

Universität Stuttgart

Auslandsorientierter Studiengang Wasserwirtschaft Master of Science Program Water Resources Engineering and Management - WAREM

Master's Thesis:

Cost Optimization of Small Hydropower

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Date : October 9, 2007

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ABSTRACT

As the world economy grows, electricity demand grows along with it. In considering the possible future energy sources, hydropower provides several advantages: it is highly efficient, can be easily incorporated into multipurpose projects, has a low annual maintainence cost and a long life span. Although industrialized nations have already exploited most of their large-scale hydropower potential, there remains much room to construct large hydropower plants in the developing world. Small hydropower however, still has a place in both. The largest economic challenge facing a small hydropower project is the high initial investment cost relative to competing fossile fuel sources. This Thesis provides a new type of preliminary costing methodology which first optimizes preliminary design components of a small hydropower plant based on a limited set of site-specific data and then uses stochastic simulation to determine the cost uncertainty of four costing catagories and the resulting net present value (NPV) of the project.

First, the suitability of using the RETScreen formula-based costing method for four cost catagories is assessed using a Case Study in Neumühle, Southern Germany. Next, the NPV is determined for a 30-year design life and optimized using a continuous Genetic Algorithm. The final chapter of this work performs stochastic simulations using the Monte Carlo method comparing the expected prefeasibility cost accuracy against the Case Study results.

It was found that for the Case Study, the initial accuracy of the individual costing equations had the strongest affect on the outcome of the cost analysis. Additionally, the optimized design performed better then the original assessment in determining the preliminary values of design flowrate and operating head.

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1. The Global Energy Game and Small Hydropower

1.1. The Current State of Affairs

Energy is big money. At only US\$ 3 cents per kWh, the worldwide production of hydropower would yield an annual income of US\$ 79.8 billion, a scant 1.8 billion more than the entire GNP of the Phillippines [Koch, 2002]. Furthermore, the electrification of industrialized nations using hydropower 120 years ago further enhanced the speed and efficiency of production, giving many today a lifestyle unimaginable just some 100 years ago [Burke, 1996]. Through international partnerships such as the Organization for Economic Cooperation and Development (OECD), the World Bank, and International Monetary Fund (IMF), the global marketplace enjoys continued economic growth. This seemingly boundless economic prosperity resulting from increasing industrial globalization continues to be enjoyed by the richest few nations, and is now rapidly spreading to developing countries as well. However, many developing nations continue their existence under conditions which have seen little change, and have reaped far fewer benefits from the Industrial Revolution and electrification than their fully industrialized counterparts. The modern uses of and access to electrical power are key to both the industrialized nation's ability to further satisfy increasing demand in the production of goods, and the developing nation's capability to increase it's position in the globally-competitive economic marketplace. Thus, for developing countries to succeed, it can be reasonably expected that their rapid economic growth will be accompanied by a commensurate increase in electricity demand. World wide, the net consumption of electricity is expected to more than double from its consumption of 14,781 billion kilowatt hours (kWh) in 2003 to 30,116 billion kWh by 2030 [US DOE, 2006].

Fuel sources to satisfy production demand for such an increase will be put under intense economic pressure due to increasing extraction and processing costs, expanding global fossil fuel consumption, and environmental considerations [IEA, 2005]. Key to understanding the future role of small hydropower in the global electricity market is an assessment of the effects of an increasing electricity consumption coupled with a decreasing fossil fuel supply. As an example of anticipated effects due to this coupling, the results of the oil price shock of October 1973-April 1974 on selected macroeconomics by Pisarski and DeTerra [1975] underscored the widely ranging and seemingly unpredictable responses of both civil society and private concerns alike. This uncertainty should be unsettling. The analysis of future global market behavior including energy trade and environmental considerations is often assessed through the application of neoclassical or contemporary macroeconomic theory in the form of mathematical model predictions. Although they use hard data for validation, these models have become increasingly complex, and now include energy tax implementation and carbon abatement in an attempt to quantify the effects of social and ecological concerns [Böhringer et al., 2003], [Böhringer and Rutherford, 2002], [Conrad, 2000], [Tahvonen, 1995]. History has shown that although such models may give an indication of the direction of change, the fundamental complexity of modern commerce's markets results in systems which simply cannot be accurately predicted with the assumptions required by macroeconomic models [OECD, 2005]. Policy makers should ask themselves, where were these models during the Asian market crisis of the 1990s, or in the run-up to the current international credit crunch? The attempts of the British Conservative Government reforms based on such models in the 1980s should serve as an example [Curtis, 1992]. With so much uncertainty in the future of the energy supply and the effects of policy change on the public at large, only one thing can be firmly assumed - that demand will increase.

The following two sections outline the results of 2 major studies predicting the future of global energy demand, and provide a picture of the electricity consumption worldwide. The last section discusses the future role of small hydropower as it relates to these predictions and lays out the objectives of this Thesis.

1.2. Predicted Trends in Global Energy Demand

Energy demand world wide is predicted to increase sharply into the coming decades [US DOE, 2006], [IEA, 2005]. Principle reasons for this increase are the expanding economies of Asia lead by China and India, along with energy policies from most western industrialized nations which do not substantially plan on reducing overall electricity consumption. This section compares two long-term estimates for global energy consumption from 2003 to 2030. Data¹ is taken from the US Energy Information Administration's 2006 International Energy Outlook Report (EIA) and from the International Energy Agency's World Energy Outlook 2005 (WEO).

A well-functioning global economy depends on a mixed and consistent energy supply. Current global energy consumption can be broken down by its most common sources; coal, natural gas, nuclear, oil, and renewables. Although large hydropower can in many cases be considered as a separate category, for this report it has been included in the renewables category exclusively. Figure 1.1 shows the global energy use by fuel type from both reports. It can be seen that both reports more or less agree in both the past, and in the future. Major differences arise in the estimation of renewables, and in the future role that coal and natural gas are going to play. The WEO predicts that the global primary energy demand for their reference scenario will increase by about half from 2003 to 2030, while in contrast, the EIA 2006 predicts a higher increase of 71% over the same time span. For the WEO 2005, this

¹Units of energy are provided in either quadrillion British Thermal Units (1 Btu = 1.055 kJ), or in Watthours (Wh) when referring specifically to electrical energy.



Figure 1.1.: Comparison of the predicted world marketed energy use by fuel type Sources: IEA [2005], US DOE [2006]

corresponds to an annual average increase of 1.6%, and the EIA 2006 predicts a 1% annual rate for OECD member countries and 3% for non-members.

The WEO predicts for their reference scenario that the primary energy demand is to increase by more than half between 2003 and 2030, reaching 16.3 billion tons of oil equivalent (TOE). Of this, more than two-thirds is expected to come from developing countries. Fossil fuels will continue to dominate energy supply. Alone, coal, natural gas and oil are expected to meet 81% of the primary energy demand by 2030. This is only 1% higher than in 2003. Renewables, grouped as geothermal, solar, wind, tidal and wave energy is expected to expand at the fastest rate. The share of nuclear power in total primary demand is forcasted to fall, mostly due to the shutting down of older facilities in North America and in Europe. Transportation and power-generation are expected to be the largest global consumers of energy, where transportation consumes the most oil. Although the world resources are deemed as adequate to meet the requirements of the projected demand, they are predicted to remain unequally distributed. Almost all of the increase in energy production will occur in non-OECD countries. This will lead to long-term net energy exports from non-OECD countries to OECD members. The reference scenario predicts that global energy related CO_2 emissions to increase by 52% from 2003 to 2030. Of this, 73% is expected to result from developing countries. Future energy-sector investment is forcasted as US\$ 17 trillion (2004), half of which will occur in developing countries.

The EIA forecasts an overall increase in energy consumption from 2003 to 2030 of 71%. Of this, non-OECD countries will account for more than three fourths. Like the WEO, the EIA predicts continued dominance of fossil fuels as the dominant energy source, but predicts a sharper increase in the use of natural gas and coal resulting from the higher world oil price path. Interestingly, the EIA predicts that net electricity consumption will double between 2003 and 2030, but that only natural gas and renewable sources will increase their share of total world electricity generation. Additionally, higher fossil fuel prices are expected to allow renewable sources to compete more effectively overall. Here too, transportation and industry are expected to be the largest oil users at 50% and 38%, repectively of the total projected oil use from 2003 to 2030. Of all the renewables, hydropower is predicted to grow the fastest at a rate of 2.4% per year, approximately the same as that of coal and natural gas. China is singled out at the highest potential consumer of energy, and by 2020 it is expected to have the world's largest economy by comparison of GDP. The EIA also mentions high and low growth cases in which the possible 2030 total energy consumption varies by 205 quadrillion Btu, or around 30% of the reference case 2030 total. Levels of CO_2 emissions were found to be equal for OECD and non-OECD members in 2003, and by 2030 non-OECD members are predicted to produce about 40% more.



Figure 1.2.: Marketed use in non-OECD countries by region for all fuel types Source: US DOE [2006]

Not all of the predictions have come true. One major assumption made in in the WEO was that: "the average price for IEA crude oil imports is assumed to fall back from recent highs of over US\$ 60 a barrel to around US\$ 35 in 2010 then climb to US\$ 39 in 2030." Nothing today, two years later indicates that oil prices will be back around the US\$ 35 mark anytime

soon. Volatility in the Middle East fueled by the conflict in Iraq has in fact fueled a sharp, prolonged peak, having a strong resemblance to crude prices observed in the run-up to, and aftermath of the 1980 Iran-Iraq war. Thus neither report should be taken as the future foretold, rather as the logical conclusion of a series of assumptions, each carrying their own uncertainties.

1.3. Energy Consumption Worldwide as Electricity

Here the electrical energy consumption is broken down for the top 20 consuming nations, and both current and predicted future sources are discussed. The possible role of small hydropower for the future predictions is also presented.



