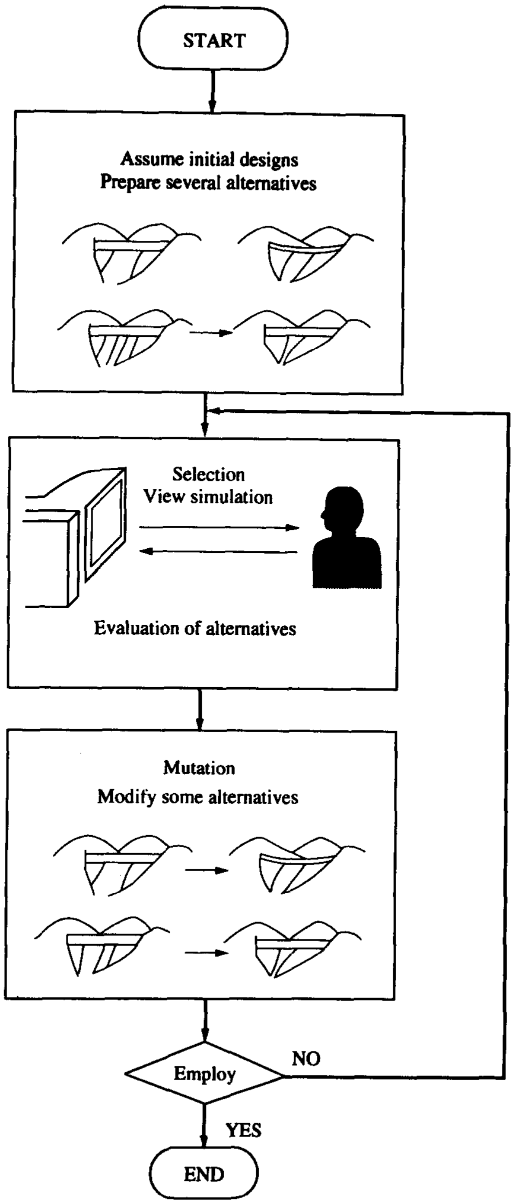


Fig. 1. Flowchart of GA calculation.

design alternatives automatically. Figure 1 shows the flow diagram of GA operation, i.e. evolution simulation. For living beings, evolution takes place on chromosomes which are organic devices for encoding the structure of living beings. A living being is created through a process of decoding chromosomes. Here, each design alternative corresponds to individual chromosomes which are expressed by strings of binary digits, i.e. 1s and 0s. The simulation evolution is performed on a population of such chromosomes. Superiority of each chromosome is evaluated by the designer's preference. The evaluation is used to bias the selection of chromosomes so that those with the best evaluations tend to reproduce more often than those with bad evaluations.

The process of GA can be implemented as follows:[4]

Step 1: Initialize a population of chromosomes.
Step 2: Evaluate each chromosome in the population.
Step 3: Create new chromosomes by mating current chromosomes; apply mutation and recombination as the parent chromosomes mate.
Step 4: Delete members of the population to make room for the new chromosomes.
Step 5: Evaluate the new chromosomes and insert them into the population.
Step 6: If time is up, stop and return the best chromosome; if not go to Step 3.

In general, GA has such a high ability that it can pursue an optimal solution even for combinatorial optimization problems with vague and imprecise objective functions. From this fact, it is considered that GA is suitable for the aesthetic design of structures.

The system is composed of a hardware supporting CG (Graphic Workstation Personal IRIS 25GT) and software for controlling CG and GA. In the GA program, the determination of initial population, reproduction, crossover, mutation are performed. Because the objective of this system is to stimulate the inspiration and creativity of the designer, the number of initial population (i.e. parents) is small and the mutation rate is rather high. A design alternative is encoded by using some chromosomes. The evaluation of each alternative is done based on the analytical hierarchy process (AHP) method which was invented by Saaty[5] to treat qualitative data.

CODING OF DAM STRUCTURES FOR GA

In the application of GA, it is necessary to encode the design alternatives so that GA can recognize them. Needless to say, an alternative cannot be a candidate if it is unable to be encoded as a chromosome.

In the determination of structural configuration, design is performed from overall design to detail design. Since the information regarding the structural configuration is enormous, it is impractical to deal with each design process at the same time. Moreover, the detail is not important from a long-range point of view, and the overall view cannot be seen from a short-range point of view.

At each design level, a design is achieved as a combination of subparts which are designed as simple objects. Since a structure is not natural but artificial, it is desirable to design the subparts as a unification of lines and surfaces. For example, a gravity dam structure is considered to consist of slopes, banks, flood mouse, gate houses, gate piers, handrails, intake facilities and control facilities, as shown in Fig. 2. Considering the variety of outline configurations, a number of alternatives can be prepared.

