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Hydropower Unit Commitment Using a Genetic Algorithm with Dynamic Programming

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Abstract: This study presents a genetic algorithm integrated with dynamic programming to address the challenges of the hydropower unit commitment problem, which is a nonlinear, nonconvex, and discrete optimization, involving the hourly scheduling of generators in a hydropower system to maximize benefits and meet various constraints. The introduction of a progressive generating discharge allocation enhances the performance of dynamic programming in fitness evaluations, allowing for the fulfillment of various constraints, such as unit start-up times, shutdown/operating durations, and output ranges, thereby reducing complexity and improving the efficiency of the genetic algorithm. The application of the genetic algorithm with dynamic programming and progressive generating discharge allocation at the Manwan Hydropower Plant in Yunnan Province, China, showcases increased flexibility in outflow allocation, reducing spillages by 79%, and expanding high-efficiency zones by 43%.

Keywords: hydropower unit commitment (HUC); dynamic programming (DP); genetic algorithm (GA); progressive generating discharge allocation (PGDA)



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1. Introduction

Short-term scheduling is crucial in guiding hydropower operations by devising a cost-effective plan for one-day generation. As a hydropower station consists of multiple units, incorporating unit start-up and shutdown status into short-term planning becomes imperative to minimize associated costs and enhance efficiency. The hydropower unit commitment (HUC) problem, a longstanding research topic, holds significant importance in system economic dispatch.

The relationship among the output of a hydropower unit, the water head, and the discharge is intrinsically characterized by its complexity and non-linearity. Various techniques are employed to address this non-linearity and non-convexity of hydroelectric production functions [1], including dynamic programming (DP) [2], mixed-integer linear programming (MILP) [3], lagrangian relaxation (LR) [4], and a heuristic algorithm (HA) [5], to mention a few. The decomposition of the problem into multiple stages allows DP to preserve optimal solutions at each stage, effectively trading space for time to achieve its objective. As illustrated by Yi et al. (2003) [6], the DP model possesses the flexibility to seamlessly incorporate complex if-then logic, integer or binary variables, and non-linear functions, making it well-suited for handling complex optimization problems. In theory, a

DP formulation can effectively address various crucial aspects of hydropower unit commitment, such as mitigating vibration zone generation, minimizing wear on turbine units, and ensuring system reliability and flexibility. The dimensional complexity of DP makes it more suitable for small-scale problems, while the intricate hydraulic interconnections between hydropower units pose challenges in meeting the stage separability requirements of DP. Wang et al. (2018) [7] introduced a novel approach to HUC, involving the decomposition of the problem into a zone commitment (ZC) phase that employs MILP to determine optimal operating zones and one-stage sub-problems that utilize the hill-climbing method for outflow allocation among units. To address the issue of solution efficiency arising from too many binary variables in MILP, Lucas et al. (2016) [8] proposed an aggregated MILP approach that reduces the number of binary variables. In formulating the optimal unit commitment, considering that start-up costs are crucial, as the start-up process incurs wear on valves, mechanical equipment, and generators, it is necessary to minimize start-up times [9]. Fleten et al. (2008) [10] examined the impact of start-up costs within a multi-stage mixed-integer linear stochastic programming framework for a price-taking hydropower plant operating under uncertainty, highlighting the importance of forbidden zones to prevent adverse phenomena, such as turbine vibrations, cavitation, and low-efficiency. To address the combinatorial nature introduced by forbidden zones, Finardi et al. [11] proposed three different decomposition strategies in LR to decompose the original problem into a series of smaller ones, solved using the Sequential Quadratic Programming (SQP) algorithm.

HA has recently gained popularity for solving the HUC problem due to its intuitive and straightforward nature. However, challenges, such as premature convergence, susceptibility to locally optimal solutions, and low efficiency must be addressed [12]. Arnel et al. (2014) [13], for instance, proposed a novel approach by applying a parallel self-adaptive differential evolution algorithm to optimize hydropower generator scheduling based on 24 h system demand, incorporating multi-population and a preselection step to enhance the global search capabilities of the algorithm. Li et al. (2012) [14] utilized a decomposition approach for the HUC problem, separating it into unit commitment and economic dispatch sub-problems, and incorporated a flexible memory system of Tabu Search (TS) into particle swarm optimization (PSO) to maintain swarm diversity, expand the search space, and improve convergence properties. Hu et al. (2019) [15] introduced the improved cloud adaptive quantum-inspired binary social spider optimization (ICAQBSSO) algorithm, which leverages the cooperative behaviors of social spider colonies to achieve higher quality solutions and reduce the computation time compared to other algorithms.