Figure 1.3.: 2005 total annual electricity consumption - top 20 consumers Source: CIA [2007]

Looking at the top 20 electricity consuming nations world wide, Figure 1.3 shows that the list is made up of the G8, (accounting for about 14% of the world's population and roughly two thirds of the world's economic output) and other leading and upcoming economic powers. This is not very surprising. Since most energy, and therefore electricity is consumed by industry and transportation, this is exactly what one should expect to find. What is interesting however, is the comparison between per capita electricity consumption as seen in Figure 1.4 and total consumption. The first eight countries, from Iceland to Qatar indicate that those countries which do not need to import energy allow the consumer to use the most. Iceland is almost exclusively powered by renewable energy from geothermal and hydro power, and Norway is 99.95% hydro-powered. The UAE, Canada, Kuwait, and Qatar have considerable oil and/or natural gas reserves. Canada also has a high percentage of hydropower. Where then do Finland and Sweden come into play? Although climatic differences between the Nordic countries and those in the Middle East certainly play a role in the amount of energy consumed, especially for heating, there is another important reason why these countries consume so much electrical energy. This is due to the Nord Pool, a semi-regulated energy market first developed in Norway in 1996. Since 1971 generators were allowed to trade amongst themselves, setting the spot price for electricity. Today, both supply and demand sides are traded one day ahead, and a balancing market exists for real-time adjustments, where generators must adjust according to bids within 15 minutes [Mork, 2001]. What this indicates is the power of hydro power in the open energy market. Because Norway can throw a huge amount of hydro into the mix, spot price adjustments allow for a great deal of market liquidity. This has allowed the Nord Pool to incorporate thermal (Finland plans on building the world's largest nuclear plant in the coming years) power sources both financially and physically easier than many of the other European energy markets. For further reading on this topic, Mork [2001] and Koch [2002] are highly recommended, and provide more detailed comparisons of other European markets and the global importance of hydropower.

This relation between consumer choice, price, and energy seems to be promising for hydropower's future as a global energy source. Indeed, Koch [2002] predicts that the global remaining hydropower potential is 5400 TWh/yr, which is roughly twice the currently installed capacity. In a free market, this energy could not only be used to create a more liquid and stable energy market, but could also aid in the offset of greenhouse gas production. To this end it is worth noting that China itself has an expected 16% of the total global potential. Additionally advantageous is that hydropower is a scalable technology, (can build many small plants or one large plant all having roughly the same efficiency) and is often coupled with other water resources projects such as water supply or irrigation. Egre and Milewski [2002] also points out an additional benefit of the diversity of hydropower is highly decentralized, and does not require expensive civil works or electrical equipment [Dragu et al., 2001]. This bodes well for developing countries where the necessary infrastructure may not yet be available to easily widen a national grid.

Globally, large hydro (here defined as plants ≥ 10 MW) makes up about 86% of the total renewable energy generated world wide. Small hydro does have the next largest share, at 8.3% [Dragu et al., 2001]. Looking again at the top 20 electricity consumers world wide, Figure 1.5 shows that the big industrial nations have taken hydro seriously in the past, indicating that developing nations are also likely follow suit in the future. Additionally, retrofitting and building newer, smaller hydropower plants offer countries like Germany and Norway the opportunity to export goods and know-how to developing countries, generating further economic gain. Furthermore, the increased worldwide demand for renewable and sustainable



Figure 1.4.: 2005 annual electricity consumption per capita - top 20 consumers Source: CIA [2007]

energy sources can provide a boost to hydropower development in the new millenium. The final section of this chapter provides a rough idea of just how this might be done.

1.4. Small Hydropower - It's "Inconvenient Truth"

The previous sections laid out what many might see as a overwhelming picture of our energy future, a world with a seemingly endlessly growing energy demand, but with little foresight into how exactly we are to cope with its effects. Competing market forces, the rapid expansion of Asian economies, a growing world population, the reduction in fossil fuel reserves, and ecological consequences of energy production all affect a nation's ability to produce electrical energy. These often conflicting interests need not necessarily be harbingers of doom. Indeed, the practical aspects of globalization may lead to cooperation and innovation where energy problems arise. Today's often-revered, often-reviled world marketplace offers many opportunities for cooperative investment and the implementation of strategic plans on a scale formerly unknown. Huge increases in industrial and consumer product efficiency did come as a result of the Oil Crises in the 1970s. It is therefore to be expected that when industrialized nations, both eastern and western, are faced with shortages in the future, technological



Figure 1.5.: Hydropower percentage of total electricity generated - top 20 consumers Source: US DOE [2006]

advances will once again surface to confront these challenges. It is not enough, however to allow for these assumptions to guide national policy, nor is it reasonable to blindly add more fossil fuel to the energy mix. Rather, the solution to satisfy future energy demand may be realized by using a three-pronged approach:

- Increase the diversity of energy sources
- Make good on the promises of technology
- Aggressively target governing institutions, private industry, and the individual to reduce needless consumption and encourage the efficient use of electrical energy

Hardly earth shattering but certainly possible, this approach still begs the question: Where does small hydropower come into play?

This work argues that the role of small hydropower is not a singular one, but rather touches each of the three key above mentioned approaches. Using more hydropower will certainly increase the renewable share of the energy mix, and can help in the reduction of greenhouse gases. Although an old technology, advances in materials, electromechanical equipment, and engineering design tools can further improve the operation of existing plants, and make new plants more efficient and may even lessen their environmental impact [Avellan, 10-13 June 1997], [Staubli, 10-13 June 1997]. Communities with operational small hydropower plants are by nature "tied into the grid" tighter than those who live far away from a power source. Effective management of power consumption by the government, local industries, and the individual may be made easier when it is decentralized to a larger extent. The conclusion, the "inconvenient truth" of small hydopower is that it loses it's immediate appeal of being efficient, relatively environmentally friendly, and local, simply due to economies of scale. In terms of energy generation and market economics, bigger really is better. The cost per kWh installed for large hydropower projects is significantly lower, and thus larger projects have, and for the foreseeable future will continue to, make up the lion's share of the hydropower energy produced.

There is, however a possibility to make small hydropower more than just the sum of its proverbial parts. Recently, the discussion regarding international trading of greenhouse gases, especially CO_2 has provided a possible redemption for small hydro, at least economically. If the trade picks up to an extent which can offset the high investment cost and low economic productivity of a small hydro plant, additional income could be generated by the carbon trade, and small hydro could be in for a renaissance. This idea may not be so farfetched as it seems, especially when one considers that the additional income could then be at least partially reinvested into other forms of renewable energy, a kind of non-governmental "renewable subsidy". Thus, the more renewable energy created with hydro, the more carbon that could be sold to those industries and governments which needed to make use of it. In this way, those producers of energy from small hydro would support other renewables, and increase their role in the energy market, if not as a larger percent of energy produced, then at least as a more profitable one.

Considerable hurdles would still exist for small hydro, even in the idealized case presented above. One overriding question would still remain, namely how to assess quickly and accurately the economic performance of a small hydro plant. As previously mentioned, site variability and low annual profits are the two main hurdles in enticing investment in small hydro projects. Thus, the initial economic assessment of a project must be able to provide a fairly accurate picture of future economic performance to attract investors. This requires a costing methodology in the feasibility stage of the project which is sensitive enough to allow for local conditions (site conditions, wages, equipment costs, etc.) and which can be prepared with a minimal amount of effort and detailed information. It is the purpose of this work to try and sort out if such a method exists, and if it does, to assess its performance. The main objectives of this Thesis are:

- 1. Review small hydropower plant cost estimation methods
- 2. Perform a cost estimation using a case study
- 3. Carry out an economic optimization of the preliminary design using a case study
- 4. Compare the optimized design with the cost estimation including cost uncertainty
- 5. Discuss the differences between the chosen cost estimation approach, the optimized design, and cost uncertainty

Chapter 2 provides a discussion of small hydropower costing methods. It first distinguishes between the two major costing approaches; those which are formula-based and those which make use of computer programs. Preference is given to those methods which are free to obtain, have been widely used, and for which literature can be found. The RETScreen method is then chosen from those discussed as the method to be used in this work.

Chapter 3 discusses the chosen case study, the Neumühle hydropower plant in Wolfegger Ach, southern Germany (from here on simply referred to as the Case Study). The site conditions, hydrologic data, and results of the economic analysis for the original design are presented. The RETScreen approach is then carried out for the Case Study to determine its performance.

Chapter 4 covers the widest scope of material in this work. First, a brief discussion of optimization is presented. Following is an explanation of the Genetic Algorithm (GA), and its application as it relates to the Case Study is discussed. Next, the objective function is throughly discussed, especially concerning the implementation of the RETScreen costing method. Finally, the optimization results are presented in the context of the Case Study.

Chapter 5 is the final chapter of this work, and introduces the concept of a uncertaintybased costing approach. The errors of individual hydropower costing equations are calculated and the Monte Carlo method is applied for the total initial investment cost determined from the RETScreen-based optimized costing method. The results of the stochastic simulations are presented and discussed.