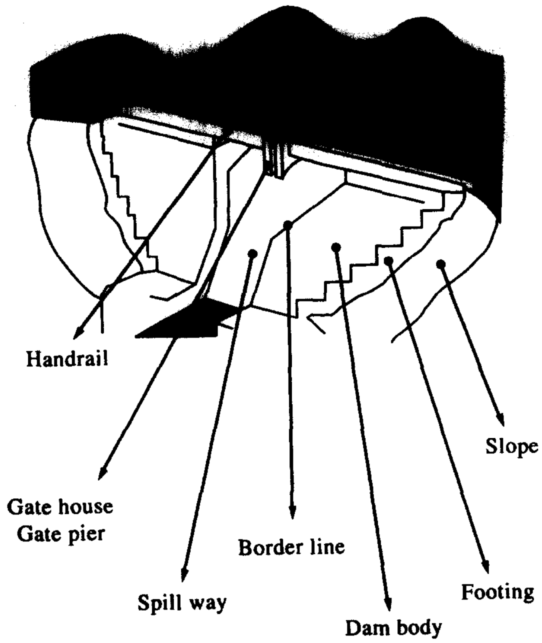


Fig. 2. Coding of a dam structure.

In the system, information regarding parts or elements is described by dividing into three categories; configuration, color and location. For the configuration, uneven configurations are avoided for consideration because they are not feasible from economical and technical points of view. Coloring is made by paying attention to the boundaries between each part. Each color is defined by three principle colors: red, green and blue.

The parameters of configuration, color and location are discretized and encoded to a chromosome. For crossover, occurrence rate is set a rather high value for the boundaries between every part, and lower values for the boundaries between curves, colors and locations. Mutation is generated by a method which eliminates and adds a unit element in the chromosome.

EVALUATION METHOD

In the evaluation of alternatives considered, the user gives his/her preference with the aid of the views made by CG. Although the preference level may fluctuate from time to time, GA can provide an optimal or reasonable solution for the case in which the evaluation has a variation due to the fluctuation of preference, because it is derived after many generations through the process of evolution. This is one of the advantages of using GA for the present system.

Then, the problem is how to express the preference of the user and introduce it into the optimization procedure. It is impossible for human beings to compare and evaluate many items simultaneously. Therefore, AHP is employed to compare several alternatives, in which a pair of design alternatives are compared successively. Dealing with only a couple of items at one time, it is possible to express his/her preference exactly. Since the minimum difference between perceivable stimuli is known to be proportional to the intensity of the stimuli, a measure which keeps the minimum difference constant is desirable.

In this method, an evaluation matrix E is first calculated using the evaluation value for each alternative through a pairwise comparison, where

$$E = \begin{bmatrix} 1 & v_1/v_2 & \cdots & v_1/v_n \\ v_2/v_1 & 1 & \cdots & v_2/v_n \\ \vdots & \vdots & \ddots & \vdots \\ v_n/v_1 & v_n/v_2 & \cdots & 1 \end{bmatrix} \tag{1}$$

In eqn (1), v_i is the evaluation value for the ith alternative and n is the number of possible alternatives. For the ith and jth alternatives, v_i and v_j should be evaluated in some range, e.g. 0–1 without taking account of other alternatives. Denoting the eigenvalue of E by λ,

$$\begin{vmatrix} 1-\lambda & v_1/v_2 & \cdots & v_1/v_n \\ v_2/v_1 & 1-\lambda & \cdots & v_2/v_n \\ \vdots & \vdots & \ddots & \vdots \\ v_n/v_1 & v_n/v_2 & \cdots & 1-\lambda \end{vmatrix} = 0 \tag{2}$$

Then, the following condition can be derived through some transformation.

$$\begin{vmatrix} n-\lambda & 0 & \cdots & 0 \\ \frac{v_2}{v_1}\lambda & -\lambda & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \frac{v_n}{v_1}\lambda & 0 & \cdots & 1-\lambda \end{vmatrix} = 0 \tag{3}$$

Equation (3) is equivalent to

$$(n-\lambda)\lambda^{n-1} = 0 \tag{4}$$

Therefore, λ should be 0 or n. Then,

$$\begin{bmatrix} 1 & v_1/v_2 & \cdots & v_1/v_n \\ v_2/v_1 & 1 & \cdots & v_2/v_n \\ \vdots & \vdots & \ddots & \vdots \\ v_n/v_1 & v_n/v_2 & \cdots & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} nv_1 \\ nv_2 \\ \vdots \\ nv_n \end{bmatrix}, \tag{5}$$

therefore

$$E \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = n \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} \tag{6}$$

This implies that the eigenvector corresponding to the maximum eigenvalue n is equivalent to the vector whose elements are the evaluation values for each alternative. The above procedure was developed for AHP to determine the weights of each item. It is noted that a real eigenvalue can exist because all elements of E are positive.