The Genetic Algorithm (GA), initially proposed by Professor J. Holland in 1975, is a randomized search method inspired by the principles of evolution in the biological world, exhibiting inherent implicit parallelism and global optimization capabilities. However, numerous constraints pose challenges for GA to solve the HUC problem directly. The use of GA as a generative and performance-design technique often involves, in practice, constraint handling, which can be a complex task [16]. Similarly, in the HUC problem, the equation constraints, such as the water balance and operating zones, and the inequality constraints, such as the number of starts of the unit, the feasible zones of generating discharge, make the GA have a low probability of satisfying all of the constraints when randomly generating solutions, and thus, the introduction of an auxiliary correction strategy for the initial solution to enhance its feasibility is necessary. Santos et al. (2004) [17] proposed a decomposition approach for the HUC problem, decomposing it into two sub-problems: the first sub-problem involved determining the start-up/shutdown schedule using a genetic algorithm technique, while the second sub-problem focused on calculating the power output of the hydro units selected by the genetic algorithms. Borce et al. (2022) [18] introduced a novel metaheuristic approach combining GA with adaptive strategies and two constraint-handling repair mechanisms to address the Security Constrained Hydrothermal Unit Commitment (SCHTUC) problem, effectively considering a broad range of thermal, hydraulic, and security constraints.

This study aims to minimize spillage and the duration of the unit operation in low-efficiency zones by combining DP with a GA to solve the HUC problem. The start-up cost of the unit is considered through constraints related to the start-up frequency and operation duration. By dividing the operating zones into high and low-efficiency zones, forbidden zones can be effectively avoided. The backward recursive process in DP is constructed to minimize spillage using the start-up times and periods, keeping the shutdown or operation of the units as the state variables and the discharge and operating zones as the decision variables. All of the constraints in this HUC problem, except water balance, are satisfied by restricting state variables. The integration of DP ensures that the solutions generated by the GA can be locally modified into feasible ones, thereby improving the overall feasibility of the generated solutions. To further optimize the solution, a sequential manner to unlock the capacity of the units is adopted, resulting in an improvement in the DP process with the flexibility of outflow distribution. The proposed GA with DP method is then applied to a HUC problem involving five units at the Manwan Hydropower Station, and its performance will be compared with the use of DP alone.

2. Problem Formulation

This study is originally centered around the short-term optimization scheduling of a cascade reservoir, which can be decomposed into two sub-problems: interplant load allocation and the internal HUC problem. The primary objective of the first problem is to allocate the load efficiently among the power plants while ensuring load balancing. Consequently, each power plant's releases and water heads are yields, which serves as a crucial boundary condition for the subsequent HUC problem. Given the hourly releases \hat{Q}_t and water heads \hat{h}_t over a day provided after the operation of cascaded reservoirs, the hydropower units in a hydroplant are committed to sequentially minimizing spillages and the frequency of generating in low-efficiency zones, mathematically expressed as

$$\min W_1 \sum_{t=1}^{24} spl_t + W_2 \sum_{i=1}^N \sum_{t=1}^{24} z_{it}^{(1)} \quad (1)$$

where $W_1 \gg W_2$ are weights to prioritize the spillage over generating efficiency; spl_t = spillage in m^3/s in hour t from the reservoir; $z_{it}^{(k)}$ = binary variable to indicate whether the unit i is operating in the k th zone in hour t , with $k = 1$ to indicate the low-efficiency zone in generation.

The constraints include the following:

- (1) The water available for generation,

$$\sum_{i=1}^N q_{it} + spl_t = \hat{Q}_t \quad (2)$$

where q_{it} = generating discharge in m^3/s from unit i in hour t ; \hat{Q}_t = the release/outflow in m^3/s hour t from the reservoir, determined from the operation of cascaded reservoirs.

- (2) The generating discharge to be in an allowable zone,

$$\sum_{k=0}^2 [LW_i^{(k)}(\hat{h}_t) \cdot z_{it}^{(k)}] \leq q_{it} \leq \sum_{k=0}^2 [UP_i^{(k)}(\hat{h}_t) \cdot z_{it}^{(k)}] \quad (3)$$

with the unit operating in only one of the zones,

$$\sum_{k=0}^2 z_{it}^{(k)} = 1 \quad (4)$$

where \hat{h}_t = water head in meters in hour t ; $LW_i^{(k)}(\cdot)$ and $UP_i^{(k)}(\cdot)$ = lower and upper bounds of generating discharge in the k th allowable zone, functions of the water head; there will be three generating zones allowable for $k = 0, 1, \text{ or } 2$, with $k = 0$ to indicate a shutdown status.

(3) A unit to keep shutdown or operating for predefined time periods,

$$\sum_{n=t-UDMIN}^{t-1} z_{in}^{(0)} = UDMIN \text{ if } u_{it} = -1 \quad (5)$$

$$\sum_{n=t-UDMIN}^{t-1} z_{in}^{(0)} = 0 \text{ if } u_{it} = 1 \quad (6)$$

where, UDMIN = number, at least, of hours for a unit to remain operating after start-up or rest after shutdown, which means that the unit cannot be shut down/started up if the continuous operation/rest hours of the unit does not reach UDMIN; $u_{it} = (-1, 0, 1)$ indicates (starting up, remaining unchanged, shutting down) the beginning of hour t .

(4) A unit to start up for no more than a maximum number of times,

$$\sum_{t=1}^{24} s_{it} \leq SMAX \quad (7)$$

where s_{it} = binary variable to indicate whether unit i starts up at the beginning of hour t ; SMAX = number of times a unit is allowed to start up at most, which means that the unit cannot be started if the start times reach SMAX.