2. Project Assessment and Cost Determination

The development of a hydropower plant depends ultimately on the decision made by the investor as to whether or not they choose to provide financing. Therefore, a broad overview of the economy of the project is necessary at the pre-feasibility stage. Crucial to the decisionmaking process is however, an assessment of not only the economic costs and benefits, but also the sensitivity (the corresponding economic risk and uncertainty). For this reason, a variety of methods exist to calculate costs and illustrate the risks and uncertainty [Jenssen et al., March 2000]. This chapter deals exclusively with the particulars of the costing methods only, and details of uncertainty analysis can be found in the last chapter of this work. Furthermore, the costing methods applied in this study are representative of only the initial planning stages of the design, and are therefore not meant to provide a high level of detailed design information. Most importantly, the decision of whether or not the project should be undertaken can be adequately addressed at this stage of planning. Basic design parameters are used to size individual components of the proposed small hydropower plant, taking into account some degree of localized conditions. Due to the complexity of small hydropower design, the considered costing methodologies are limited to simplified mathematical formulations relating parameters such as gross head and design flow rate to the specific investment costs for several major cost categories (structural costs, electromechanical equipment costs, etc.) Such simplified equations are found frequently in literature, [Christos, 2002], [Horlacher and Kaltschmitt, 1994], [Giesecke et al., 1987] but provide cost ranges which may not be sensitive enough to consider the highly location-specific nature of small hydropower plants adequately. Therefore, it is of the utmost importance to choose a costing formulation which is both easy to apply in the preliminary investigation stage, and yet remains flexible enough to include location-specific conditions. Figure 2.1 shows that at the pre-feasibility stage, cost estimation can be assumed to vary by as much as 50%! Additional to the objectives given in the previous chapter, this work also aims to match or better this cost variance, through the combined use of optimization and stochastic simulation. The final chapter of this work will reveal whether or not this was achieved.

Costs of small hydropower projects as previously mentioned, are extremely variable. This study does not intend to promote a universal range of specific costs applicable for all small hydropower projects. Rather, the idea is to try to provide a systematic approach including site-specific factors and to provide an economic sensitivity analysis so that a certain level of uncertainty can be accounted for. This chapter provides a review of hydropower costing and assessment, its equations, parameters, and limitations. Based on this review, the RETScreen



Figure 2.1.: Accuracy of small hydro project cost estimates. Source: Gordon [28 September 1989]

formula-based costing method was chosen. The Case Study data is then used to test the RETScreen approach and is presented in the following chapter.

2.1. Small Hydro Assessment Considerations

Most commonly found in literature are costing formulations based on the specific/unit investment cost, defined as total annual cost of the power plant divided by the useful energy produced per year [Harvey, 1993]. Although for large hydropower schemes this estimation method is often appropriate, for small or micro hydropower, even a small change in the plant or load factor calculations can result in the project being ruled out as completely economically unfeasible. The sensitivity lies in two major factors: The first is that the operating time of small or micro hydro can vary considerably over the year due to seasonal changes in flow conditions. The second factor is that the determination of the daily load behavior for the life of a project often proves to be difficult, especially in developing countries. This is often due to rapidly changing socioeconomic conditions, as consumers move from less costly and inconvenient fuel sources (wood, dung) to more expensive, convenient types of energy (kerosene, electricity from hydropower) [Adelekan and Jerome, 2006]. Addressing these two factors requires specific in-depth knowledge of both onsite hydrologic and hydraulic conditions and predicted energy consumption patterns. It is for this reason that one very important assumption is made in this study - that the hydropower plant in question

is connected to a central power grid, and therefore the energy demand can be assumed to be infinite and remains so indefinitely. Another fundamental assumption when using any costing method is that some basic a priori knowledge exists regarding the onsite conditions.

The following subsections in this chapter provide a summary of the current state of preliminary cost estimation and site assessment methods for small hydropower plants. In general, the costing and assessment methods used can be divided into two main categories; simple formula-based, and program-based. The simple formula-based methods are those which are most commonly found in practice and are presented first since they form the background for the program-based methods. The program-based methods commonly use a combination of the simple formulas along with more detailed computational approaches incorporating database data, GIS, optimization algorithms, etc. in order to develop a more sensitive and site-specific cost analysis. There are additionally several assessment methods for small hydropower projects which may not directly calculate individual project costs, but can provide insight into the risk and uncertainty of choosing a particular design alternative. Although a small hydropower project may be deemed economically viable, it is equally important in the prefeasibility stage to determine if additional factors (usually environmental and ecological considerations) render the project infeasible. Koch [2002] states that future hydropower sites can be divided into three rather broad groups:

- 1. Sites which are economically feasible and have obtained social and environmental acceptance
- 2. Sites which are not economically feasible, but are socially and environmentally acceptable
- 3. Sites which are not acceptable based solely on problems stemming from social and environmental issues

The engineer always hopes of course, that their project falls right into the first category. Today it is often the case that the chosen project site is at first glance somewhat closer to the third category, and thus detailed environmental studies and accompanying remediation measures must be provided. Social acceptance of small hydro projects is also important, but is out of the scope of this work. Due to the almost certain requirement of some type of minimum flow or aquatic habitat study, programs including environmental considerations are also provided in the program-based method summary. For further reading on this topic, a concise outline of many of the program-based methods described below can also be found in the IEA Assessment Report by E. M. Wilson [April 2000].

2.2. Formula-Based Methods

There has been considerable research in determining the applicable cost ranges for hydropower plants on regional, national, and international levels. The range of costs per MW installed varies considerably depending on the size and type of hydropower project (see Table 2.2), but indicates that larger plants achieve lower costs per kW installed, and fair much better when estimating costs. This simple economic reality proves difficult for

Quantile (N=56)	Inst. Capacity (MW)	Actual Cost	Appraisal Estimate	% Diff
1	16	37.3	28.8	23
5	22	61.7	39.3	36
10	40	90.3	63.4	30
25	67	109.7	110.0	0.3
50	200	220.8	212.9	4
75	400	419.3	387.8	8
90	1050	766.4	762.1	2
95	1800	1139.7	1082.3	5
99	2460	1564.2	1425.5	9

Table 2.1.: Project size distribution, installed capacity and costs in millions of 1987 US\$Source: [Merrow and Shangraw, 1990]

supporters of small hydropower, especially today when wind energy is fast becoming the most economically competitive renewable. In a comprehensive look at a total of 56 World Bank supported hydropower projects, Merrow and Shangraw [1990] examined the possibility of creating a comprehensive costing methodology depending on region, hydraulic, geologic, and scheduling conditions to better estimate project costs. In the end, total capital cost estimations were determined through a use of a series of equations based on the results of regression models using the parameters MW, H, Q, and more specific details such as the dam height, if rock was present, etc. A plethora of similar approaches exist, presenting the designer with a wide variety of formula-based equations from which to choose. Should they use a formulation for the entire specific investment cost, after Harvey [1993] or Horlacher and Kaltschmitt [1994] or something more exotic? Though the results of the World Bank study show that the cost variance in larger projects can be fairly accurately estimated at one go, this approach tends to provide a highly insensitive estimate, unable to take into account local considerations and is therefore unsuitable for estimating the specific cost of small hydropower. A more accurate estimating method for small hydro [Jenssen et al., March 2000] can be obtained by separating the total cost into sub-costs such as equipment, construction, engineering, etc, and then taken their sum as the total investment cost. This has been done by Gulliver and Arndt [1991], WBW [1994], GTZ [1980], and Gordon and Penman [1979].

Three equations are shown below to demonstrate the similar functional form used in estimating equipment costs for small hydropower projects. Some results using this approach are shown in Figure 2.2 for the equipment cost estimation for projects up to 1.5 MW. Equipment cost estimate after GTZ [1980]

$$C = 48,000(P/H)^{0.53} \tag{2.1}$$

where

C = the cost of machinery (DM 1980)

P =the installed capacity (kW)

H = the available head

For units below 1.5 MW data used from Swedish small hydro plants, Gordon and Penman [1979] estimates the equipment cost as

$$C = 4,000(P/H^{0.3}) \tag{2.2}$$

where

C = the cost of machinery (DM 1979)

P =the installed capacity (kW)

H = the available head

Gulliver and Arndt [1991] take a slightly more sophisticated approach by using producer price index values. These were used to determine the constant factor and the two exponential values for the following equipment cost equation

$$C = 16,100(P^{0.82}/H^{0.35})$$
(2.3)

where

C =the cost of machinery (US\$ July 1987)

P =the installed capacity (kW)

H = the available head

Still, the wide range of the costing formulas seems to allow more to the imagination than anything else. Indeed, Figure 2.2 shows min (1 m head) and max (10 m head) equipment cost ranges for plants up to 10 MW. It can be seen that although the ranges in some places overlap, there does not generally seem to be a good agreement, and this is only showing three of the dozen plus available equations. Additionally, the costs of system components,



Figure 2.2.: Equipment costs vs. installed capacity for 1 to 10 m fallhead designs. Sources: GTZ [1980], Gordon and Penman [1979], WBW [1994]

and raw materials change over time (especially the costs of concrete and steel). Thus, the equations need to be periodically reassessed to determine their validity. A better solution may be found by including more detailed information into the costing process, as is discussed in the next section.

2.3. Program-Based Methods

2.3.1. Uniform Criteria of U.S. Hydropower Resource Assessment

This method is known as the Hydropower Evaluation Software $(HES)^1$ method, and is a Windows-based computer model developed at the Idaho National Engineering and Environmental Laboratory (INEEL). HES can be used to measure potential hydropower resources in the United States applying national uniform measuring criteria. The computational engine of the software is based on Visual Basic and linked to a Microsoft Access database. HES software and a user's manual can be downloaded at no charge from the internet. Each potential project can be assigned environmental attributes used in calculating a development suitability factor. HES can then be used to create project-based reports based on the suit-

¹both the program and user's manual can be downloaded from http://hydropower.id.doe.gov/ resourceassessment/software/

ability factors. The main purpose of the HES software according to Francfort et al. [June 2002] is to:

- 1. Provide the capability to create an environmental attribute database using the Hydroelectric Power Resources Assessment (HPRA) database as a foundation
- 2. Assign environmental attribute values (0-1) for each site (fish, geologic, wildlife, etc.)
- 3. Calculate a development "suitability factor" based on the environmental attribute values
- 4. Provide a report capability based on this suitability factor

The US Federal Energy Regulatory Commission (FERC) maintains an up-to-date Hydroelectric Power Resources Assessment (HPRA) database of nation-wide hydropower potential. More recently, an online GIS-based system, the "Virtual Hydropower Prospector", (VHP) was created for the nationwide display of new potential hydropower plant locations. Mapping capabilities include the display of gross power potential as calculated using the HES method. Additional features such as cities, roads, power infrastructure, land use, etc. are also displayed to aid in performing preliminary site assessments.