Assuming that the variation of evaluation of the measure, in which the minimum perception is kept constant, follows the normal distribution, the variation of perception follows the lognormal distribution. Then, the most reliable estimated values can be obtained as the geometrical average of each row of the evaluation matrix E, using the technique of minimizing the mean least square. Denoting the ith and jth element of E and the estimation value for the ith alternative by e_{ij} and $i\,(i,j = 1,2,\ldots,n)$, the minimum least-square condition is expressed as follows, because e_{ij} follows the log-normal distribution:

$$\sum_i \sum_j (\log \hat{v}_i - \log \hat{v}_j - \log e_{ij})^2 \rightarrow \min \tag{7}$$

For the condition of $e_{ii} = 1$,

$$\log \hat{v}_i - \log \hat{v}_i - \log e_{ii} = 0 \tag{8}$$

For $e_{ij} = e_{ji}$,

$$\log \hat{v}_j - \log \hat{v}_i - \log e_{ji} = -(\log \hat{v}_i - \log \hat{v}_j - \log e_{ij}) \tag{9}$$

Therefore, the condition of eqn (7) is equivalent to the following condition:

$$\sum_i \sum_{j>i} (\log \hat{v}_i - \log \hat{v}_j - \log e_{ij})^2 \rightarrow \min \tag{10}$$

Since the condition of eqn (10) can provide only relative values, the following condition is introduced so as to determine a set of solution:

$$\sum_i \log \hat{v}_i = 0 \tag{11}$$

Then, Lagrangian L can be obtained as

$$L = \sum_i \sum_j (\log \hat{v}_i - \log \hat{v}_j - \log e_{ij})^2 + \eta \sum_i \log \hat{v}_i \tag{12}$$

where η is the Lagrange multiplier. From eqn (12), the following relation can be derived:

$$\log \hat{v}_i = \frac{1}{n} \sum_j \log e_{ij} \tag{13}$$

therefore,

$$v_i = \sqrt[n]{\prod_j e_{ij}} \tag{14}$$

The above method is often used as an approximation method of determining the weights in AHP, because this method requires less computation time than that of the method based on the eigenvalue analysis.

Although the above method is very useful, it requires $n(n-1)/2$ times of pairwise comparison which is tough for the user if n is a large number. Therefore, a sorting method is also employed, in which every alternative is sorted in the order of preference. This method requires less load for the user, whereas it has such a limitation that the selection process cannot be done on the basis of the fitness function. This implies that this method is less reliable than the method based on AHP.

DESIGN EXAMPLE OF COLORING DAM STRUCTURE

To illustrate the applicability of the system, some simulation experiments are conducted. The surface of a dam structure is divided into 12 regions, each of which is differently painted by a color among 512 colors (see Fig. 3). To make the discussion simpler, only eight design alternatives are treated in the GA operation. As the initial design, one of the designs shown in Fig. 4 is employed. Each alternative is encoded by a string of 36 digits, in which a 3-digit corresponds to the color selected for 12 regions. Each color is defined by a combination of red, green and blue. Each design alternative is evaluated by the designer with the aid of CG. Using two view simulations of upstream and downstream pictures of a dam structure, the designer gives the weights for a pair of alternatives. The allover evaluation of eight alternatives is performed by both the AHP method and the sorting method. The value of fitness function can be given by the weights derived by the AHP method, whereas in the sorting method the preference order of alternatives is singly needed so that the evaluation is not done by the weights but by the order. One-point random crossover occurs two times in one generation. On the contrary, mutation occurs four times in one generation. The mutation is done by rewriting a digit in chromosome. To obtain unique and different designs, the rate of mutation is set to be larger than usual GA calculations.

The numerical experiment is conducted by two designers for two kinds of conditions. The four design cases are listed in Table 1, where A and B denote the designers. In each case, the GA operation is terminated after 20 generations because of time limitation. It is, of course, desirable to continue the computation until the convergence is completely achieved. For the computation, graphic workstation Personal IRIS 25GT (Silicon Graphics) is used as a hardware, whereas Alias (Silicon Graphics) is used as a software for drawing and rendering.

Figure 5 presents representative design plans derived in design case 1. As seen in design plan (a), a mutation occurred in the bank at the first generation. Looking at design plan (d), it is understood that design plan (d) is generated by the crossover between design plan (b) and

