SELECTION OF OPTIMUM SMALL HYDROPOWER SITES WITH THE APPLICATION OF OPTIMISATION TECHNIQUES - THE CASE OF THE GELANA BASIN IN ETHIOPIA

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Abstract

Decision makers in developing countries require appropriate decision making tools for allocating limited financial resources on alternative energy projects. This paper discusses the particular case of selecting optimum sites from alternative small hydropower sites.

Conventional methods of screening or prioritising hydropower development alternatives consider economic feasibility measures for pre-determined system capacities. Optimisation techniques are more flexible because they are able to assess specific features of alternatives for variable system capacities. This advantage of optimisation can be applied in comparing small hydropower alternatives which are generally characterised by site-specific nature of the cost function.

The paper demonstrates the application of optimisation on the basis of a theoretical small hydropower system established from local data of the Gelana basin in Ethiopia. The system is established for two alternative small hydropower sites and seven demand centres situated at different levels of proximity from the hydropower sites.

Non-linear cost functions were developed for each site based on local information such as hydrological, field survey, local unit prices and related information. The cost functions are expressed in terms of the variable power capacities which serve as the decision variables of the system. The objective function is then defined as the sum of cost functions of the involved alternatives and the cost of associated transmission lines. That way, both the conditions at specific sites and the relative proximity of load centres are made to contribute to the optimisation.

Since there exists no universal method of optimisation which can handle all types of problems, it was found necessary to identify an appropriate method for the small hydropower system. The identification was done by testing the applicable optimisation methods on the theoretical small hydropower system.

Global as well as local methods of non-linear optimisation were tested and one of the local methods i.e., the Generalised Reduced Gradient (GRG2) method, was found to be appropriate. The advantages of the method in testing the sensitivity of decisions is also demonstrated by running the optimisation for changed constraint conditions.

1 Background

In a country like Ethiopia with available large potential of hydropower and also an very large unsatisfied demand, it is very essential to search for optimum ways of allocating financing for hydropower development.

Past studies have identified numerous small hydropower sites in the country. In reality, it is far from possible to practically develop all technically feasible sites. Therefore, optimisation is necessary to guide development planners in prioritising projects. This applies to the case of many African and other developing countries as well.

The paper focuses on optimisation in a rural context because the large proportion of unsatisfied demand exists in rural zones. However, the optimisation methodology can be extended to systems that include both rural and industrial demand centres.

The primary problem in rural energy supply in developing countries lies in the traditional energy policy which does not take proximity of demand centres in the choice of power development.

Economically attractive sites are chosen based on factors which disregard proximity of load centres to the hydropower sites. Because of this, many remote demand centres could not be connected to the grid even at times of excess power capacity due to heavy transmission line costs.

It is, therefore, important to have a policy that considers the energy needs of rural centres at early planning stage. On this regard, the need for the inclusion of the effect of transmission line costs in a regional grid small hydropower supply system has been underscored by several authors, Hildebrand 1993. Hence, the small hydropower system developed in this study is designed so as to include the cost of transmission system as an important factor in the optimisation.

1.1 Optimisation Models for Rural Electrification

Many recent optimisation models for rural electrification give more emphasis to other renewable energy sources and even to diesel systems than to small hydropower. For instance, there exist user-friendly models that have been developed to study a wide variety of hybrid power systems, Barely 1996, Seeling-Hochmuth 1997.
These models are mainly designed for simulating hybrid systems consisting of wind turbines, photo-voltaics, multiple diesel generators, and battery storage. The models consider specific details of these energy converters. In comparison, small hydropower system are left with just *a mention of the possibility to integrate them in the hybrid system*.
One reason for this may be because small hydropower in itself consists of many components which are not easy to define in general terms. In fact, the preparation of system cost function for small hydropower remains to be a challenge. This is caused by site specific nature of cost function on small and micro hydropower range.
The challenge is even more apparent in the context of developing countries in which hydropower technology is relatively far less developed. That is partly the reason why most of the efforts to standardise the design of small hydropower have not been successful, MHPG 1997.

1.2 Application of Non-linear Methods to Small Hydropower Systems

Hybrid systems for rural electrification are characterised by non-linear objective function, Seeling-Hochmuth 1997. This is also the case with small hydropower systems which are characterised by non-linear objective function and constraints, Gulliver and Roger 1991.

