Applying Multiobjective Genetic Algorithm for analyzing the trade-off of water use return among different sectors

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Abstract

The water use struggle among different sectors is a serious water resource problem during the drought in Taiwan. The irrigational use water is frequently been transferred to industrial use water due to its lower economic value, although agriculture sector will be compensated from other water use sectors when water transfers occur, the reasonable amount of compensation is still controversial How to obtain a quantitative support for helping different water use sectors to achieve an acceptable resolution is vital. Therefore, this study develops a multiobjective model of water resource management to evaluate the trade-off among different water use sectors. The shortage index is used to perform the water deficit of different water use sectors. The model integrates operating rules, stepwise linear programming (SLP) and multiobjective genetic algorithm (MOGA) to solve a mutiobjective regional water allocation problem. Moreover, simulation results clearly demonstrate the trade-off relationship between shortage indexes for agriculture and that for industry. The computed trade-off curve, non-inferior solutions, is a valuable quantitative support for the transfer negotiation of water use among various sectors.

1. Introduction

The increasing expense and environmental impact of developing traditional hydraulic facilities (e.g., reservoirs) have encouraged expanding demand-management effort [1]. In Taiwan, the water transfer is a common demand-management approach during the drought. Owing to the lower output value of agriculture, the irrigation use water is usually been transferred to other water use sectors with higher output values such as industry sectors. However, irrigational use water not only supports the crops growth for obtaining economic incomes, but also conserves the groundwater for sustaining ecological environment. Hence, the irrigational use water transferred should be compensated base on its internal costs and external costs. Since the environmental cost is difficult to estimate, the compensation of water transfers is determined traditionally by the Coordination Committee in Taiwan, but without a satisfactory water market system and reference data, a proper decision is not easy to achieve. Generally, the Coordination Committee needs to consider many possible “trade-off” solutions before choosing the one that suits their need the best. This paper presents a Multiobjective Genetic Algorithm (MOGA) to derive a set of optimal operation policies for a multipurpose reservoir system. The results offer many alternatives for the Coordination Committee to select the best policy flexibly.

Optimizing water management strategies is a complicated matter, as some impact relations are nonlinear and interdependent [2]. A common problem in multiobjective optimization is that the various objectives may be conflicting and incommensurable, or may affect different groups of people or interests [3]. Traditionally, multiobjective optimization problems have been solved using the weighting method or the ε-constraint method [4]. Those methods deduce multiobjective to single objective base on the weighted sum of the original multiple objectives or incorporating portion of objectives into the constraint set. However, those methods still have some shortcomings such as how to determine the weightings of incommensurable objectives. In contrast, MOGA is an attractive approach which does not stipulate the differentiability of the objective function. Additionally, MOGA can identify convex and non-convex points on the Pareto frontier [5].

MOGA has been successfully employed in water resources for various purposes. For example, Cieniawski et al. [6] presented an optimization method of MOGA to solve a multiobjective groundwater monitoring problem. The objectives in this case are maximum reliability and minimum contaminated zones. In order to overcome the rising complexity when both location and sizing of detention dams are involved in a multiobjective framework, Yeh and Labadie [7] utilized MOGA for the

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planning of a watershed-level detention dams system. In terms of water distribution problem, Prasad and Park [8] applied MOGA to produce a set of Pareto-optimal solutions to design a water distribution network with the objectives of minimizing pipe network costs and maximizing reliability. Yang et al. [9] developed a multi-objective programming algorithm that integrates a MOGA with constrained differential dynamic programming (CDDP) to solve a conjunctive use problem. The objective is to minimize the fixed costs and the operating costs. The CDDP is herein adopted to distribute optimal releases among reservoirs to satisfy water demand as much as possible.

Although various applications of MOGA have been successfully employed in solving multiobjective optimization problems, there are still some difficulties to be overcome, such as discrete variable treatment or huge computational requirement. Therefore, this study embeds a stepwise linear programming (SLP) model to compute the reservoirs releases. Since SLP is a stepwise optimal model instead of a global optimal model, the problem of variable numbers increase with time will not occur. Additionally, SLP is not constrained by discrete variables, so it can deal with the reservoir operation with rule curves.