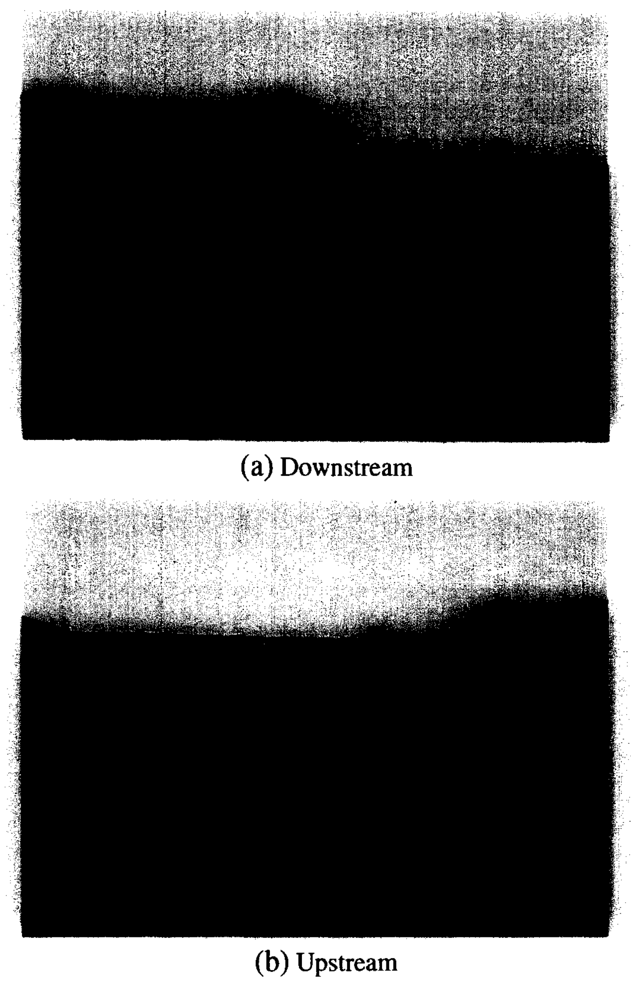
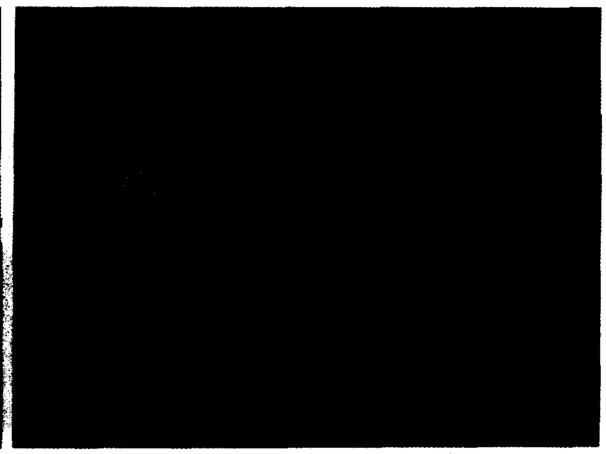
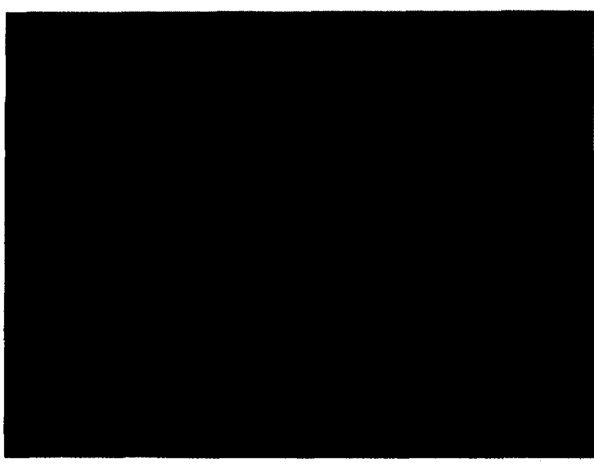


Fig. 3. Divided regions: (a) downstream, (b) upstream.

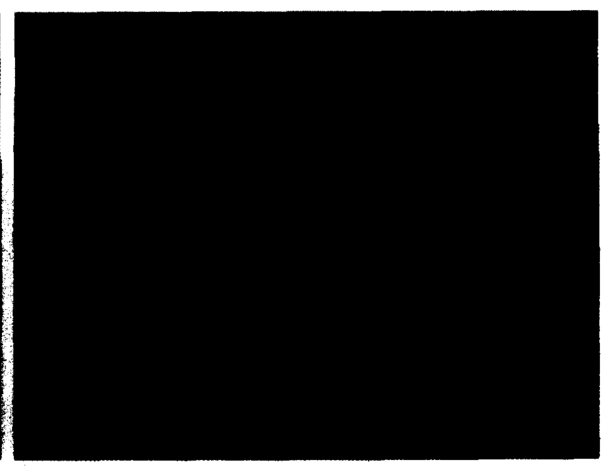
(a) Initial design A (downstream)



(b) Initial design A (upstream)