Tingsanchali and Carlos 1989 demonstrated the application of non-linear programming for the planning and preliminary design of an optimum diversion scheme for hydropower in the Cho Shui River basin in Taiwan. The optimisation problem was defined with a non-linear objective function and linear constraints. The derivative-free Rosenbrock's method of rotating co-ordinates was applied for the purpose. Although this is a popular method, it finds application only as a sub-program in non-linearly constrained systems.

Hildebrand 1997 demonstrated the application of the Branch and Bound method to a local grid small hydropower system by taking the case of Grenada. The approach involves successive linearisation on the non-linear objective function to enable solution by the common Linear Programming algorithm. Moreover, assumption is made of linearity of constraints. However, the nature of hydropower problems does not permit assumption of linearity of constraints for all cases. For this reason, a general optimisation methodology for a regional-grid small hydropower system should be designed such that it can handle non-linearly constrained problems as well.

Less restrictive or non-restrictive methods are preferred for the problem at hand which is non-linear both in terms of the objective function and the constraints. In this regard, this paper attempts to find out the most convenient non-linear optimisation method for the small hydropower system.

Finding such a method is a necessary condition towards developing a user-friendly model that can identify optimum small hydropower sites from among competing alternatives. Such model can by itself serve as a decision making tool for selecting optimum hydropower sites. Furthermore, it can be integrated into a larger model that considers all types of renewable energy sources in a hybrid power system.

2 Scheme for Establishing Small Hydropower System

Although portrayed as challenging, the establishment of specific cost function remains to be an unavoidable precondition for practical optimisation problems. This is so because the use of a cost function developed on some specific features of a site is regarded better practice than using fixed specific costs, Tung 1993.

Often, all the necessary database may not exist at a preliminary stage for preparation of a very accurate specific cost at a site. However, it is possible to consider variable magnitudes of the essential components of a small hydropower scheme. Producing a cost function for the site will effectively distinguishes it from other alternative sites. Similar cost functions of alternative developments in a region can provide the basis for establishing the objective function for optimisation.

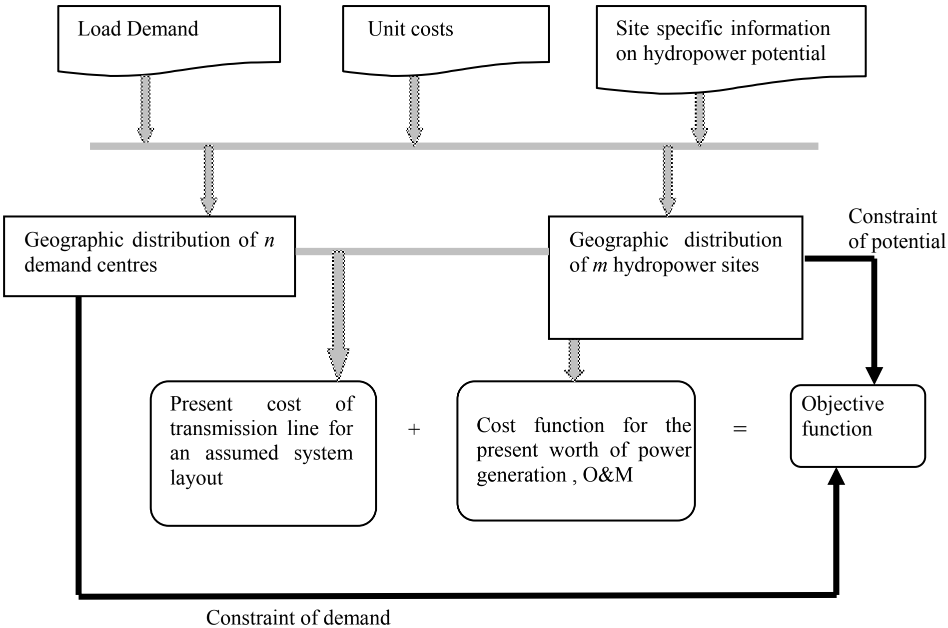

Figure 1 Procedure for small hydropower system development

This study made use of computer subroutines which were designed to facilitate the dimensioning of hydraulic structure components for run-of-river type small hydropower schemes. The use of computer program was found to be convenient because the establishment of the cost function involves repetitive dimensioning of the hydraulic components for variable range of power supply.