2. Methodology

The proposed multi-objective planning model is developed by embedding the SLP model into the MOGA algorithm. Figure 1 shows the flowchart of the multi-objective planning model. First the population is initialized within the specified variable ranges. The variables are the supply discounts of different water use sectors; in this case, they are agriculture sector and public sector. After evaluation of this population, estimate the respective objective of each member of the population by SLP approach. This study uses shortage index (SI) of different water use sectors to perform the respective objective. The shortage index is proposed by U.S. Army Corps of Engineers and it is used to indicate water shortage severity in Taiwan.

The SI is defined as:

$$SI = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{Sh_i}{T_i}\right)^2 \qquad (1)$$

Where N denotes number of periods; Sh_i is the shortage volume during period i ; T_i represents public use demand or irrigation use demand during period i. Each period has 10-days and it is commonly used in Taiwan when performing long-term studies for water resources planning.

Next, we use enumeration algorithm to derive the Pareto front to denote any member of the feasible region which is not dominated by any other member. These solutions have least objective conflict compare with any other solutions, which provide the best alternatives for decision making (Feng) [10]. The fitness calculation of MOGA is modified base on convex hull distance provided by Feng et al. [10]. First, we determine the trade-off curve and the convex hull of the existing generation (the parent generation). The trade-off curve is the Pareto front of a generation and it can be determined by the step mentioned above. The convex hull denotes a convex boundary that enclosed all members of a population from a generation. The difference between trade-off curve and convex hull can be shown as Figure 2. The fitness is shown as equation (2).

$$f_i = d_{\max} - d_i$$

Where f_i is fitness value of parent i; d_i is the minimal distance (di) between the parent I and each of the segments j of the convex hull (see Figure 3), d_i =min(d_{ij}, for all j); d_{max} denotes the maximum d_i in the generation, d_{max} =max(d_i, for all i)

The population members are ranked according to their fitness value and are selected for genetic operation, on a pair-wise comparison to produce an offspring in the generation. The selection probability (P_i) of parent i refer to their fitness and it can be shown as equation (3).

$$P_i = \frac{f_i}{\sum f_i} \qquad (3)$$

To change the attributes of the offspring, crossover and mutation operations were performed. Furthermore, this study applies elitism approach to preserve the best solutions through generations and to speed up the convergence. We sort the alternatives (chromosome) and classified into different fronts, then selecting the best fronts for next generation. The procedure is repeated until the convergence condition is achieved to attain the optimal solutions. The definition of a convergence condition is that the variation rate should be lower than 5% during ten consecutive generations. The variation rate is defined as the change ratio in the noninferior solutions sets [9]. The detailed description of SLP and MOGA are illustrated as following.

. 2.1 SLP model

Generally, the release decisions of a water distribution system can be determined by the dynamic programming (DP), linear programming (LP) or non-linear programming (NLP) [11]. In this paper, LP is employed to distribute the release among reservoirs in every time step. The model can handle demand for water from various sectors (such as agriculture and public sectors), base flow and agricultural return flow. Since LP is used to optimize stepwise instead of global optimization, we call this model stepwise linear programming (SLP). Model development requires a mathematical description of system behavior and other constrains. The objective function of SLP model can be shown as equation (4).

$$Z = Min \left\{ \left(\sum_{i \in N_D} W_{SH,i} SH_i^t \right) + \left(\sum_{F \in N_F} W_{G,F} G_F^t \right) + \left(\sum_{j \in N_S} W_{SP,j} X_{SP,j}^t \right) \right\}$$
$$W_{SH,i} > W_{G,F} > W_{SP,J} \tag{4}$$

Where SH_i^t denotes shortage of ith demand during period t; G_f^t is slack variables of the index balance equation during period t. $X_{SP,j}^t$ is overflow of jth reservoir during period t. $W_{SH,i}$, $W_{G,F}$, $W_{SP,J}$ these weightings represent the priorities for different objectives. The greater the weighting number, the higher the priority of the objectives.