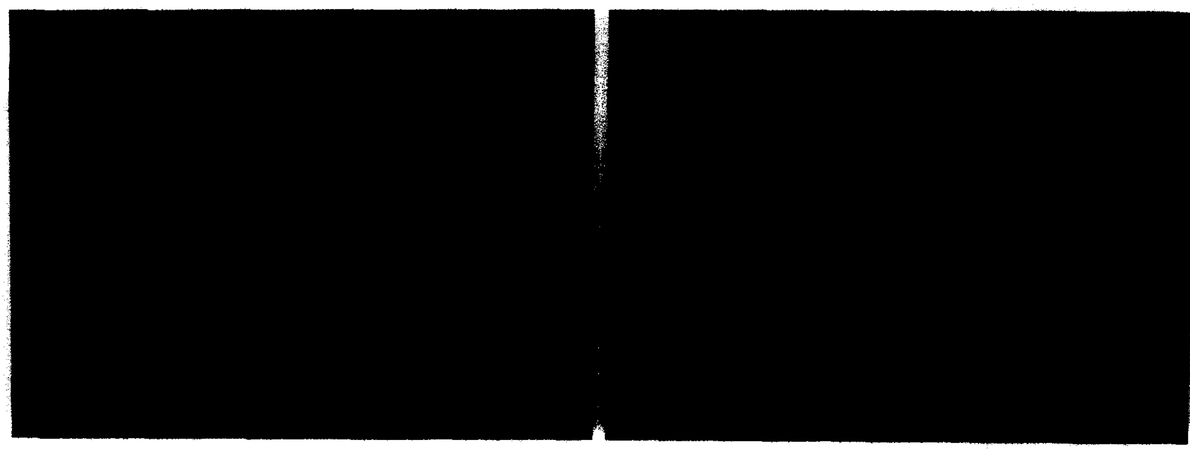


(c) Initial design B (downstream)

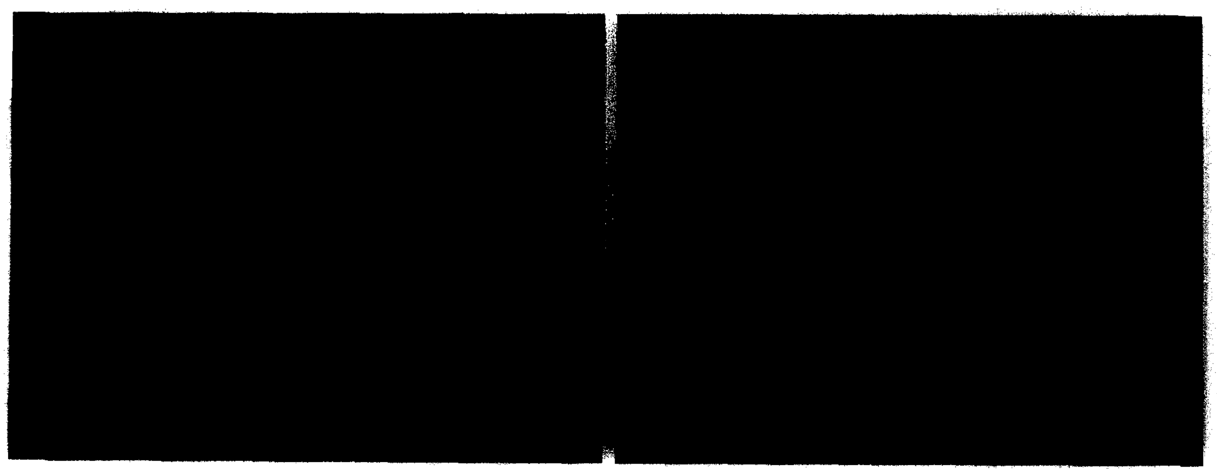


(d) Initial design B (upstream)

Fig. 4. Initial designs: (a) initial design A (downstream), (b) initial design A (upstream), (c) initial design B (downstream), (d) initial design B (upstream).