(5) Relationship between variables,

$$u_{it} = z_{it}^{(0)} - z_{i,t-1}^{(0)} \quad (8)$$

$$s_{it} = \begin{cases} 1 & \text{if } u_{it} = -1 \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

3. Solution Techniques

As illustrated in the previous study [7], the original problem can be reformulated with objective (1), subjected to (3), (4), and

$$\sum_{i=1}^N \sum_{k=0}^2 [LW_i^{(k)}(\hat{h}_t) \cdot z_{it}^{(k)}] \leq \hat{Q}_t - spl_t \leq \sum_{i=1}^N \sum_{k=0}^2 [UP_i^{(k)}(\hat{h}_t) \cdot z_{it}^{(k)}] \quad (10)$$

$$\sum_{n=0}^2 x_{it}^{(n)} = 1 \quad (11)$$

$$UDMIN \cdot x_{it}^{(0)} \leq \sum_{n=t-UDMIN}^{t-1} z_{in}^{(0)} \leq UDMIN \cdot [x_{it}^{(0)} + x_{it}^{(1)}] \quad (12)$$

$$z_{it}^{(0)} - z_{i,t-1}^{(0)} = x_{it}^{(2)} - x_{it}^{(0)} \quad (13)$$

$$\sum_{t=1}^{24} x_{it}^{(0)} \leq SMAX \quad (14)$$

where $x_{it}^{(n)}$ = binary variables for $n = 0, 1, \text{ or } 2$. The problem can be solved with a GA solver.

The solution efficiency of a GA is very likely, not satisfactory, when it encounters difficulty in generating individual solutions that can meet all the constraints. With the help of DP to meet all of the constraints, this study will solve the problem indirectly using

$$\min_{\hat{q}_{it}} f = DP(\hat{q}_1, \hat{q}_2, \dots, \hat{q}_N) \quad (15)$$

subject to

$$\sum_{i=1}^N \hat{q}_{it} \leq \hat{Q}_t \tag{16}$$

with

$$\hat{\mathbf{q}}_i = [\hat{q}_{i1}, \hat{q}_{i2}, \dots, \hat{q}_{i,24}] \tag{17}$$

where \hat{q}_{it} = decision variables of the GA, interpreted as the generating discharge randomly allocated to unit i in hour t ; DP (...) = a function that involves the dynamic programming to return the fitness of an individual solution in the GA and output results of unit commitment.

Using S_{it} and Y_{it} as the state variables, $z_{it}^{(k)}$ and q_{it} as the decision variables, and t as the stage, DP is applied one by one to a hydropower unit to minimize spillage at each stage, and it is formulated for unit i with a backward recursive objective,

$$f_{it}(S_{it}, Y_{it}) = \min_{z_{it}^{(k)}, q_{it}} [spl_{it} + f_{i,t+1}(S_{i,t+1}, Y_{i,t+1})] \tag{18}$$

subject to the boundary conditions

$$f_{i,25}(S_{i,25}, Y_{i,25}) = 0 \tag{19}$$

the spillage

$$spl_{it} = \begin{cases} \hat{q}_{it} & (Y_{it} < 1) \\ \hat{q}_{it} & (Y_{it} \geq 1; \hat{q}_{it} < LW_i^{(1)}) \\ 0 & (Y_{it} \geq 1; LW_i^{(1)} \leq \hat{q}_{it} \leq UP_i^{(1)}) \\ \hat{q}_{it} - UP_i^{(1)} & (Y_{it} \geq 1; UP_i^{(1)} \leq \hat{q}_{it} \leq LW_i^{(2)}) \\ 0 & (Y_{it} \geq 1; LW_i^{(2)} \leq \hat{q}_{it} \leq UP_i^{(2)}) \\ \hat{q}_{it} - UP_i^{(2)} & (Y_{it} \geq 1; \hat{q}_{it} \geq UP_i^{(2)}) \end{cases} \tag{20}$$

the state transfer equations

$$Y_{i,t+1} = \begin{cases} Y_{it} + 1 & (Y_{it} \geq 1; z_{it}^{(0)} = 0) \\ -1 & (Y_{it} \geq 1; z_{it}^{(0)} = 1) \\ Y_{it} - 1 & (Y_{it} \leq 1; z_{it}^{(0)} = 1) \\ 1 & (Y_{it} \leq 1; z_{it}^{(0)} = 0) \end{cases} \tag{21}$$

$$S_{i,t+1} = S_{it} + s_{it} \tag{22}$$

with

$$s_{it} = \begin{cases} 1 & \text{if } z_{i,t-1}^{(0)} - z_{it}^{(0)} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

and the stage constraints (3) and (4), and available flow

$$q_{it} + spl_{it} = \hat{q}_{it} + spl_{i-1,t}^{(*)} \tag{24}$$

the times of start-ups at most,

$$S_{i,t+1} \leq \text{SMAX} \tag{25}$$

and the minimum up or down hours,

$$z_{it}^{(0)} = \begin{cases} 0 & (1 \leq Y_{it} < \text{UDMIN}) \\ 1 & (-\text{UDMIN} < Y_{it} \leq -1) \end{cases} \tag{26}$$

where S_{it} = number of start-up times of unit i from the 1st hour until the beginning of the t th hour; Y_{it} = hours of remaining up (+) or down (−) of unit i at the beginning of hour t ; for example, $Y_{it} = -3$ means the unit i has kept in a shutdown status for 3 h; spl_{it} = the flow that unit i cannot utilize for generation; $f_{it}(S_{it}, Y_{it})$ = the cost-to-go function at the beginning of hour t , which represents the minimum of spillage that the unit can achieve from the beginning of hour t to the end of the day; $spl_{i-1,t}^{(*)}$ = the flow remaining after it is utilized for generation by units from 1 to $i - 1$.