A flow-chart of the procedure for establishing the cost function and the constraints of the small hydropower system is given in Fig. 1. For the considered case study, concave type non-linear functions were found to be appropriate in representing the cost function. Moreover, the optimisation problem appeared to be non-linearly constrained due to the non-linear nature of the power loss through the transmission lines.

3 Elements of the Hydropower System

The elements of the hydropower system consist of the decision variables, the objective function and associated constraints. As shown in Fig. 1, the elements of a general hydropower system are defined with *n* demand centres and *m* power plants. The definition of the system is made on the basis of the additional variables described below:

$D_1, D_{2,} \ldots D_n$ demand centres (n in number)
$HP_1, HP_{2,} \ldots HP_m$ identified power plants (m in number)
L_{ij} - distance of demand centre i from the jth power plant or from an intermediate demand centre served by the power plant (km)
P_{ij} - power transmitted to demand centre i from the jth power plant (kW)
PT_{ij} - total power transmitted through line L_{ij}
PD_i – power demand at demand centre i (kW)
PG_j - power generated at power plant HP_j (kW)
$P\max_j$ – maximum power potential at site HP_j (kW)
Pl_{ij} - power loss associated with the transmission of PT_{ij} (kW)

3.1 Decision Variables

Decision variables are the independent variables that are to be determined by solving the model. The power transmitted from a power plant to a demand centre i.e. the P_{ij} s are the decision variables in the hydropower system. Generally, the decision variables can assume values within a restricted range. The values that the decision variables attain at the end of an optimisation run give information on the optimal power supply.

3.2 Objective Function

The objective function changes value as a result of changes in the values of decision variables. It provides measures for testing the desirability of the consequences of a decision.
The flow-chart in Fig. 1 shows that the objective function considers power generation cost at each site and also the transmission line costs corresponding to the related system layout. In general terms, the objective function can be described as the sum of power generation costs (*CP*) and the associated transmission layout cost (*CT*).

$$f = CP + CT \qquad [1]$$

The optimisation procedure consists of minimising the value of the function f to yield values of P_{ij} which when analysed give the optimum sites for power generation.

*3.2.1 Cost of Power Generation (*CP*)*

$$CP = \sum_{j=1}^{m} (a_j PG_j^{n_j} + \beta_j) \quad [2]$$

The evaluation of the magnitudes of CP is based on the formula:
where PG_j is the total sum of the power generated at any plant j as given by:

$$PG_j = \sum_{i=1}^{n} (P_{ij} + Pl_{ij}) \qquad j = 1,2...,m \quad [3]$$

in which an expression for a site cost function of the form $Cost = a\ Power^n + \beta$ is considered where a_j, n_j, and β_j stand for the parameters of the cost function at the j[th] power plant.

*3.2.2 Cost of Transmission (*CT*)*

Optimisation begins with an initial layout of power transmission with optional but feasible magnitudes of power supply to the demand centres. The cost of transmission line in the system is then found based on the initial layout of power transmission lines. The weighted average length of transmission is used to evaluate the average length of transmission for different layouts. The power transmitted through each particular line is used as the weighting factor as given in equation [4].

$$CT = \left[\frac{\sum_{i=1}^{n}\sum_{j=1}^{m} PT_{ij}\, L_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} PT_{ij}} \right] (nm)\alpha \text{...} [4]$$

where α - unit cost of transmission line (50 000Birr/km for 33 kV)

3.3 Constraints

The constraints restrict the range of the decision variables as a result of technological, socio-economic, legal or physical constraints on the system. The flow-chart in Fig. 1 indicates that constraints are imposed by limits of power potential and demand of load centres. These constraints are described below in mathematical form. In addition to these constraints, there are also bound constraints on each decision variable which are mandatory in some types of optimisation techniques, Michaelwicz 1996.