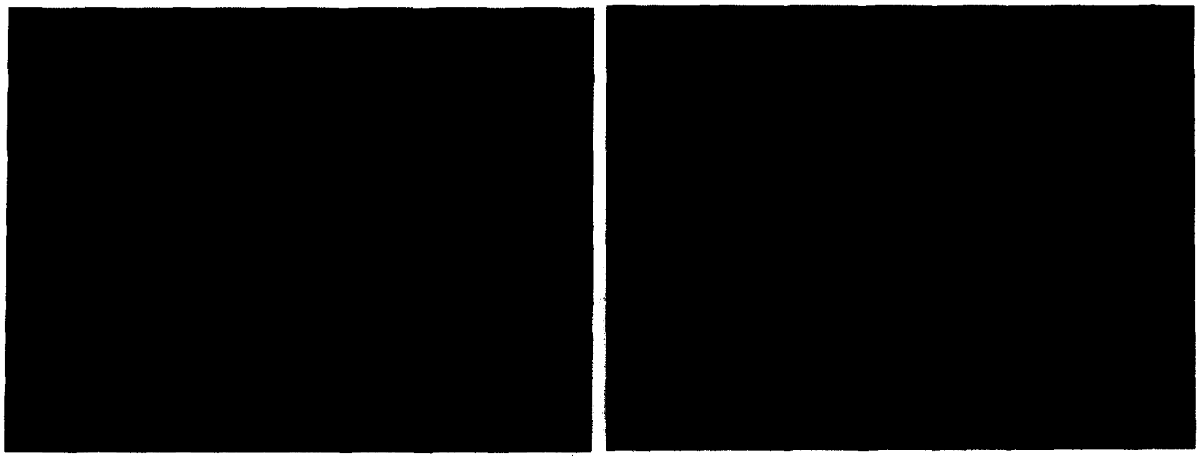


(a) Design plan (a) generated for case 1

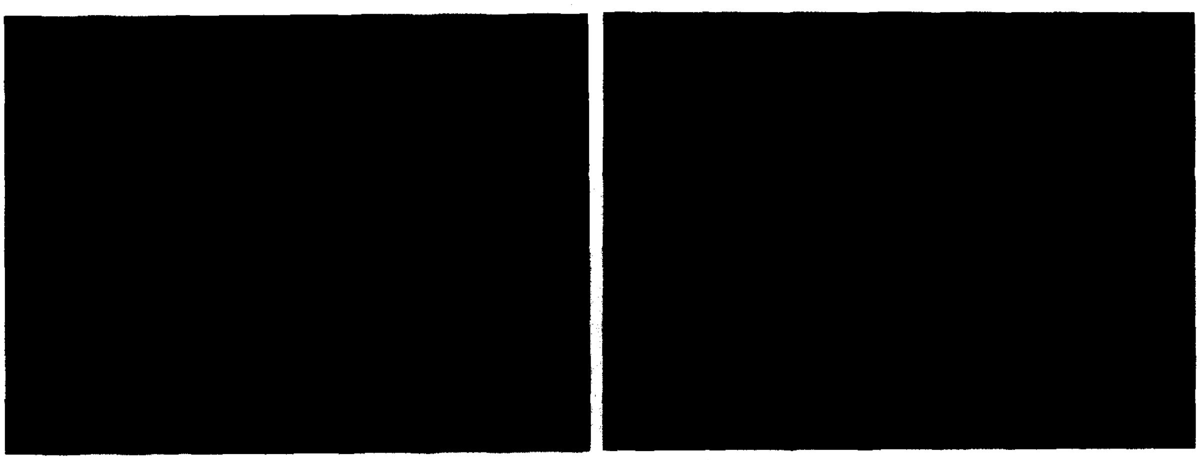


(b) Design plan (b) generated for case 1

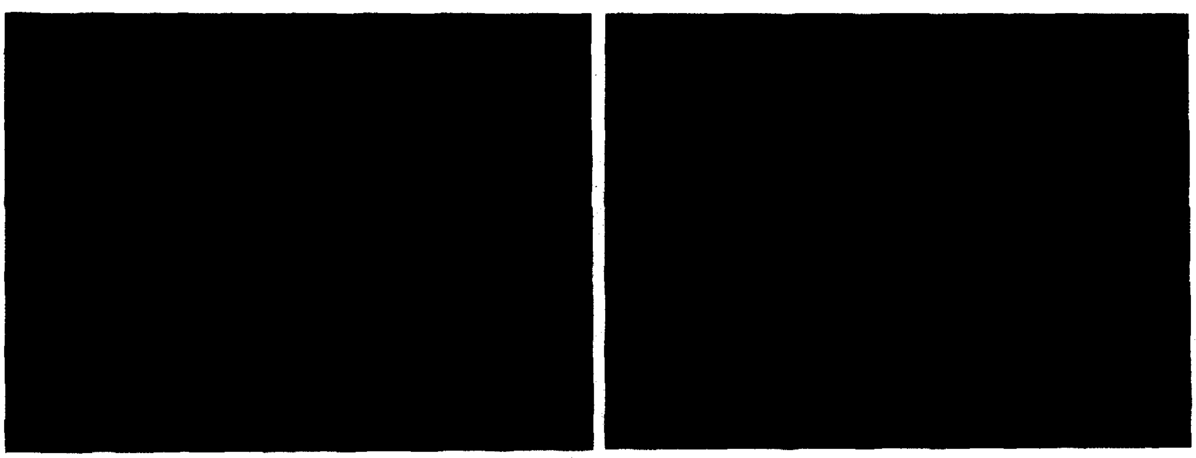
Fig. 5. Representative design plans: (a) design plan (a) generated for case 1, (b) design plan (b) generated for case 1.