The HPRA database itself contains information about existing and potential hydropower plants through the use of descriptive fields such as Plant Name, Plant Type, River Basin, and Potential Annual Power Production. HES calculates for individual locations a nameplate rating of the total potential power (it may or may not be the same as the installed power) and applies suitability factors based upon national or regional-scales. Thus, HES can be extremely useful when considering selections of alternative small hydropower plants. However, it must be pointed out that HES can be used for the economic prefeasibility assessment of specific cases, but only yields data which are meaningful when compared to data at regional or national scales. Indeed, the work of Hall et al. [2003] does carry out largescale preliminary economic evaluations of 2,155 sites for small hydro in the U.S., but again with regards to regional and national scales. Since this study only considers the economic criteria based on the evaluation of a single hydro power plant, the HES method was not considered suitable.

2.3.2. ASCE Small Scale Hydro Guidelines

The guidelines were prepared as a five volume set by the Hydropower Committee of the ASCE Energy Division. The first three volumes cover conventional-sized hydropower plants, (vol 1 - dams and environmental concerns, vol 2 - waterways design, vol 3 - powerhouses and related equipment) and the fourth is solely focused on planning, design, and construction of small-scale hydropower. The fifth volume is like the fourth, a comprehensive volume and covers pump storage and tidal power plants. Although out of print, the books can be found

for sale on the internet, and each volume can be ordered as hardcover reprints for around 45 EUR.

Focusing mainly on the USGS's National Water Data Storage and Retrieval System, the guide outlines how to use available gauge data to create the intensity flow duration curves (IFD) for a given site. The approach also allows the user to take ungauged reaches into account by weighting available gauge data based on catchment area, topography, soils, and rainfall patterns. Additionally, the approach includes power calculations which include tail-water rating curves using residual and minimum turbined flows [E. M. Wilson, April 2000].

These guidelines have the advantage that they use a readily-accessible data set and that their application for power generation analysis is straight forward. The major disadvantages in application are that the guidelines are not readily available to the public (out of print, and not for free) and that a cost and risk analysis is not inherent in the approach (the engineer must resort to his own means). For these reasons, this methodology was considered unsuitable for further use in this study.

2.3.3. Integrated Method for Power Analysis (IMP) v5.0

One of the more interesting and comprehensive site assessment programs for small hydropower, IMP^2 is a Windows-based freeware program to aid in the environmental impact assessment of small hydropower projects. As mentioned earlier in this chapter, it is often equally important to be able to consider possible ecological effects at the prefeasibility stage as well as the economics. Although this work covers only economic considerations, the author has included a brief review of this software since it is likely the only freely available software of its kind.

In total, IMP consists of a total of five modules:

- 1. Atmospheric Model using an annual rainfall series based on a database (oddly only until 1976) of nearly 10,000 Canadian weather stations, this module reads in an calculates the average annual precipitation and 24-hour maximum ten-year rainfall. Data can also be entered via Excel or as raw .txt data for use in other regions as well. Additionally, stream flow and temperature can be entered into this module.
- 2. Flood Frequency Analysis Model evaluates flood frequency at the site through use of catchment, streambed, precipitation, and observed stream flow data for flood hydrograph routing.
- 3. Watershed Model this module includes the parametrization of the watershed in a database which allows for the calculation of average daily runoff based on precipitation, temperature, elevation, slope, area, and land use values. A water budget is output

²both the program and user's manual can be downloaded from http://www.small-hydro.com

to allow for the calibration and verification of the watershed module with observed hydrographs and rainfall data.

- 4. Hydroelectric Power Simulation Model turbine types with their corresponding efficiency curves can be chosen, or the user can create their own. Additionally, reservoir operation and its influence on the downstream tailwater depth is interpolated, allowing for a net operational head including tailwater effects to be included. Penstock parameters (including a loss calculation) and reservoir operation constraints are also included in the power simulation module. A simple economic optimization routine is also included to assess the correct sizing of the penstock and turbines with respect to the spillway operations for optimum installed capacity.
- 5. Fish Habitat Analysis Model using stream cross-sectional information and the discharge rating curve, Manning's equation is used to determine the mean flow velocity and depth for individual transects. The Weighted Usable area vs. Discharge and Weighted Usable Area vs. Time relations are used in relation with selected fish preference data for sub-areas (panels) of a given river cross section. The frequency of suitable habitat conditions for different life stages of a selected fish species are then reported by the program. This can then be used to determine which cross sections and flow rates provide the best conditions for a given hydropower plant design.

IMP as a site assessment tool has the advantage over many of the other program-based assessment methods in that it is free, has a decent graphic user interface, remains flexible to user-defined data sets and turbine types, and adds a fish habitat analysis module. The major drawbacks are that the economic assessment is limited only to annual power production, and that it is necessary to calibrate and validate a hydrologic model, something most likely not in the budget of a prefeasibility study. This program is however, highly recommended for later use when assessing the possible ecologic impacts on fish. Since the program did not include a more detailed economic assessment capability, it is also not suitable for use in this study, but may provide useful for the designer confronted with the task of weighing the effects of economy on ecology.

2.3.4. NRC's RETScreen Pre-Feasibility Analysis Software

Natural Resources Canada (NRC) was created in 1994 by merging the Canadian Departments of Energy, Mines and Resources with Forestry Canada. The NRC is one of the largest scientific departments in Canada, employing around 4,200 people and has an annual budget of CAN\$ 812 million. In order to support the spread and development of sustainable technologies, the Renewable Energy Technologies Screening Software (RETScreen) was created by the NRC in order to build the capacity of planners, decision makers, and industry to implement renewable energy and energy efficiency projects [NRC, 26 June 2007].

The RETScreen model consists of several modules which evaluate energy production, lifecycle analysis and greenhouse gas emission reductions for several renewable energy technologies (RETs) (solar, wind, hydro, etc.). Each technology model is comprised of several standardized Excel spreadsheets coupled together into a single workbook file. The cells in each of the workbooks are color-coded according to input, output, and their connectivity to the additional online databases. Additionally, product, weather, and cost databases are included, but are recommended only for use in Canada. The program used for small hydropower assessment consists of Excel spreadsheets linked to Visual Basic code, and provides an extremely user-friendly interface. From the website³, the user can download free of charge software, manuals, tutorials, engineering textbooks, and a variety of case studies. Additionally, the programs are available in 21 languages, allowing for simplified international project application.

The RETscreen International Small Hydro Project model is designed for central-grid, isolatedgrid, and off-grid projects. Seven project worksheets are used in this model; Energy Model, Hydrology Analysis and Load Calculation, Equipment Data, Cost Analysis, Greenhouse Gas Analysis, Financial Summary, and Sensitivity and Risk Analysis. Data can be input for both gauged and ungauged catchment areas, and can also be linked via the internet to a series of databases, but only for Canadian conditions. This section will only address how the cost project worksheet is calculated.

The cost project worksheet allow for the consideration of costs based on the initial investment costs, or from the annual recurring costs. An online product database can be used to obtain specific supplier information. Two main options exist in selecting the costing method: the "formula" method, or the "detailed" method. Since the detailed method requires more input data than is available for the pre-feasibility stage, the formula-based method was chosen.

The formula costing method takes the most simplified approach: data from a large number of existing small hydropower installations are aggregated and used to produce functions which allow for component cost estimation. This costing method is especially useful in the planning stage since it requires only a minimum amount of information to complete the cost analysis. Additionally, it is good for site suitability assessment where multiple options may exist, and decisions can be made based on more general figures. Appendix A provides the full list of costing equations.

Relative costs of construction equipment relative to Canadian costs are entered as a decimal percentage. Fuel costs, number of turbines, labor costs, equipment manufacture, exchange rate, and cold climate (more than 180 days per year with frost) effects (higher transport costs, shortened construction season, etc.) are also included. Because the RETScreen method is free of charge, easy to use, up-to-date, and has been successfully implemented, it has been chosen as the costing method for this work. Chapter 3 applies the RETScreen approach to the chosen Case Study and compares its performance to the highly detailed costing analysis in the Case Study report. Chapter 4 follows with an in-depth analysis of the costing equations used, and carries out an optimization based on the RETScreen formula-based costing method.

³the program, user's manual, and documentation can be downloaded from http://www.retscreen.net

3. Case Study - Neumühle Project

This chapter puts the RETScreen method to the test by comparing the costs from a Case Study with that of the formula-based costing method. The chosen Case Study is the Neumühle Project in Wolfegger Ach, and was the September 2006 Master's Thesis of Phan Anh Nguyen, also from the Universität Stuttgart. This particular project was especially helpful as the Case Study fulfilled two important conditions; the first being that a highly detailed economic assessment and design was carried out, and the second being that the RETScreen costing method was not referenced or used in any way by the previous author, so no bias on his part can be assumed. These two conditions allow for the pre-feasibility cost analysis to be compared to a more detailed set of information, such that the suitability of using the RETScreen method could be more closely evaluated.

This chapter begins with the presentation of the Case Study history and overview of the project. Next, the underlying assumptions and for project costing using the RETScreen approach are discussed. The results are then compared to the costs resulting from Nguyen's in-depth study of the site.