Moreover, this model constraint should comply with the mass balance of each nodes and index level balance of reservoirs. The index level balance is provided by U.S. army corps of engineers for keeping all reservoirs at the same index level as much as possible after releasing. The capacity constraints for each water treatment plant and each pipe should also be observed during releasing.

. 2.2 MOGA model

MOGA has many attractive features such as be able to solve NP-hard problems, easy to interface with simulation models and to be integrated into a hybrid system. The objectives of the model are minimization of irrigation and public sector deficits. These two are mutually conflicting objectives and we use the shortage index to perform them. These two competing objectives of the system are expressed as follows:

Objective function:

$$\vec{J} = \underset{\vec{L}}{Min} \quad \vec{Z}(\vec{L}) = \underset{\vec{L}}{Min} \quad (\vec{Z}_1(\vec{L}), \vec{Z}_2(\vec{L})) \tag{5}$$

Subject to,

LP-based simulation Model (6)

where $\vec{Z}_1(\vec{L})$ and $\vec{Z}_2(\vec{L})$ are the shortage index of agricultural demand and public demand, respectively, and both are to be minimized. $\vec{L}$ is the decision variable (the rule-curve).

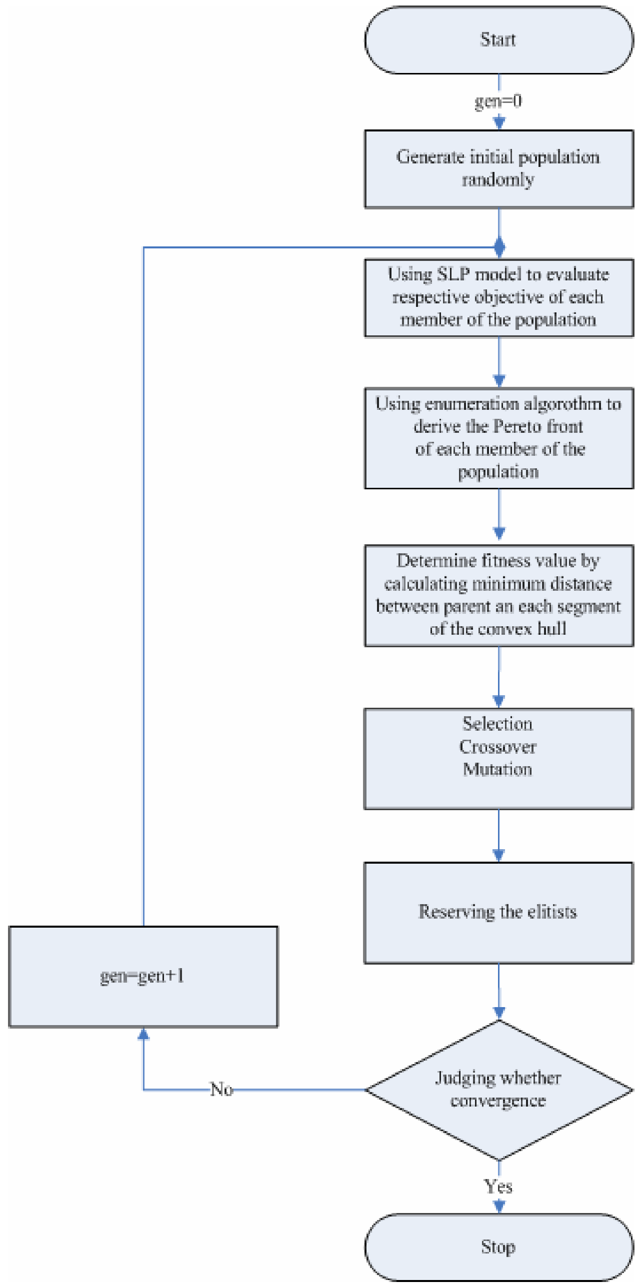

Figure 1 Flowchart of multi-objective planning model

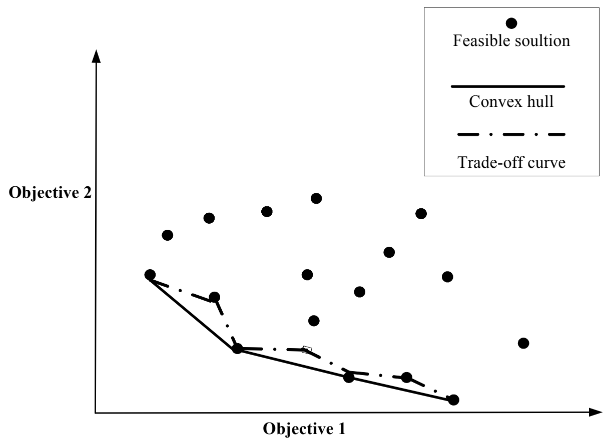

Figure 2 Trade-off curve and convex hull of population

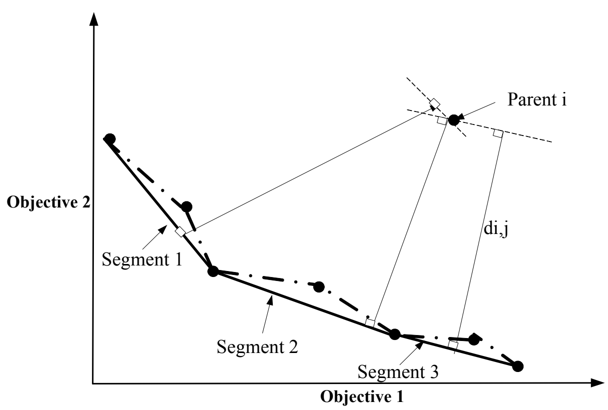

Figure 3 Fitness calculation

3. Case study

The study region covers two metropolitan areas, Tainan and Kaohsiung in southern Taiwan. The water distribution system is shown in Figure 4. The main water sources are from the Nan-Hua Reservoir, the Tseng-Wen Reservoir, the Wu-Shan-Tou Reservoir, and the Kaopin-Hsi Weir. Among these facilities, the Kaopin-Hsi Weir is located at the downstream of the KaoPin River and the others are settled in the Tseng-Wen river basin. There are four main water treatment plants in southern Taiwan; the Pin-Tin water treatment plant, the Nan-hua water treatment plant, the Wu-Shan-Tou water treatment plant and the Tan-Tin water treatment plant. The basic water distribution principle is to use water from the Kaopin-Hsi Weir first, and then from the other three reservoirs.