(c) Design plan (c) generated for case 1

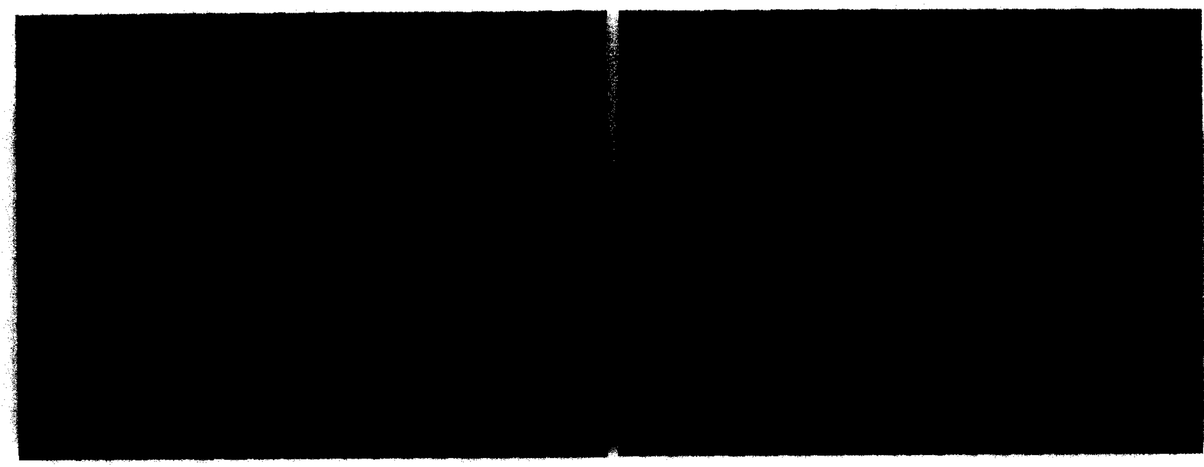


(d) Design plan (d) generated for case 1

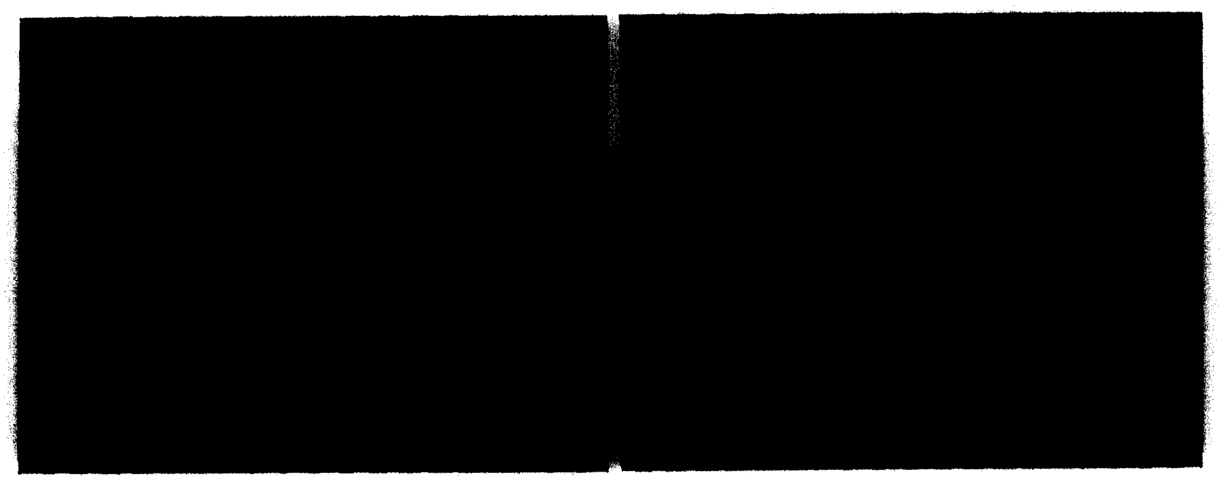


(e) Design plan (e) generated for case 1

Fig. 5. (c) design plan – generated for case 1, (d) design plan (d) generated for case 1, (e) design plan (e) generated for case 1.