As shown in Figure 1, the critical steps of GA with DP, when applied to the HUC problem, are summarized as follows:

1. Initial Population Generation. Generate the initial population of generation discharge \hat{q}_{it} for each unit randomly subjected to the constraint (16) when the reservoir outflow is given.
2. Fitness. Solve the DP problem for unit i , sequentially giving the optimum spillage $spl_{it}^{(*)}$, generation discharge $q_{it}^{(*)}$, and operation zone for each unit, and the fitness of the individual solution \hat{q}_{it} can be evaluated with

$$DP(\hat{q}_1, \hat{q}_2, \dots, \hat{q}_N) = W_1 \sum_{t=1}^{24} spl_{N,t}^{(*)} + W_2 \sum_{i=1}^N \sum_{t=1}^{24} z_{it}^{(*,1)} \quad (27)$$

3. Crossover. According to the rank of the fitness and crossover probability, two parents are selected from the population. Choose a node T randomly to chop portions of the parent's decision variable \hat{q}_{it} vertically and swap them to generate new individuals, while it is against the constraint (26) but still filling the constraint (16).
4. Mutation. According to the mutation probability, one individual is selected. Choose a node T randomly to redistribute the \hat{Q}_T and obtain a new decision variable \hat{q}_{it} for the individual.

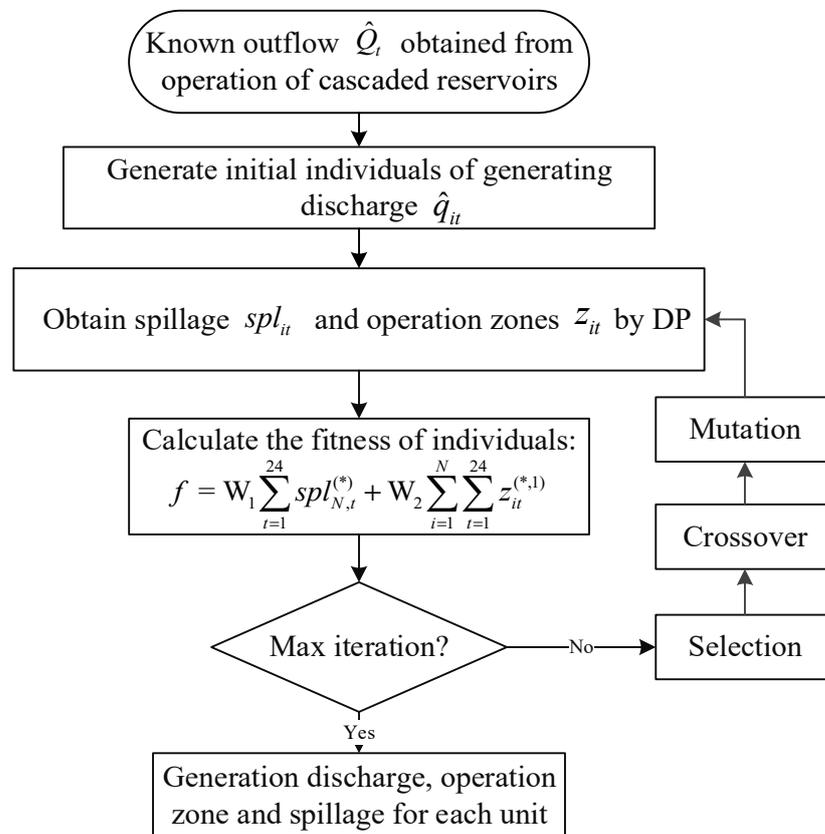


Figure 1. Flowchart of GA with DP to solve the HUC problem.

According to the fitness, the GA optimizes the decision variables \hat{q}_{it} , which determines the maximum discharge available to the unit. DP then obtains the discharge and operating zones of each unit under the given \hat{q}_{it} when minimizing the spillage. The GA can select the optimal decision variables \hat{q}_{it} , and the optimal unit commitments can be obtained with the help of DP.

4. Case Studies

The model and methods, which are coded in C++ on Microsoft Visual Studio 2022 and run under an Intel Core i5-8250U computer environment, will be applied and evaluated through a case study conducted on five identical units in the Manwan Hydropower Station, which was constructed in the third development stage of the Lancang cascade hydropower reservoirs in Yunnan province, China. In June 1995, the Phase I project of the Manwan Hydropower Station was completed, and all five units were successfully commissioned, resulting in a total installed capacity of 5×250 MW. The hydropower station achieved a firm output of 384,200 kW and an annual electricity production of 6.3 billion kWh. The three-dimensional characteristic curve of hydropower units is simplified to facilitate modeling and solving. The relationship between output and discharge is described linearly by the water rate, and the operating zones are divided into low- and high-efficiency zones. Table 1 gives the water rate and the lower (LW) and upper (UP) bounds of the two operating zones at different water heads for one of the five identical units.