3.1. Background

In 2005, a feasibility study was carried out for Neumühle Verwaltung GmbH for the reactivation of a small hydropower plant located on the Wolfegger Ach in southern Germany (see Figure 3.1). The original plant had been constructed in the early 1890's, but was destroyed in a flood in the 1980s. SJE Ecological Engineering GmbH was given the task to investigate the economic potential and ecological consequences of reactivation. As a part of this investigation, Nguyen's Thesis work was incorporated. The major tasks in Nguyen's work regarding the reactivation of the Neumühle plant were:

- 1. Review the current status of the plant site to determine salvageable structures and materials
- 2. Ascertain which legal issues play a key role in the plant operations, such as water rights and the German Renewable Energy Act (EEG)
- 3. Provide detailed design options for each of the projects major components, such as turbines, fish ladder, etc

- 4. Present an detailed economic analysis detailing the costs for each of the design options
- 5. Compare potential ecological effects of plant operation under the mandated minimum instream flow requirements using the fish habitat model CASiMiR
- 6. Determine the economic viability of the project including additional operational constraints when considering the results of the habitat model results



Figure 3.1.: Conceptual site plan of the Neumühle Project.

Three detailed design alternatives were presented, and of them the following design was recommended:

- An Ossberger cross flow turbine to keep investment, installation, and maintenance costs at a minimum. This option also provides a high efficiency over a wide range of flow rates.
- Keep a minimum low flow of 400 l/s in the river at all times to provide adequate habitat conditions for native fish species, and add stones to the river bed to maximize flow depth while minimizing the ecological damage.
- The 150 m pipeline from the weir to the existing underground canal should be buried and made from concrete due to steep side banks, which would require extensive excavation to meet minimum bank slope requirements when considering an open channel.

- An overtoppable rock weir combined with a block stone passage acting as a fish ramp will increase operating head and provide connectivity for upstream migration.
- In front of the weir structure, a wedge wire screen and bypass channel are to be constructed in order to prevent fish and to block debris from entering the turbine.
- The existing building located directly above the existing underground canal will be used as the powerhouse. It most likely will be retrofitted to mitigate noise from the turbines, as the adjacent building is now a residence.

3.2. Assumptions

In incorporating the information from Nguyen, it must be taken into account that the author was aware of both the total design costs for each of the alternatives, and the costs of various intangibles (that is, those things which would normally not be able to be factored in directly in the pre-feasibility stage without specific, prior knowledge). For this reason, it is important to demonstrate that the data used was not included in the RETScreen methodology simply to produce a satisfactory result. This was achieved in two steps: The first step was to categorize the costs from the Case Study. The second took those categories and assessed as to whether they fit into one of two criteria, either as "CS" or "Assumed" inputs (see Table 3.1). CS inputs were those values taken directly from the Case Study and could be entered into the RETScreen methodology without any further assumptions, such as the number of turbines, flow duration curve data, etc. Assumed inputs were those values included in the RETScreen methodology costing equations but needed to be assumed by the user. The comparison of CS and Assumed inputs gives the user an indication of where the RETScreen formula-based costing approach may or may not cover key issues in the pre-feasibility stage. Furthermore, in this work the clear delineation between input types serves to provide the reader with a critical view of the effects of the Assumed values which were open to interpretation by the author. The intent was to make the choice of values for all the used inputs as transparent as possible.

It is also important to note that two important assumptions regarding the turbine efficiency curve must be made: that for changing head conditions that the curve remains the same as the one supplied by Ossberger, and that RETScreen methodology only allows for one curve to be used over the whole range of Q. According to the efficiency curve supplied by Ossberger, and previously used in the Case Study, the Ossberger turbine allows for an increase in efficiency at flows lower then Q_d as the guide vane reduces the effective contact area on the turbine blades to either 1/3 or 2/3. Since this study uses only the curve for the operational state in which the whole contact area is used, an additional power loss is introduced into the costing calculations for flow rates less than 0.5 Q_d . Based on the averaged flow duration curve, these flow conditions are expected to occur during 40% of the total operational time. However, the total calculated power using the RETScreen approach will underestimate the power output during this flow range by about 2.6%, and is thus considered acceptable.

Parameter	Value	Type
Q_d	$3 (m^3/s)$	CS
Residual flow	$0.4 \ (m^3/s)$	\mathbf{CS}
H_g	4.88 (m)	\mathbf{CS}
Dam crest length	12 (m)	\mathbf{CS}
Penstock length	150 (m)	\mathbf{CS}
Turbine type	Cross flow	\mathbf{CS}
Number of turbines	1	\mathbf{CS}
Generator efficiency	95%	\mathbf{CS}
Discount rate	4.5%	\mathbf{CS}
Turbine efficiency	Same curve	\mathbf{CS}
Flow duration curve	Same curve	\mathbf{CS}
Cost of energy produced	$0.0967 \; (EUR/kWh)$	\mathbf{CS}
Annual maintenance cost	1.5% of Investment Cost	\mathbf{CS}
Project life	30 (yr)	\mathbf{CS}
Maximum hydraulic losses	5% of H_g	Assumed
Intake & misc. losses	1% of H_g	Assumed
Transformer losses	1% of H_g	Assumed
Allowable Penstock losses	1% of H_g	Assumed
Rock at dam site	yes	Assumed
Access road required	No	Assumed
Exchange rate	0.72 (EUR/CAD)	Assumed
Distance to borrow pits	0 (km)	Assumed
Transmission line length	$0 (\mathrm{km})$	Assumed
Transmission line voltage	$25 \; (kV)$	Assumed
Penstock adjustment factor	0.3	Assumed

 Table 3.1.: Necessary RETScreen costing input parameters, their values, and types

Furthermore, it will be shown later that the power calculation performed by RETScreen is not far off that of Nguyen.

Table 3.1 lays out all of the required input parameters to carry out the costing analysis. As mentioned previously, all of the CS inputs come without modification directly from Nguyen's Thesis work. As to the Assumed inputs, a few comments should be made regarding the values, and are presented in the order they are found in the table:

- Hydraulic/Intake/Transformer/Penstock Losses The losses cannot be taken directly input from the Case Study because they are needed in the equation system of the program to calculate the energy production for a the given flow duration curve. The values chosen are assumed to be reasonable, if not a little conservative.
- Rock at dam site It was assumed that there would be rock at the dam site since the work will be in a river bed area.
- Access road required There is a road running parallel to the length of the proposed project site which precludes the construction of an access road.
- Exchange rate The exchange rate was chosen based on the time that the report was written, and more detail about the chosen rate can be found in the next chapter.
- Distance to borrow pits Since a cut and fill trenching method was proposed, it was also assumed that there would be no use for a borrow pit.
- Transmission line length/voltage The powerhouse is situated next to an existing residence with presumed access to the grid, thus no transmission line would be necessary. This assumption depends on the electromechanical equipment's ability to produce AC with the correct voltage.
- Penstock adjustment factor An adjustment factor for using the penstock for concrete pipe is required. This is because the RETScreen costing equation for the penstock assumes a pressure pipeline, and calculates the cost based on steel. Thus, an adjustment factor of 0.3 was applied to reflect the difference in cost/length. The value of 0.3 was determined from data taken from Nguyen's detailed economic calculations comparing the costs of equivalent steel and concrete pipelines.

3.3. Running the RETScreen Small Hydropower Module

The values obtained from the RETScreen economic analysis are to a great extent the end product of the energy calculations. Thus it is important to briefly discuss how the annual energy production calculations are carried out. Figure 3.2 shows the six steps required for central grid, and seven steps for isolated grid delivered energy calculations. As previously mentioned, this work only considers central grid projects and so will neglect the use of project-specific load duration curves. This section concisely covers some important aspects of the following relations: the flow duration curves, turbine efficiency curves, calculation of power duration curves, and the resulting annual energy production.



Figure 3.2.: RETScreen energy calculation flowchart

3.3.1. Flow Duration Curves

Upon receiving the contract to carry out a pre-feasibility study for a small hydro plant, the engineer is confronted with an exasperating number of variables and assumptions. One of the most important decisions is that of choosing a design flow rate which will on the one hand provide a stable, long-term source of electrical energy, and on the other allow hydropower operations which do not substantially conflict with a site's ecologic and sociologic considerations. One tool which the engineer has at their disposal and which aids in determining the design flow is the flow duration curve (FDC). Essentially, the FDC is simply a depiction of relevant flow statistics for the site in question. This subsection quickly discusses what exactly the FDC is, what it is good for, and how they are generated.

Choosing the design flow rate is tricky business. Firstly, the project cannot simply use all of the water available in the river, some minimum, residual flow must present to maintain the site's ecological integrity. Additionally, irrigation, cooling, seepage and other abstractions from the total flow rob the engineer of their precious Q. If the turbine is oversized, the operating efficiency will suffer, and if the turbine is undersized, the economic benefits will be squandered. For these reasons, the FDC was created to allow the engineer to combine annual flow statistics into an easy-to-understand graphic, and to provide a powerful analytical "what if" tool to determine the economic efficacy of a given Q. Figure 3.3 shows the 2001 daily flow series for the Neumühle site. It can be seen that the discharge at the site varies considerably, having markedly different high (Case 1) and low (Case 2) flow periods throughout the year. When obtaining the annual flow data, two things are especially important: First, that the total data set covers a long time span (ie. the daily values in Figure 3.3 are taken for a number of years to obtain *average daily* values). For the Case Study, Nguyen used a total of 66 years of daily data to compile the FDC used. The second important consideration is that if no data is directly available (more often the case than not), the engineer should look for locations as close to the site as possible which do have reasonable data, and study the data carefully before changing it in any way to fit the given site. Nguyen did not have data for the exact cite location, and used a correction factor to convert the discharge reading from a nearby station to values suitable for the Case Study site. Harvey [1993] also points out that the use of annual or monthly averages should not be used in determining the flow duration curve when considering daily energy production. Furthermore, datasets based on daily values aid greatly in calculating the average daily flow (ADF) for seasons in which a part of the flow will be used by other uses, such as irrigation.