Another operating rule is to fulfill the demands in sequence depend on the water source withdrawn. For water withdrawn from the Kaopin River, Kaohsiung public use demand has high priority over Tainan public use demand; for water withdrawn from above three reservoirs, the water supply priority is to meet Wu-Shan-Tou irrigation demand, Tainan public use demand, and Kaohsiung public use demand in sequence. In which the public use demand includes water for domestic and industrial uses. The three reservoirs operate together as a multi-reservoir system and the amount of water release from each reservoir is managed according to the index level method of storage balancing provided by U.S. army corps of engineers.

Additionally, reservoirs operation should be based on the operating curve of an equivalent reservoir. The original operating curve is based on the equivalent reservoir combining the Tseng-Wen Reservoir with the Wu-Shan-Tou Reservoir. The operating curve varies by months according to the changes in meteorological and hydrologic conditions. To avoid excessive groundwater extraction and to promote the water economization concept, the groundwater operation is based on the same operating rule and not to supply water more then target demand. The current operating curve divides equivalent reservoir volume into five operating zones; they are inactive, low buffer, high buffer, conservation, and flood control zones (Figure 5). Each zone has different criteria for decreasing target demand depends on how much water has been stored in the equivalent reservoir.

In this study, the decision variables are weightings (supply discounts) of diverse zone for different water use sectors and they must be coded as chromosomes. Each decision variable is coded as ten binary bits. In the problem considered here, there are 100 chromosomes in each population, and the initial population is randomly generated. Fig. 6 shows that the variation rate decreases from the initial value with convergence, and that the final noninferior solution appears in generation number 27. Fig. 7 indicates the trend of the results for the final noninferior solutions set. When the noninferior solutions from the multiobjective problem are identified, the decision maker's preference has to be provided for choosing the compromise solution from noninferior solutions.