Table 1. Water rate and zone bounds.

Head (m)	Water Rate (m ³ /kWh)	LW (1) (m ³ /s)	UP (1) (m ³ /s)	LW (2) (m ³ /s)	UP (2) (m ³ /s)
70.0	6.4	329.6	417.5	439.5	549.4
70.5	6.3	326.5	413.6	435.4	544.2
72.0	6.2	318.3	403.1	424.4	530.4
73.5	6.0	310.5	393.3	414.0	517.5
75.0	5.9	302.8	383.5	403.7	504.6
76.5	5.7	296.6	375.7	395.4	494.3
78.0	5.6	289.9	367.1	386.5	483.1
79.5	5.5	283.1	358.6	377.5	471.9
81.0	5.4	277.5	351.4	369.9	462.4
82.5	5.3	271.8	344.2	362.4	452.9
84.0	5.2	266.6	337.7	355.5	444.3
85.5	5.1	260.9	330.5	347.9	434.9
87.0	5.0	256.3	324.6	341.7	427.1
88.5	4.9	251.1	318.1	334.8	418.5
90.0	4.8	245.9	311.5	327.9	409.9
91.5	4.7	240.8	305.0	321.0	401.3
93.0	4.6	235.6	298.4	314.1	392.7
94.5	4.5	230.4	291.9	307.2	384.1
96.0	4.4	225.3	285.3	300.4	375.4
97.0	4.3	222.2	281.4	296.2	370.3

4.1. Solved by DP Sequentially for Individual Units

Applying the DP to only a unit has proven effective in addressing the challenge of generating individual solutions that satisfy all constraints and overcoming the inefficiency of relying solely on the GA to solve the HUC problem. The hydropower units will be committed in quarterly intervals during a day, with the parameter UDMIN, defined as the minimum required number of consecutive hours for a unit to remain shut down or operating, set to 3 h, and the SMAX, representing the maximum allowable number of times a unit can start up during the day, limited to up to three start-ups. The following two procedures will be investigated by sequentially applying the DP to allocate available outflow among units.

- DP-1: Units sequentially utilize their maximum capacity at a single chance. The procedure starts without any flow allocated among the units,

$$\hat{q}_{it} = 0 \tag{28}$$

thus, all available outflow from the reservoir is assumed to be spilled,

$$spl_{0,t}^{(*)} = \hat{Q}_t \tag{29}$$

Applying the DP approach sequentially to each unit from 1 to N , the quarterly generating discharges of the five units in the Manwan hydropower plant are determined, along with the corresponding spillages, as shown in Figure 2. The absence of cooperation among the units incurs significant spillages, resulting in a loss of water resources.

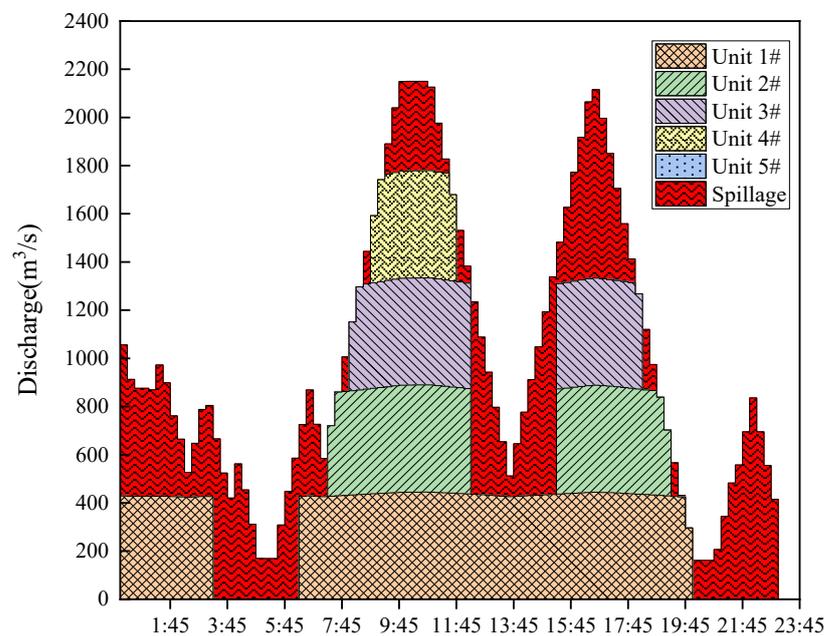


Figure 2. Generating discharge for each unit and spillage for Manwan with DP-1.

- DP-2: Units progressively unlock their capacity in a sequential manner.

Firstly, the units are sequentially committed to utilizing their capacity up to the lower bound of the first operating zone, with

$$\begin{cases} \hat{q}_{it} = 0 \\ spl_{0,t}^{(*)} = \hat{Q}_t \\ UP_i^{(1)} := LW_i^{(2)} := UP_i^{(2)} := LW_i^{(1)} \end{cases} \tag{30}$$

for the DP to derive the optimum, $\hat{q}_{it}^{[1]}$.