i) Constraints to satisfy power demand

$$\sum_{j=1}^{m} P_{ij} = PD_i \qquad \boldsymbol{i = 1,2 \ldots. N} \qquad \boldsymbol{[5]}$$

ii) Limitation of power potential at the hydropower sites

$$PG_j = \sum_{i=1}^{n} (P_{ij} + Pl_{ij}) \le P\max_j \qquad \boldsymbol{j = 1, 2, \ldots, m} \qquad \boldsymbol{[6]}$$

iii) Non-negative condition of the decision variables

$$P_{ij} \geq 0 \qquad \boldsymbol{i = 1,2 \ldots n; \;\; j = 1,2,\ldots m} \qquad \textbf{[7]}$$

iv) The sum total of the delivered energy must be equal to the sum total of demand

$$\sum_{i=1}^{n} \sum_{j=1}^{m} P_{ij} = \sum_{j=1}^{m} PD_j \qquad \textbf{[8]}$$

v) Domain constraints restrict the value of deliverable power through a particular transmission line by lower and upper limits i.e $P_{low,ij}$ and $P_{up,ij}$ respectively.

$$P_{low,ij} \leq P_{ij} \leq \qquad \textbf{[9]}$$

4 The Case of the Abaya-Chamo Basin

The Abaya-Chamo basin which is located in the south-west of Ethiopia is taken as a typical rural region for a case study to establish a theoretical self-contained local grid system. Abaya-Chamo is a sub-basin of the Rift Valley Lakes Region with rivers draining to the Abaya and Chamo Lakes.
A sketch of the geographic location of 7 demand centres and 2 hydropower sites within the study site is shown in Fig. 2. The target is to find the optimum power supply to serve the demand centres by either or both plants.

The optimisation begins with assumed initial values of power supply to the demand centres. Table 1 gives the initially assumed values of the 14 decision variables and the associated objective function value for a diesel-hydropower hybrid system.

The system cost includes initial investment on site construction, cost of transmission lines and the present cost of diesel fuel for back-up supply. The value is expressed in Ethiopian local currency (1 USD ≈ 8.5 Birr). The cost of diesel fuel is discounted over an assumed operation period of 30 years.

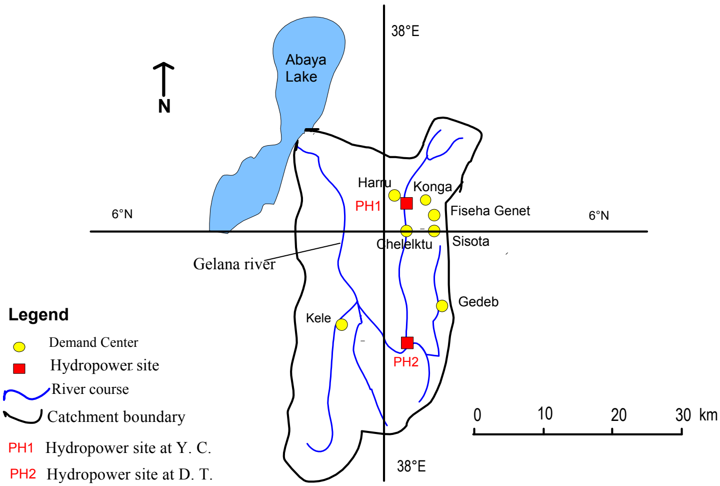

Figure 2 The case study area

Table 1 Assumed initial system for the Gelana system

	Initial power supply set up (kW) to								
From	Chelelktu	Kele	Gedeb	Sisota	F.G.	Konga	Harru	ΣRow	Power Potential
Y.C	143.6	98.3	160.6	101.5	80.7	160.6	185.5	930.8	≤ 2000
D.T	142.4	111.7	163.4	100.5	79.3	154.4	184.5	936.2	≤ 2000
ΣCol.	=286	=210	=324	=202	=160	=310	=370	*O.F.=115.4 M. Birr*	

To help visualisation of the nature cost function for the Gelana system, the decision variables are summarised to 2 major decision variables i.e. the power to be generated at the two alternative sites. It appears that the sum of the capital cost functions for the two sites is non-convex type as shown by the surface of the cost function in Fig. 3-A. The actual search path as restricted by the constraints of demand is shown in Fig. 3-B. The concave type of curvature in the search path clearly shows that the particular problem does not fall under convex programming. Therefore, focus is made on non-convex programming problems.