Figure 3.3.: 2001 daily flow data at the Neumühle Site

After the discharge data has been obtained, a few intermediate steps need to be taken in order to transform the daily average dataset into the FDC. First off, the daily values need to be ranked, from 1 having the highest flow rate, to 365 having the lowest. After this has been done, the following formula can be applied to transform the ranked dataset into probabilities:

$$P = 100[M/(n+1)] \tag{3.1}$$

where

P = the probability of a given flow being equalled or exceeded (% of time)

M =the ranking of a given flow rate (-)

n =the total number or records, for one year 365 (-)



Figure 3.4.: Flow duration curve with low flow requirement (400 l/s) at the Neumühle Site

Graphing the relation of P vs. Q, the engineer now has the FDC. Some important features according to Harvey [1993] and Klingeman [19 August 2007] of the FDC are as follows:

- The area under the curve represents the annual ADV, and the median daily flow is given by the 50% value.
- Case 1 on Figures 3.3 and 3.4 corresponds to the FDC's response to the high discharges from the original dataset.

- If Case 1 is steep, the FDC indicates a basin with rocky and shallow soil, low vegetation, a steep bed slope, and irregular rainfall patterns (ie. frequent storms with long dry periods).
- Case 2 on Figures 3.3 and 3.4 reflects the influence of low discharges on the FDC.
- As the low flow region, Case 2 gives a good indication of what kind of flows the engineer should have to consider during dryer periods, especially if irrigation abstractions may be present.
- In general, if the FDC as a whole is relatively flat, than this indicates a basin having deep soils, heavy vegetation, gently sloping streams, and relatively even annual rainfall patterns.
- If abstractions due to residual flow, irrigation, etc. are already known or can be estimated, they should be subtracted out (resulting in the available flow) before carrying out any energy calculations. Figure 3.4 shows the FDC including a constant residual flow requirement.

After determining the FDC, the engineer now has the ability to determine the frequency of occurance of a given flow rate, including abstractions from other uses and residual flow requirements. This is certainly a step in the right direction, but one last step must be carried out: the calculation of the power duration curve. The following subsection gives a short introduction on the subject, referencing the Case Study as an example.





Figure 3.5.: Turbine efficiency curves for typical small hydro turbine types
Calculation of the power duration curve (PDC) is based on two sets of data; the FDC, and the turbine efficiency curve. Figure 3.5 shows typical turbine efficiency curves for various turbine types. The efficiency can be seen to drop radically (Case 2) when the turbined discharge is far below that of the design discharge, and for most turbine types remains almost constant for higher discharges (Case 1). To include the turbine efficiency curve, RETScreen allows both the use of standardized curves, and user-defined curves. The actual power, P corresponding to a given flow rate Q, and gross head H_g , is calculated in RETScreen (input variable values are found in Table 3.1) using Equation 3.2. Figure 3.6 provides a graphic representation of the losses, where H_{usable} is the head available for energy production.

$$P = \rho g Q \left[H_g - (h_{hyd} - h_{tail}) \right] \eta_t \eta_g (1 - l_{trans}) (1 - l_{para})$$
(3.2)

where

 $\rho = \text{density of water (1000 kg/m^3)}$

g = gravitational constant (9.81 m/s²)

 $H_g = gross head (m)$

 $h_{hyd} = hydraulic losses (m)$

 $h_{tail} =$ losses (m), due to the tailwater level rise, assumed negligible

 η_t = turbine efficiency (-), taken from manufacturer's data for a given Q

 $\eta_g = \text{generator efficiency (-)}$

 $l_{trans} = transformer losses, (fraction of H_q)$

 l_{para} = parasitic energy losses before reaching grid (fraction of H_q), assumed negligible

The resulting power equation allows for the simultaneous plotting of flow and power vs. the exceedance as shown in Figure 3.7. Differences between high flow (Case 1) and low flow periods (Case 2) are compounded with the loss in efficiency resulting in a substantial reduction of energy output. This underscores both the importance and the sensitivity of choosing the correct Q even at the pre-feasibility stage.

Total annual energy production can now easily be calculated as it is the area under the power curve. RETScreen calculates this in annual increments of 5 %, or 18.25 days. Nguyen's calculation of the annual energy production is however, slightly different. The author believes that the main causes of the difference are due to how the area under the power curve was calculated, and that Nguyen used highly-detailed methods of calculating hydraulic losses. Table 3.2 gives the results of both Nguyen's energy calculation, and that of RETScreen. It can be seen that RETScreen gives a resonable estimation of annual energy production, even including the assumptions used in implementing Equation 3.2.



Figure 3.6.: Head losses as applied in Equation 3.2 - not to scale



Figure 3.7.: Power and flow duration curve for the Case Study for $Q = 4 \text{ m}^3/\text{s}$

3.4. Cost Estimation Comparison RETScreen vs. Reality

This section provides the results of the costing analysis based on the assumptions and input parameter values from the Case Study. The overall outcome of the RETScreen approach shows that the costing methodology worked fairly well - up to a point. Table 3.2 provides the most important results of both the energy calculations, and the cost comparison analysis.

	Nguyen	RETScreen	% Diff
Plant Capacity (kW)	105	103	2
Plant Capacity Factor	0.52	0.51	2
Annual Energy Production (MWh)	489	458	6
Annual Energy Income (EUR)	47,280	44,253	6
Total Investment Cost (EUR)	$358,\!687$	$571,\!176$	59
Annual Maint. Cost (EUR)	$5,\!380$	8,568	59
Pay-off Period (yr)	11	16.6	51
Benefit-Cost Ratio	1.9	0.97	49
30-yr Net Present Value (EUR)	$323,\!805$	-19,236	106
Specific Cost (EUR/kWh)	0.0584	0.0993	70

Table 3.2.: Comparison of cost and financial analysis - Nguyen and RETScreen

First, it can be noted that the energy and income calculations are represented very closely, at only differences of 2-6%. This is due to slight differences in how the calculations were made, such as the 18.25 day discretization of the FDC in RETScreen vs. the daily energy calculations made in the WASKRA program used by Nguyen. The difference in plant capacity is due to the RETScreen model's use of a static, gross operating head H_g of 4.88 m which is converted to H_{usable} through the efficiency calculations, whereas Nguyen included more realistic conditions, using a dynamic range of operating heads (4.07-5.07 m).

RETScreen seems to fall flat on its much-heeded ability to accurately calculate the investment costs, off by 59%. Key to remember here is Figure 2.1, in which Gordon lays out the worst-case cost estimates at 50% from the actual costs. Errors in the investment cost are propogated over a 30-year period, resulting in even more extreme estimations of the NPV. Thus, a closer look was needed to see if the formula-based costing system failed systematically, or if there were certain cost catagories which faired better than others. The following table provides an overview of the costs estimated by catagory for both Nguyen and RETScreen. It is important to note that Nguyen's cost estimate included several things not in the RETScreen estimation, such as a fish pass, trash rack, and cleaning machine. Additionally, Table 3.3 presents the cost catagories as they are defined by RETScreen and thus there are some catagories for which no comprable costs could be taken from Nguyen. In any case, the comparison gives a clear overview of the strengths and weaknesses of using the formula-based method. It can clearly be seen that the costs of energy equipment worked out quite well, but that the engineering and design, and penstock costs were grossly overestimated. The estimation of the civil works costs are close to what is expected, around 50%.

	Nguyen	RETScreen	% Diff
Energy Equipment	150,000	172,800	15
Engineering and Design	$22,\!310$	66,240	197
Substation and Transformer	-	2,160	-
Penstock	19,500	$73,\!656$	277
Civil Works	$166,\!877$	$256,\!320$	54

Table 3.3.: Comparison of total investment cost categories (EUR) - Nguyen and RETScreen

The main problem with this cost estimation is that the RETScreen formula system does not include the option to choose a concrete penstock (more of a diversion pipe in our case, since there is very low pressure). The costing formulation also includes the possibility of including a canal (instead of the penstock) in the costing equations, requiring the following additional inputs:

Canal Required = Yes

Length in impervious soil = 150 m

Terrain side slope in soil (average) = 45°

The resulting economic calculations were significantly improved, indicating that the concrete pipe penstock could be better considered as a canal then as a steel penstock using a correction factor, as had been done previously.

Table 3.4.: Results using a canal instead of a penstock (EUR) - Nguyen and RETScreen

	Nguyen	RETScreen	% Diff
Total investment cost (EUR)	$358,\!687$	450,720	59
Annual maint. cost (EUR)	$5,\!380$	6,761	26
Pay-off period (yr)	11	12.3	12
Benefit-cost ratio	1.9	1.3	32
30-yr Net Present Value (EUR)	$323,\!805$	$136,\!839$	58
Specific cost (EUR/kWh)	0.0584	0.0783	34
Energy Equipment	150,000	$172,\!800$	15
Engineering and Design	$22,\!310$	66,240	197
Substation and Transformer	-	2,160	-
Canal	19,500	14,400	26
Civil Works	166,877	$195,\!120$	17

Based on the results of the Case Study, it follows that the RETScreen method can be applied to estimate the total initial investment cost within reasonable means, however the costing equations themselves showed considerable variance. The the following remarks illustrate the results of the Case Study comparison:

- Annual energy production was well-represented.
- Energy equipment costs were reproduced better than expected.
- Engineering and design costs were grossly overestimated.
- Substation and transformer costs were not able to be directly compared, but were minimal when compared to the total initial cost.
- **Penstock costs** were not able to be accurately represented through use of a constant (reflecting on the difference in material costs between concrete and steel), but estimates by RETScreen considering the concrete penstock as a canal were more representative.
- Civil works costs are linked to a large part the costs of the penstock. Thus they were overestimated when considering the penstock, and within a reasonable range when considering the canal.