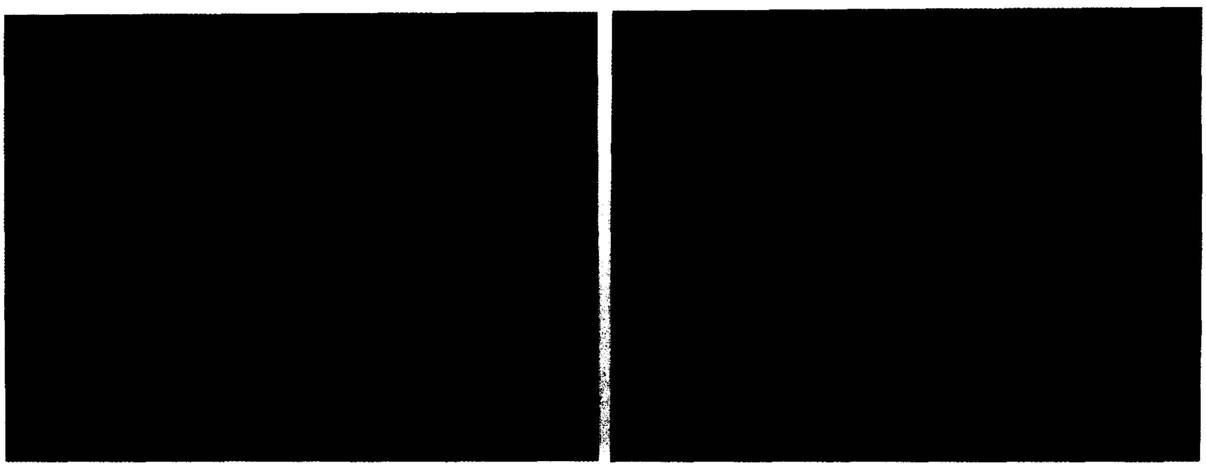


(a) Final design for case 1

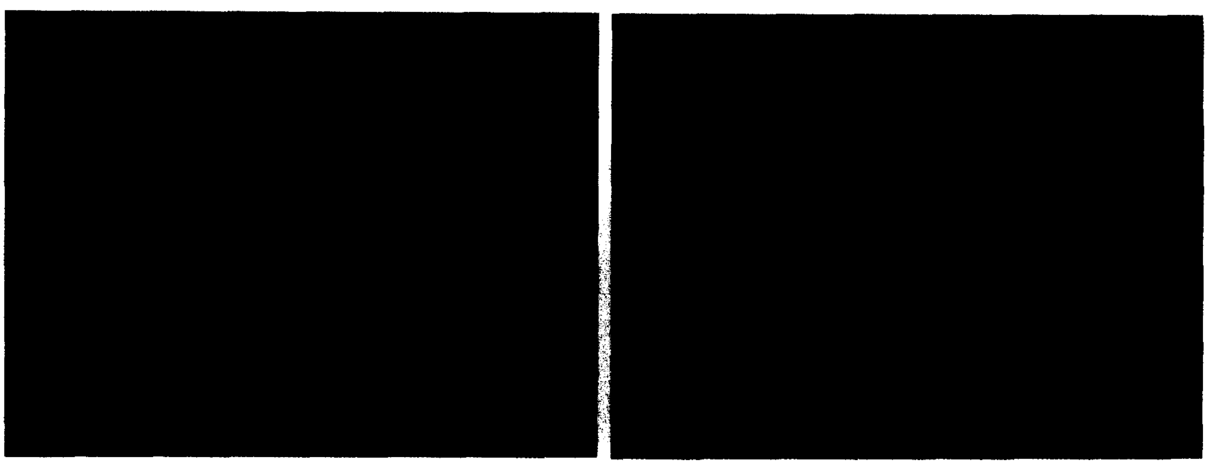


(b) Final design for case 2

Fig. 6. Final solution: (a) final design for case 1, (b) final design for case 2.



(c) Final design for case 3



(d) Final design for case 4

Fig. 6. (c) final design for case 3, (d) final design for case 4.

Table 1. Experiment cases

Case	Designer	Initial design	Evaluation method
1	A	A	Sorting method
2	A	B	Sorting method
3	B	A	Sorting method
4	B	A	AHP

Table 2. Numbers of comparison and rendering

Case	Number of comparison	Number of rendering
1	302	216
2	289	218
3	293	238
4	527	240

design plan (c). Although various combinations are generated through the GA operation, most of them are eliminated as a result of selection. Design plan (e) is very close to the final plan. Also, design plan (f) is generated but eliminated in the evolution process. In the former generations, the mutations to violet and yellow are often seen, while green and blue are seen in the latter steps. This is due to the fact that yellow and green are complementary colors of principal colors.

The final solution is given in Fig. 6, and Table 2 presents the number of rendering and the number of comparison of design alternatives for each design case. It is, however, noted that the final solution is not the optimal solution, because the GA operation terminated before reaching the optimal one due to the limit of computation time. Using case 1 and case 2, the effect of the initial designs is examined. Design (a) and design (b) in Fig. 4 are employed as the initial design. The final solutions for both cases are not so different from the initial ones. This means that the initial design chosen at the beginning is quite influential on the following results. It is, however, noted that 20 is too small a number of generation and the values of parameters, e.g. rates of crossover and mutation, should be checked whether they are adequate or not.

Through the numerical experiment, it is concluded that improvements are gradually done according to the designer's preference and, further, some design candidates that could not be expected before the experiment are often generated.

CONCLUSIONS

In this study, a decision-making supporting system was developed for the aesthetic design of dam structures. This system is built on a graphic workstation that can utilize its high ability of computer graphics and numerical computation. Introducing the GA technique into the aesthetic design process, it is possible to aid a designer in creating an original design by stimulating his/her inspiration. In the evolution process, AHP is useful in evaluating the superiority of aesthetic feature of design alternatives. Also, the sorting method can be sufficiently applied from the practical point of view.

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