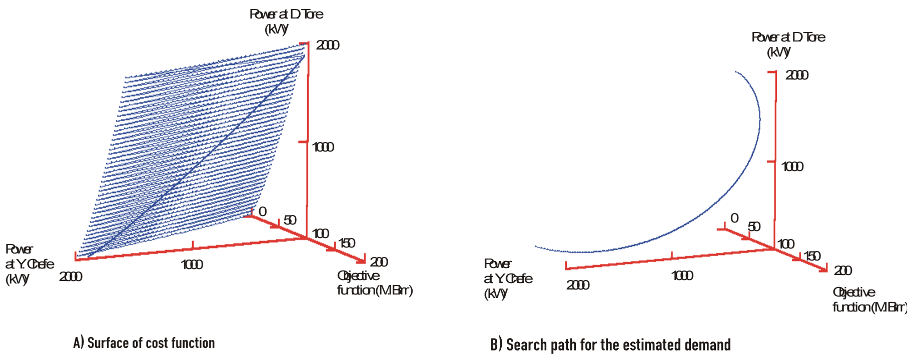

Figure 3 Nature of objective function

5 Applied Non-linear Optimisation Methods

It is unrealistic to expect one general non-linear programming code that works for every kind of non-linear system. The only way to find out an appropriate method is to test the alternative techniques on the specific system being examined.

Particularly well studied areas are unconstrained or linearly-constrained convex systems for which the global optimum is the same as the local optimum. In non-convex optimisation problems, local optimum can also exist beside the global optimum. The result of the search on such spaces have to be carefully checked to differentiate between local and global optimum, Horlacher 1987.

Alternatively, global search methods can be applied to avoid getting stuck in a local optimum. Pham et al 2000 discuss intelligent optimisation techniques that seek the minimum following the example of natural processes. Genetic Algorithm and Simulated Annealing are among such natural algorithmic methods.

Seeling-Hochmuth 1997 mentions the superiority of Genetic Algorithm in non-linear systems. Her application of Genetic Algorithm for the optimisation of hybrid power system did indeed prove to be appropriate for that particular case. However, genetic algorithm can not be regarded as a universal solution method for every non-linear problem, Haupt and Haupt 1998.

Therefore, genetic algorithm should also be tested to find out whether it is suitable for the hydropower system at hand. Gradient search methods are calculus-based, and are obviously more restricted than derivative-free methods. The paper aims to find out whether these restricted methods are perhaps suited to the small hydropower system. The answer to this question can be found by testing the performance of these methods and comparing the results with non-restrictive methods such as Genetic Algorithm.

6 Discussion of Results

In the following sections, presentation of results of the applied method is made. The presentation is preceded by a brief description of the underlying principle of the method. It starts with gradient search methods and proceeds to Genetic Algorithm methods.

6.1 Result of Application of Gradient Search Methods

Three gradient search methods i.e. the penalty function method, the method of feasible directions, and the generalised reduced gradient method were tested on the system. The penalty function method transforms the constrained optimisation problem into a sequence of unconstrained optimisation problems. This is done by adding constraints, multiplied by a large penalty term, to the objective function, Bhatti 2000.

Appropriate unconstrained mutli-variable optimisation routine and also a one dimensional optimisation routine must be included as sub-programs with the penalty method. In this study the Davidon-Fletcher-Powell method is used as the unconstrained subroutine.

A cubic-interpolation method is employed as the underlying one dimensional minimisation. Fig. 4 shows the result of optimisation for the penalty method. Although the program was tried for different set of initial values, no interesting and visible improvement in the objective function could be attained.

A second type of gradient method considered in this study is based on the principle of useable feasible directions. A search direction is termed useable feasible if it leads to a better point than the starting point and if it does not violate constraints.

A Fortran program by Vanderplaats 1991 which uses Zoutendijk's strategy of useable feasible direction was applied to the small hydropower system. The optimisation run from different starting points failed to show any reaction. Therefore, it is considered not to be useful for optimising this particular problem. The difficulty lies more on the nature of the objective function and constraints than on the program. The program performed very well on other types of non-linearly constrained problems.