Although the RETScreen model provided significantly better results after changing the costing criteria from "penstock" to "canal", this change would have been impossible to make without the use of Nguyen's prior work. Thus, the work carried out in the following chapter cannot use this change, although it may prove to be useful when considering the stochastic simulations in the final chapter of this work. The following chapter addresses the RETScreen model's performance when including design parameter optimization. Additionally, Table 3.3 shows the considerable variance in the performance of the individual costing categories, indicating that the corresponding uncertainties of the cost categories vary as well. The final chapter in this work explores the idea of including ranges of cost uncertainty into a stochastic simulation of costs.

4. Cost Optimization Using the Genetic Algorithm

In order to test the performance of the RETScreen method further, the costing method was optimized for the Case Study site. The purpose of applying optimization was to obtain RETScreen's "best" possible solution in terms of the design variables Q_d and H_d and the initial investment cost, and compare them to Nguyen's Thesis. This chapter first discusses the basics of optimization, and then provides the background on how the Genetic Algorithm can be applied to the Case Study conditions. Optimization is carried out by rewriting the RETScreen small hydropower equations in terms of gross head, H_d and design discharge, Q_d . The net present value (NPV) is used as the objective function and includes maintenance costs and the income generated from energy production. Finally, the NPV is optimized in Matlab using the continuous Genetic Algorithm after Haupt and Haupt [2004]. The optimized design was then compared to the design recommended in the Case Study.

4.1. Optimization Basics

Optimization seeks to procure the best results under a given set of circumstances [Rao, 1996]. That there can even be a "best" solution implies that there are a multitude of possible solutions, that each is not of equal value, and that there exists a method of comparing each solution's value relative to the others [Haupt and Haupt, 2004]. Thus optimization can be related to physical experimentation, mathematical formulations, and to wholly subjective circumstances, such as a beer-tasting contest! In the context of this study, optimization is more strictly defined as the search for the best outcome of a mathematical function, the objective function (described in detail in Section 4.4).

Equation 4.1 for constrained optimization after Sundaram [1996] can be read as "minimize the function f(x), subject to all values in the set D".

$$\min\{f(x) \mid x \in D\} \tag{4.1}$$

Figure 4.1 provides a graphic of the same idea, showing small hydropower equipment costs over a range of possible design flow rates Q_d , and operating heads H_g . For example, a function $f(Q_d, H_g)$ provides the estimated equipment cost, and the aim is to find the absolute

minimum value, the global optimum of $f(Q_d, H_g)$. The goal in this work is to find the best state, (a particular combination of Q_d and H_g) for all candidate states (those within the possible ranges) also called the *search space*, *D*. Thus, the problem can be boiled down to assessing a large number of possible combinations of Q_d and H_g which result in the search space's global optimum.

If D contains many peaks and valleys (local optima), and if the ranges of variable values (ie. Q_d and H_g) cannot be well estimated to begin with, then the search for the global optimum becomes much more challenging. Luckily, in this work the constraints are handily provided by nature for $Q_{d,max}$ and $H_{g,max}$ since for the Case Study it is unreasonable to consider a Q_d of 10,000 m³/s or a H_g of 50 m. In this study, interest lies in the global optimization of a search space D specifically confined by ranges of Q_d of 0-14 m³/s and H_g of 0-5 m.



Figure 4.1.: Equipment cost estimations (EUR) varying Q_d and H_g

If one is lucky enough to have a objective function which can be fully described by a mathematical formula for which the first derivative can be determined, then solving this for zero will directly yield all of the optima for a given data set. The optima only need to be sorted in order to yield the global optima (the highest and lowest points in the search space). It can be easily understood that taking the derivative and solving for zero is often difficult, and in many cases impossible for problems which one would nevertheless like to optimize. Indeed, for this study it is extremely difficult to mathematically include the direct influences of the turbine efficiency curve without including logical operations necessary to look up η for a given Q/Q_d, and to calculate energy output using a continuous function which accurately represents the FDC. In order to optimize such a system, the use of metaheuristics can be of great help.

4.2. Choosing the Right Metaheuristic

A metaheuristic is a method used to solve a computational problem using often informal means, such as first guessing the answer of a simplified version of the problem, and then iterating toward a solution. They are often used for mathematical problems for which calculating the derivatives is difficult or impossible, and for complex optimization problems. Metaheuristic algorithms try to get around the complexity of the mathematics by using constructive or iterative computational approaches based on an often simplified form of the original problem. Indeed, there is often no way to conclusively prove that a metaheuristic's solution is in fact the correct one. For combinatorial problems, the metaheuristic would have to include every state of a given search space, and thus would not be any faster than an exhaustive search. In order to get at an answer, the user must accept and be comfortable with the fact that the metaheuristic may deliver a sub-optimal result, possibly with a reduction of precision or accuracy due to any simplifications introduced. Furthermore, there is a vast array of algorithmic concepts which can be used and are applicable to a wide set of different problems [Dorigo and Stützle, 2004]. These include such methods as simulated annealing, tabu search, evolutionary computation, and ant colony optimization. Two things have lead the author to choose the Genetic Algorithm (GA): The first is that some work has already been done as Christos [2002], Hreinsson and Eliasson [May 19-23 2002], and Eliasson et al. [1999] have used the GA to optimize individual design components for hydropower projects, including their costs. Second, with respect to choosing one metaheuristic over another Wolpert and Macready [1997] have shown that in general, it can be expected that the average performance of any pair of algorithms is identical. Thus the choice of GAbased optimization was based on what previous similar works had used, even if in the end, it makes no real difference.



Figure 4.2.: Six categories of optimization algorithms after Haupt and Haupt [2004]

As seen in Figure 4.2, there are a wide variety of considerations which must be taken into

account when choosing an metaheuristic. In the case of this paper, a non-linear system of equations depending on the variables gross head, H_g and design discharge, Q_d were used to describe individual component costs of the hydropower plant. Since the FDC takes into account the dynamics of a changing flow rate over an annual cycle, the calculation method is considered to be static. Furthermore, constraints are placed on the possible range of variables, so that impossible combinations of head and flow rate are not used in the optimization routine. A continuous range of values (not quantized) for each of the two variables is allowed. Lastly, the NPV is used as the objective function, evaluated for its minimum value over the given search space. According to Figure 4.2, this would mean the optimization routine under consideration needs to be a function-based, multi-variate, static, continuous, constrained, minimum seeking algorithm. The GA can be applied fulfilling all of these requirements, and in the following section, the GA process is presented and its implementation relating to small hydro cost optimization is discussed.

4.3. The Genetic Algorithm

Genetic algorithms draw their inspiration from the biological processes of evolution and natural selection. Through natural selection, organisms are able to adapt to changes in their environment by optimizing their chances of survival. This is done through the exchange of genetic material during breeding, where those with the most "fit" genes are more likely to survive, and thus pass on their particular traits to the next generation. This section concerns itself with the computational implementation of the GA concept, using engineering cost optimization as an example. The algorithm itself consists of a series of basic steps, illustrated in Figure 4.3. First, a population of n individuals is coded with a collection of genes, or chromosomes. In our case, the values of Q_d and H_g are randomly assigned for the initial population. Next, each individual is tested for fitness by evaluating their genetic combination in the objective function. The population is then sorted by performance and a fixed percentage (this is variable) are chosen for mating. Mating is carried out by swapping (called crossover) one gene of an individual with that of another to create a new member of the population. After mating, a fixed percentage of the the new parent and child generation is then mutated. Finally, the mated and mutated population is once again assessed for fitness, and the process begins anew. In this work, the population size remains constant throughout, meaning that the worst-performing states are removed to make room for betterperforming offspring. In order to better understand this process, the following subsections provide an example of equipment cost optimization using the GA.

4.3.1. The Objective Function

The first step in optimization is determining the objective function. As an example, a simplified version of the RETScreen equation for the small hydro engineering investment cost, I_{eng} is applied where the objective is to find the minimum cost over the search space D



Figure 4.3.: GA process concept used for optimization

within the user-defined variable constraints of Q_d and H_g.

$$I_{eng} = 19,984Q_d^{0.54} H_a^{0.378} \tag{4.2}$$

 $Q_d = design flow rate (5-10 m^3/s)$

$$H_g = gross head (5-10 m)$$

Due to the mathematical formulation used to represent the engineering costs the optimum minimal state is already known, since the minimum allowable values for the ranges of Q_d and H_g [5, 5] will return the lowest overall cost. Still, this example can serve to show how the process is carried out, and which factors affects its performance. The next step involves the practitioner choosing the parameters to be used in carrying out the GA optimization. Table 4.1 lists the input parameters needed to run the GA, and their values used in this example. Appendix B provides further analysis of the individual parameters and their effects on the optimization for the engineering cost example. Note that the variable range is set to 5-10 for both parameters, in order to keep the example as simple as possible.

GA Input Parameter	Eng. Cost Example Value
Objective Function	Equation 4.2
No. of Variables	2
Variable Limits	5-10
Maximum No. of Iterations, G	10
Population Size, P	10
Mutation Ratio, M	0.2
Selection Ratio, S	0.5

Table 4.1.: Optimization of engineering investment costs using the GA

4.3.2. Generating the Initial Population

The first step the algorithm takes is to generate a random selection of Q_d and H_g providing the first 10 states to be evaluated for their fitness where states resulting in the lowest costs after Equation 4.2 are deemed the most "fit". Table 4.2 provides the GA parameters used in the example.