Subsequently, the remaining outflow will be distributed incrementally among the units in a sequential manner, prioritizing the operation of units in high-efficiency zones to the greatest extent possible, with the lower and upper bounds on operating zones restored to their initial values and the space of the second operating zone reserved for a later flexible allocation,

$$\begin{cases} \hat{q}_{it} := \hat{q}_{it}^{[1]} \\ spl_{0,t}^{(*)} := \hat{Q}_t - \sum_{i=1}^N \hat{q}_{it}^{[1]} \\ UP_i^{(2)} := LW_i^{(2)} \end{cases} \tag{31}$$

for the DP to determine the optimum, $\hat{q}_{it}^{[2]}$.

Then, the reserved space in the second operating zone will be unlocked to reduce remaining spillages, with the upper bound of the second operating zone restored to its initial value and

$$\begin{cases} \hat{q}_{it} := \hat{q}_{it}^{[2]} \\ spl_{0,t}^{(*)} := \hat{Q}_{it} - \sum_{i=1}^N \hat{q}_{it}^{[2]} \end{cases} \quad (32)$$

for the DP to determine the optimum, $\hat{q}_{it}^{[*]}$, which, along with spillages, are shown in Figure 3. It is notable that spillages occur in much fewer hours and decrease significantly compared with the result obtained with DP-1, especially from 00:00 to 07:00, 09:15 to 11:15, and 12:15 to 17:45. The generating discharges, however, remain primarily concentrated on units 1#, 2#, and 3#, suggesting a lack of flexibility.

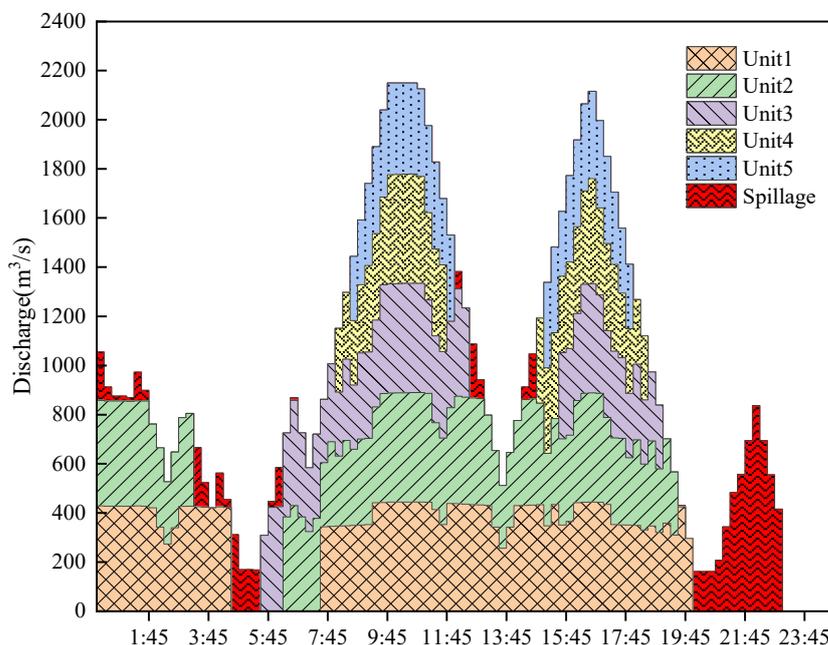


Figure 3. Generating discharge for each unit and spillage with DP-2.

Table 2 presents the operating zones of each unit over 96 periods with the DP-2. The hours when units operating in the low-efficiency zone are predominantly concentrated from 17:00 to 09:00, along with 11:30 to 16:00 for units 3#, 4#, and 5#. These periods collectively represent approximately 10.63% of the total duration. The spillages occur when the remaining outflows are insufficient to initiate a unit’s start-up or remain operational for the minimum hours.

Table 2. The generating zones of each unit with DP-3.

Unit	0:00–2:45	3:00–5:45	6:00–8:45	9:00–11:45	12:00–14:45	15:00–17:45	18:00–20:45	21:00–23:45
1#	22222221112	22222200000	00000222222	22222222222	22222122222	22222222222	21212121000	00000000000
2#	22222221112	20000000000	02221212121	22222222222	22222111222	12222222221	21212100000	00000000000
3#	00000000000	00000000012	22221211112	22222222222	22000000000	00222222211	11110000000	00000000000
4#	00000000000	00000000000	00000001111	22222222220	00000000002	22122222211	11000000000	00000000000
5#	00000000000	00000000000	00000000011	12222222212	00000000000	22122222211	00000000000	00000000000

Note: “0” for shutdown, “1” for low-efficiency zone, and “2” for high-efficiency zone.

4.2. Solved by GA with the Help of DP

The allocation of outflows among the five units across 96 quarters within a day, despite involving 480 decision variables, poses significant challenges due to the constraints

imposed on the operating zones. Specifically, the requirements for maximum start-ups and a minimum operating duration of three hours mandate that each unit remain in operation or shut down continuously for at least 12 consecutive periods. Including constraints adds complexity to the optimization process and increases the likelihood of the GA converging toward a local optimum.

Here, the GA procedure will randomly generate the initial solutions of allocating the outflow among units, for which fitness will then be evaluated by applying the DP sequentially to each unit. Two DP strategies are designed for a comparison: the first is the same as shown in Figure 1, denoted as GA-1DP; the second, denoted as GA-2DP, applies the last two steps in DP-2, but with $\hat{q}_{it}^{[1]}$ initiated randomly.