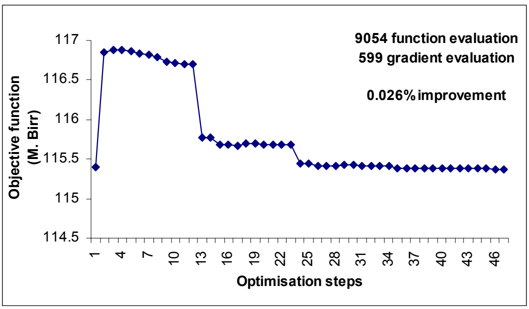

Figure 4 Optimisation result by penalty function method

The GRG2 uses principles of reduced gradients and is the third type of gradient search method applied in this study. Mays 1989 described a number of different practical problems for which the GRG2 routine has been successfully integrated with water resources simulation models. Fig. 5 shows the relatively better performance of this routine on the current problem. It clearly arrived at a smaller value of the objective function than the penalty function method did. Regardless of the starting point, four of the five trials meet the same value of the objective function

As shown in Fig. 6 the decision variables did also change in favour of one of the sites i.e. the Yirga Chefe site. The outcome suggests a decision to generate from one power plant only. In other words, power generation from a single site to cover the demand of all load centres is more economical than generating from two power plants. Economies-of-scale would also dictate this decision. However, the situation would change if either the demand levels are increased or the upper limit on power potential is reduced. Optimisation for the same system with a new upper limit of potential of 1500 kW produced a new optimum with a completely different decision that considers energy generation from both sites. Fig. 7 compares the effect of changes in upper limit of potential values based on two trials which start from different initial points. In effect, change of other factors may also lead to different decisions. Therefore, the optimisation result has to be accompanied by sensitivity analysis that take care of all possible scenarios of changes to the system parameters.

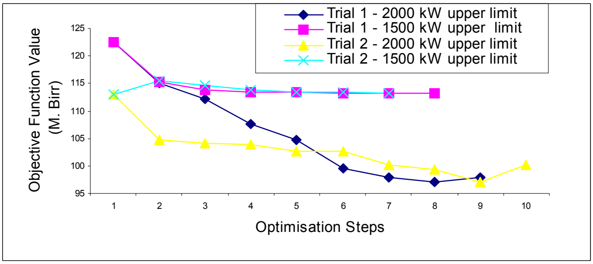

Figure 5 Optimisation Result by GRG2 method

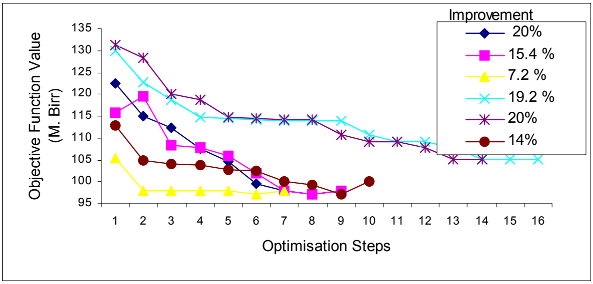

Figure 6 Decision Variables in the Course of Optimisation

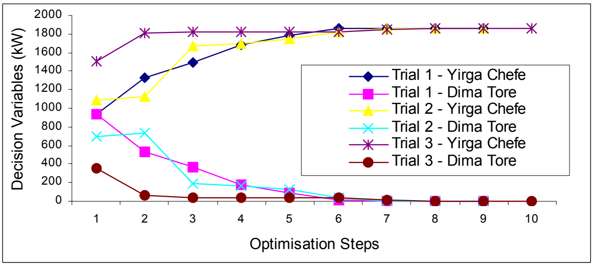

Figure 7 Sensitivity of decision to changes in upper limit of potential

6.2 Result of Application of the Genetic Algorithm Methods

A limited period evaluation version of an Evolutionary Solver was acquired from *Frontline Systems* and applied for the same set up of initial values used in the GRG2 method. The solver had to be rerun several times to find even a local minimum since the program often returns the initial values without change.
Compared to the GRG2 method, the solver did not succeed in approaching the possible global minimum. For this reason, the advantage of the solver is not apparent on this particular problem. The developers of the Evolutionary Solver also admitted that the GRG2 method performs better when it comes to this particular system.
GENOCOPIII is a genetic program by Michalewicz and Nazhiyath 1995 and its C source code has been used for testing the suitability of the program to the small hydropower system. The result of application of these method to several trials is shown in Fig. 8.
The objective function values (also called the fitness values in biological terms) decrease from generation to generation. However, non of these trials yielded results close to the minimum values obtained by GRG2 method. Although GRG2 is a neighbourhood search method, it was successful in producing better result than GENOCOPIII for this application.