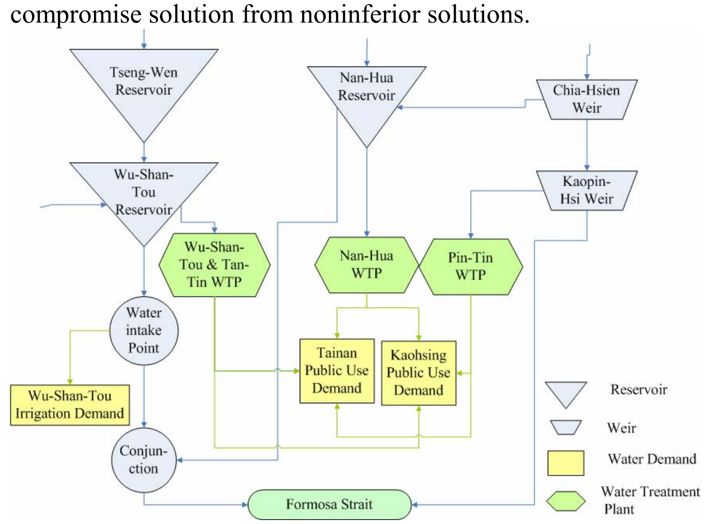

Figure 4 Water distribution system of the study area

according to societal, political or other considerations that are difficult to model.

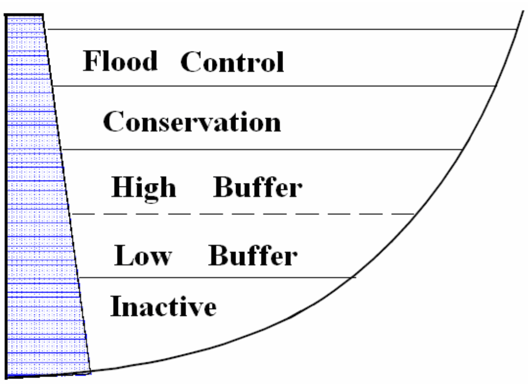

Figure 5 Definition of reservoir operating zone for the equivalent reservoir of Tseng-Wen Reservoir and Wu-Shan-Tou Reservoir

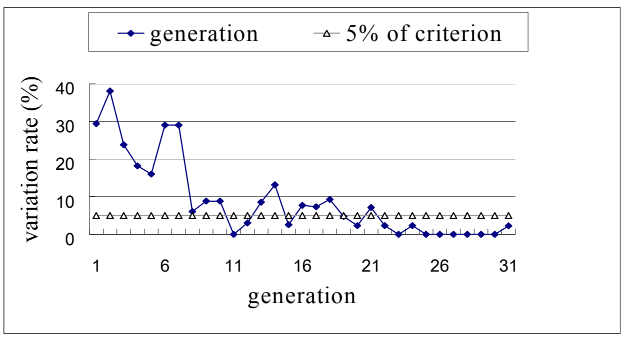

Figure 6 Variation rate of different generation

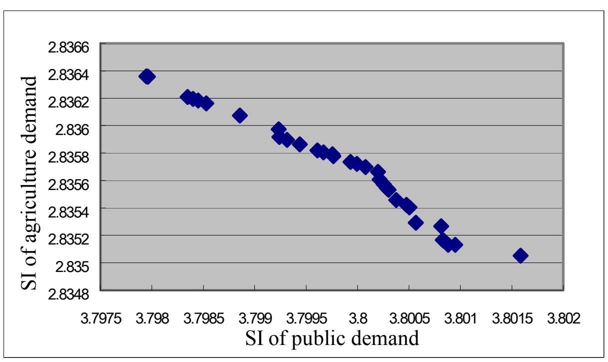

Figure 7 Variation rate of different generation

5. Conclusions

Due to the limitations of conventional multiobjective optimization methods, this paper develops a multi-objective genetic algorithm (MOGA) model. The study demonstrates that MOGA is relatively easy to embed other simulation model (SLP model) and SLP model is suit for solving a real complex water resources problem. Trade-off information can be extremely relevant in complex management scenarios, and can facilitate stakeholders to achieve an acceptable agreement

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