Figure 4 illustrates the spillage iteration process using GA-1DP (a) and GA-2DP (b). Although the population size and number of iterations, set to 400, are relatively large, the spillage ultimately converges at $16.663 \times 10^6 \text{ m}^3$ after approximately 250 iterations when employing GA-1DP. In contrast, utilizing GA-2DP with a population size of 100 and 50 iterations leads to the spillage converging at $6.0 \times 10^6 \text{ m}^3$ after just five generations, demonstrating faster convergence and lower spillage than GA-1DP.

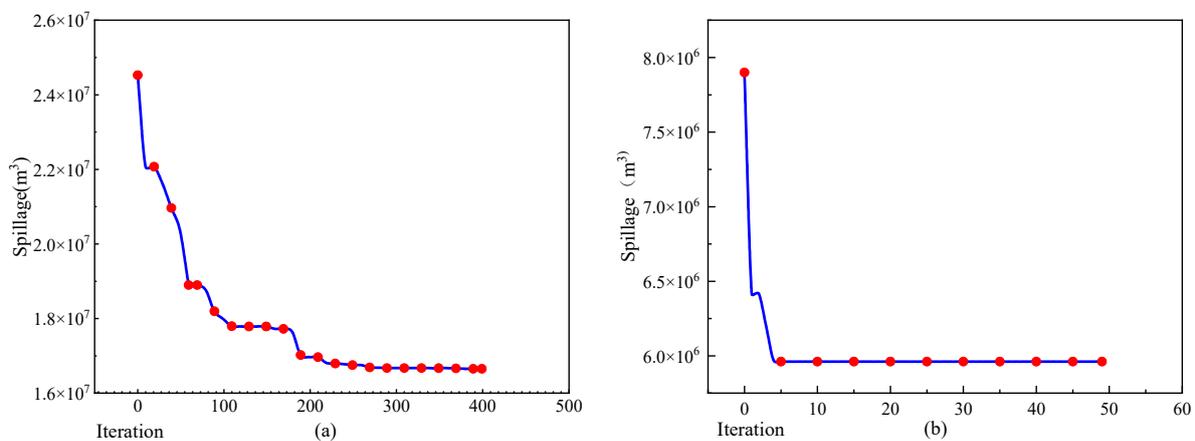


Figure 4. Converting process of GA-1DP (a) and GA-2DP (b).

Figure 5 illustrates the quarterly generation discharges for each unit and the spillage from the reservoir with the GA-2DP. The allocation of release between the units exhibits a more uniform distribution, resulting in reduced spillages, primarily occurring at 3:15, 3:30, 4:30, 6:00, 12:00, and 14:30. Consistently lower releases during the period from 20:00 to 20:45 result in the units being unable to start up between 20:00 and 23:45, leading to increased spillages during this timeframe.

Table 3 illustrates the operating zones of each unit over 96 quarters during the day with GA-2DP. To enforce operational stability, each unit is limited to a maximum of two start-ups and remains either in operation or shut down continuously for a minimum of three hours. The proportion of units operating in the low-efficiency zone is 5.21%, which is 5.42% lower compared to DP-3, indicating a notable improvement in the operational efficiency.

Table 4 compares different spillage methods and the number of periods when units are operated in the low and high-efficiency zones for the Manwan hydropower plant. The spillage is significantly reduced from $27.764 \times 10^6 \text{ m}^3$ with DP-1 to $7.089 \times 10^6 \text{ m}^3$ with DP-2 and from $16.663 \times 10^6 \text{ m}^3$ with GA-1DP to $5.961 \times 10^6 \text{ m}^3$ with GA-2DP, demonstrating the effectiveness of the applied methods (DP-2 and GA-2DP) in reducing spillage, and in addition, applying the last two steps in DP-2 results in an increase in the number of unit start-ups for both DP and GA with DP, contributing to a reduction in spillage. Compared with not employing the GA, employing the GA contributes to a reduction in spillage and an improvement in unit start-ups. Thus, the implementation of the DP strategy with the last two steps in DP-2 proves beneficial in enhancing the solution for the HUC problem, reducing spillage by 74% $[(27.764 - 7.089)/27.764]$ and increasing the

high-efficiency percentage by 29% $[(181 - 140)/140]$, and the inclusion of the GA process further contributes to reducing spillage by 16% $[(7.089 - 5.961)/7.089]$ and promoting the high-efficiency percentage by 10% $[(200 - 181)/181]$. Compared to DP-1, the GA-2DP method exhibits a 79% improvement in spillage reduction and a 43% increase in time in high-efficiency zones.