It means that according to this investigation both GENOCOPIII and the evolution solver are less suited to the small hydropower system. There is, however, a particular area of utility of the GENOCOPIII method to the small hydropower system. The program is able to produce different sets of feasible solutions when the parameters for random number generation are made to vary in the different trials. Therefore, the solutions obtained at each run represent different points in the feasible space.
These solutions could provide the necessary starting points for searching the optimum with the GRG2 method.

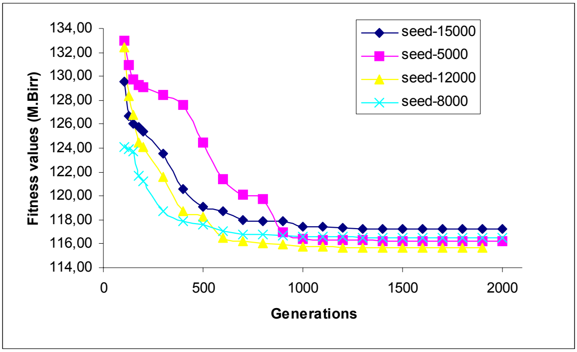

Figure 8 Optimisation result by GENOCOPIII

7 General Applicability of the GRG2 Method

The optimisation programs mentioned above have been used to the case of diesel-hydro hybrid system. Such a system is considered because of its advantages in providing guarantee to the reliability of supply. Otherwise, the GRG2 method is also tried and found to do well for a run-of-river scheme without back up. However, the limits on the upper bound of supply for each hydropower site have to be kept to an acceptably lower level to minimise periodical interruption of power supply arising from stream flow variability, Zelalem and Horlacher 2000.
The robustness of the GRG2 method was tested by using the system of the Bilate basin which is also a sub-basin in the Abaya-Chamo lakes region. The new system has 5 small hydropower sites and 9 demand centres. The GRG2 method performed as good as it did for the case of the two-alternative system in the Gelana basin.

Therefore, the authors strongly believe that GRG2 can potentially be developed to a general purpose program for optimisation of small hydropower systems.

8 Economic Viability

The objective function can be modified to show status of economic viability during the course of optimisation. This can be achieved by maximising an economic measuring criteria such as Benefit to Cost ratio (B/C). This fact is illustrated in Fig. 9 which shows the gradual increase in the value of B/C for the diesel-hydropower hybrid system in the Gelana basin. The result corresponds to an assumed life span of 30 years and energy sale price of 0.10 USD/kWh. It illustrates cases corresponding to different annual operation hours.

In general, it is desirable to test the sensitivity of the B/C value by changing other important economic parameters. An interesting observation from Fig. 9 is that the optimisation method searches and finds a better economic layout than what is assumed at the beginning. That means, regardless of whether the value of B/C is above or below its feasible limits, the optimisation finds the system layout with the best value of B/C for the prevailing economic parameters.

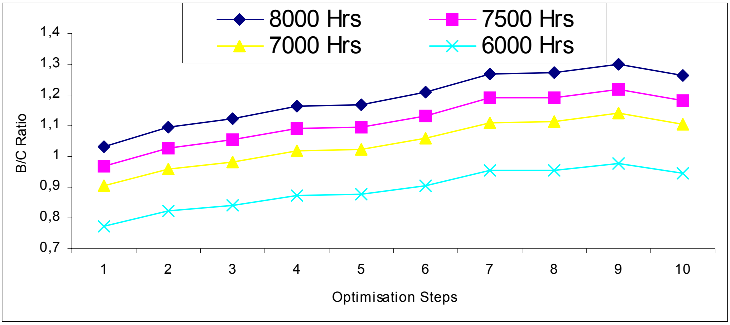

Figure 9 Optimisation of B/C values for different energy prices

9 Conclusion and Recommendation

Optimisation is successfully applied in the search for optimum hydropower site or sites from a number of alternatives in a non-linearly constrained small hydropower system. The GRG2 method is judged as the preferable method based on its success rate after being tested under comparable conditions with the other methods.

This result provided the basis for the conclusion that the GRG2 method holds a promise towards developing a decision model with a flexible mechanism for testing sensitivity of decisions in the choice of optimal small hydropower sites.

The method is not only capable of searching an optimal site or sites but also of identifying whether the optimal system is economically viable for prevailing economic parameters. Further research is recommended for developing the method to handle not only small hydropower alternatives but also other types of renewable energy sources in a hybrid type power mix.

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