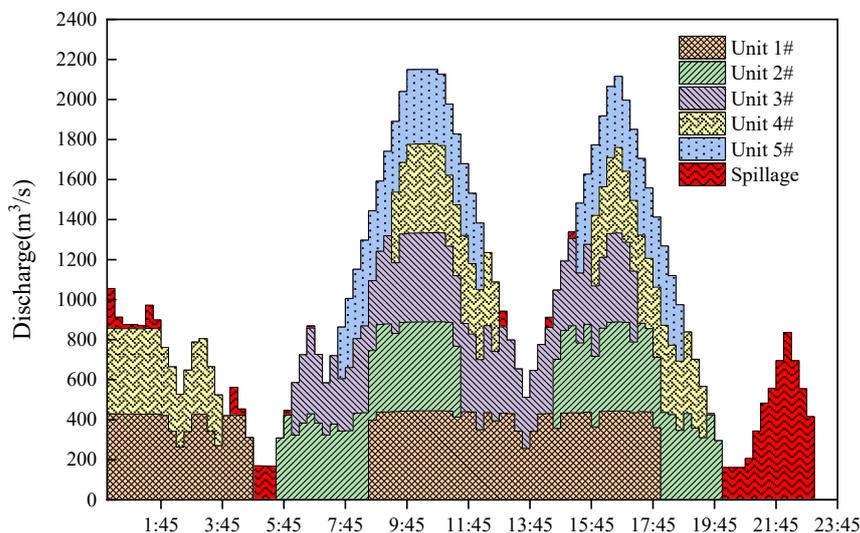


Figure 5. The generating discharge for each unit and spillage with GA-2DP.

Table 3. The generating zones of each unit with GA-2DP.

Unit	0:00–2:45	3:00–5:45	6:00–8:45	9:00–11:45	12:00–14:45	15:00–17:45	18:00–20:45	21:00–23:45
1#	22222222122	221222100000	000000000022	222222222222	222222122222	222222222222	000000000000	000000000000
2#	000000000000	000000000012	122212222222	222222222200	000000000022	222222222222	222221210000	000000000000
3#	000000000000	000000000000	122212112222	222222222222	222221112222	222222222000	000000000000	000000000000
4#	22222221112	211000000000	000000000000	022222222222	222000000000	000222222222	222221000000	000000000000
5#	000000000000	000000000000	00000122222	222222222222	100000000000	022222222222	221000000000	000000000000

Note: “0” for shutdown, “1” for low-efficiency zone, and “2” for high-efficiency zone.

Table 4. Comparison of spillage and efficiency periods using different methods.

Performance	DP-1	DP-2	GA-1DP	GA-2DP
Spillage($\times 10^6$ m ³)	27.764	7.089	16.663	5.961
Low efficiency periods	5	51	8	25
High-efficiency periods	140	181	170	200

Based on their superior performance, further investigation will be conducted by applying DP-2 and GA-2DP methods to scenarios involving one, two, three, four, and five units, respectively. Due to the lack of stage-separability between units caused by the constraints and objective functions, DP can only obtain optimal solutions for individual units based on the allocated flow, implying that DP can guarantee the attainment of the global optimum solution only when applied to a single unit in this HUC problem.

Table 5 displays the spillage from the reservoir, the percentage of time for units operating in the low-efficiency zones, and solving time for the two methods across different numbers of units. When the number of units is four or less, the spillage and the proportion of time in low-efficiency zones remain almost identical for both methods. In the case of considering five units, the GA-2DP exhibits a linear increase in the CPU time to approximately 10 s, while still maintaining an acceptable level, alongside the observed reductions in spillage and the percentage in inefficient operating zones. In contrast to the scenario where GA alone fails to produce a feasible solution, incorporating DP to satisfy

the constraints allows the GA with the last two steps in DP-2 to converge at the optimal solution more efficiently.

Table 5. Comparison between DP-2 and GA-2DP with different numbers of units.

	DP-2			GA-2DP		
	Spillage ($\times 10^6$ m ³)	Low Zones (%)	Time (s)	Spillage ($\times 10^6$ m ³)	Low Zones (%)	Time (s)
1	57.558	1.04	0.003	57.558	1.04	3.34
2	33.801	5.73	0.005	33.801	5.73	5.23
3	19.697	7.29	0.005	19.418	5.90	6.97
4	10.878	8.33	0.006	10.010	6.25	8.55
5	7.089	10.63	0.007	5.961	5.21	10.08

5. Conclusions

This study highlights the effectiveness of integrating dynamic programming into a genetic algorithm to address the challenges in generating feasible solutions that satisfy all constraints in a HUC problem, ultimately leading to significant improvements in solution quality. Four procedures are presented and compared, including the following: DP-1, which sequentially utilizes units' maximum capacity; DP-2, which progressively unlocks operating zones; GA-1DP, which includes a GA mechanism in DP-1; and GA-2DP, which incorporates the last two steps in DP-2 to enhance solution quality.

Case studies in five units of the Manwan Hydropower Plant in China suggest the following:

- (1) The strategy that progressively unlocks the operating zones of a unit improves the DP-1 in reducing spillage by 74% and increasing the high operating efficiency percentage by 29%;
- (2) The inclusion of the GA process further contributes to reducing spillage by 16% and promoting the high-efficiency percentage by 10%;
- (3) If compared to DP-1, the GA-2DP method exhibits a 79% improvement in spillage reduction and a 43% increase in the percentage of time in high-efficiency zones;
- (4) The GA-2DP achieves convergence in the fifth iteration, even with a small population size;
- (5) It is essential to acknowledge that potential deviation may arise between the total power output derived from the internal HUC problem and interplant load allocation among power plants, which will give rise to challenges in achieving load balancing within the system. This deviation mainly comes from the presence of spillage and the simplification of the three-dimensional characteristic curve of the unit. As a result, mitigating the deviation will constitute a focal point of our future study.

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