Table 4.2.: Example initial population of 10 random states (chromosomes) and their costs

Q_{d}	Hg	Cost (EUR $\times 10^5$)
7.4828	8.6356	1.3384
9.4988	6.5465	1.3711
9.1081	9.1925	1.5239
8.2246	7.8404	1.3580
9.0899	6.8521	1.3622
8.3011	8.5137	1.4080
6.7099	7.7329	1.2103
6.4486	7.2244	1.1546
6.7060	8.4728	1.2525
7.6704	8.1066	1.3244

4.3.3. Selection and Mating

The next step in the GA process is to select the top 5 performing states (the selection ratio was set to 0.5), weight them according to performance, and create pairs. This process is called *weighted random pairing* where each state is assigned a probability inversely proportional to their evaluated cost. Thus, the state providing the lowest cost has the highest probability of mating. Sets of two random numbers between 0 and 1 are generated N_{mate} times, where

$$N_{mate} = P(1-S)/2$$
 (4.3)

and the probability P_n of a given rank, n is

$$P_n = \left(\frac{PS - n + 1}{\sum_{n=1}^{PS} n}\right) \tag{4.4}$$

and are used to determine which states are selected for mating. Note that the value of N_{mate} must be rounded to the nearest integer, and may result in adding one additional state to some initial population values. Additionally, it is possible that a state is chosen to mate with itself. Both of these issues can be addressed and are dealt with later in the discussion on mating. Beginning at the top of the ranked list (see Table 4.3), the first state with a cumulative probability greater than the random number is selected for the mating pool. For example, if the first two random numbers chosen are random₁=0.45, and random₂=0.86, then the states corresponding to ranks 2 and 4 are chosen to mate. Thus their Q_d and H_g values would not only survive into the next round, but would also be used to create new states to replace the 5 removed. Next, another set of random numbers are assigned resulting in the second pair of states which are to be mated.

Rank	Q_{d}	Hg	Cost (EUR $\times 10^5$)	\mathbf{P}_n	$\sum_{i=1}^{n} P_i$
1	6.4486	7.2244	1.1546	0.33	0.33
2	6.7099	7.7329	1.2103	0.27	0.60
3	6.7060	8.4728	1.2525	0.20	0.80
4	7.6704	8.1066	1.3244	0.13	0.93
5	7.4828	8.6356	1.3384	0.07	1.00

Table 4.3.: Rank Weighting - the top 5 performing states

Mating is carried out N_{mate} times (in this case 3), where each pairing results in two offspring. This means that for an initial population of 10 with 0.5 as the replacement ratio, all successive populations will actually have 11 members, and each successive iteration will randomly choose 5 parent states to mate. The creation of offspring from two parent states can be carried out in a huge variety of ways. For more information on this topic, the reader is referred to Gen and Chen [1997]. A blended crossover mating technique is used in this work, which eliminates the possibility of identical offspring and fixes part of the problem of states being chosen to mate with themselves. The technique is based on the following relations for the two offspring, *bill* and *sally*. The parents, mom and dad are chosen as described above, where a randomly chosen crossover point α is selected from which the numerical values of each state variable are switched. Blending involves multiplying the range of a state variable from each parent \pm a random number β on the interval [0, 1]. The variable at the crossover location α is blended using the following formula, so even if a parent state is chosen to mate with itself, at least one state variable will be blended using the random number β .

$$bill = mom_{\alpha} - \beta[mom_{\alpha} - dad_{\alpha}] \tag{4.5}$$

$$sally = dad_{\alpha} + \beta[mom_{\alpha} - dad_{\alpha}] \tag{4.6}$$

For example, if random=0.023 and α =1 (the first state variable is the crossover point and is blended) then the first mating pair would result in the following offspring states

mom = [6.7099, 7.7329] dad = [7.6704, 8.1066] $bill = [6.7099-0.023 \times 6.7099+0.023 \times 7.6704, 7.7329]$ = [6.7320, 7.7329] $sally = [7.6704+0.023 \times 6.7099-0.023 \times 7.6704, 8.1066]$ = [7.6483, 8.1066]

4.3.4. Mutation and the Final Population

The last step needed in GA optimization is *mutation*. Its purpose is to add randomness to the states so that the search space can be explored on a wider basis, and to ensure that the algorithm can pull itself out of local minima and maxima. A mutation ratio of the total population is specified by the user, and that fixed percentage of the population is then randomly assigned new state variable values according to the predefined constraints (in this case variable values of 5-10). Selection is carried out by randomly choosing values a variable array for all states, such that no single state variable can be mutated more than once per iteration. It is worth noting that for highly sensitive systems, the user may not want their best states mutated, and can allow for a certain amount of *elitism*, where only the worst performers are subject to mutation. Table 4.4 shows the final population of the first iteration of the GA, where the first five states are the selected parent states from Table 4.2, followed by their 6 offspring states from 3 matings. In this example, elitism is present, since it can be observed that none of the parent states have been allowed to mutate. For the Case Study optimization, mutation was allowed for all states since only two state variables were used, and the computational effort of exploring the highly constrained search space was relatively low (30 minute max calculation times for $I \leq 1,000$). Appendix B provides a further in-depth analysis of the performance of the GA optimization for the example case. The best resulting state found in the example was [5.7002, 5.2432] with a total cost of EUR 95,961. The global optima in this example can be found at [5, 5] having a total cost of EUR 87,566. Appendix B provides additional graphs with larger numbers of iterations and also shows which input parameters (see Table 4.1) were used to tune the algorithm into finding the global optima for the example problem.

Q_{d}	Hg	Cost (EUR $\times 10^5$)
6.4486	7.2244	1.1546
6.7099	7.7329	1.2103
6.7060	8.4728	1.2525
7.6704	8.1066	1.3244
7.4828	8.6356	1.3384
6.7320	7.7329	1.2125
7.6483	8.1066	1.2103
7.3416	7.2244	1.1546
6.5898	7.2244	1.2525
6.7099	6.6698	1.3244
7.4828	8.6250	1.2525

Table 4.4.: Example population of 11 states after selection, mating and mutation

Skiena [1997] points out that it is often difficult to set up a optimization problem in terms of mutation and crossover and that the pseudobiological concept of the GA adds further complexity in understanding the value of the results. The following sections show how the same approach to optimization can applied in determining the NPV of the Case Study hydro plant using the RETScreen formula-based costing equations.

4.4. The Net Present Value Formulation

Throughout the rest of this Thesis the NPV is used as the objective function. The NPV is a commonly-used economic indicator used to estimate current project value from a series of hypothetical annual cash flows. Here, calculations are based on the *initial investment costs* (I), *annual operation and maintenance costs* (M), and the *annual revenue* (R), over the project lifetime due to energy production. Unless specifically defined as otherwise, all costs are in EUR. Note that the sign of revenue used in this text is considered to be a positive quantity, and the costs are negative quantities, assuming the algorithm is searching for the global maximum of the function. The functional relations between each of the three terms does not change if the costs are considered positive, and the revenue negative. Thus the optimization can take place either in terms of minimizing the costs, or maximizing the revenue. The outcome of the optimization will be identical. Appendix C provides both the Matlab code after Haupt and Haupt [2004] and the objective function including the

RETScreen costing approach. The NPV equation used in this work is:

$$NPV = \sum_{t=1}^{n} \frac{R_t + M_t}{(1+r_t)^t} + I$$
(4.7)

where

t = number of years from the present

n = total number of years (power plant design life of 30 years)

 R_t = annual income from energy generation at year t (+)

 M_t = annual operation and maintenance costs at year t (-)

 $r_t = annual discount rate (here taken as a constant)$

I = sum of the initial investment costs (calculated at t=0) (-)

The objective function here is driven by two main factors, the time-valued annual expenses and revenues (captured by R and M in the first term) and the initial investment cost (represented by I). This formulation has the advantage that it can account for changes in financing, such as changing the interest rate after a certain period of years, and gives the investor a way to estimate the total profit of the design over its lifespan. However, the formulation does have several disadvantages as well, namely that changing an estimation of the discount rate, annual income, or annual costs can severely impact the estimation of profit. Thus it is necessary to understand which portions of the cash flow have the highest level of uncertainty (likely to be I), and which will remain more or less constant (probably R and M), over the time period in question (30 years is indeed a very conservative estimate for hydropower plant design life, as many plants first constructed 60+ years ago are still running today!)

Annual revenue from energy generation, R_t was calculated as

$$R_t = 1,000MWh_{ann}E_{kWh} \tag{4.8}$$

where

 $MWh_{ann} = annual power production in MWh (20 interval sum based on Q_d)$

 $E_{kWh} = energy price (0.0967 EUR/kWh)$

and the following form for the total initial investment cost I, used in the Matlab optimization was

$$I = I_{eng} + I_{sub} + I_{pen} + I_{civ}$$

$$\tag{4.9}$$

where in a more general form for each component i, the total initial investment cost can be represented using a more general form of costing equations similar to those found in Section 2.2 as

$$I = \sum_{i=1}^{n} C_i Q_d^{\alpha_i} H_g^{\beta_i} \tag{4.10}$$

and each of the individual investment cost equations are described in detail in the following section. Figure 4.4 shows the general shape of the investment cost function, using the engineering investment cost equation. Also, the functional form in Equation 4.10 for the first term with constant C, and two exponential values α , β provide a good indication as to the effective weight of each of the investment cost components (see Table 4.7).



Figure 4.4.: Cost contour plot for $I_{eng} = 19,984 Q_d^{0.54} H_g^{0.378}$

Aside from the total initial investment cost, operation and maintenance is the only other cost considered in developing a small power plant. It is taken here as a fixed percentage of the investment cost, occurring annually for the life of the project. After Nguyen, the *discount rate* (r_t) is taken as 4.5%, the project life (n) is 30 years, and the annual operation cost based on investment (M_t) is 1.5% of the total initial investment cost. Additionally, an annual increase in the cost of maintainance (r_w) is included, and taken from Nguyen to be 1%. Since the (M_t) term is a function of I, it is effected by changing values of head and

flow rate, coupling the two terms together during optimization. The annual operation and maintenance cost term is represented mathematically as:

$$M_t = 0.015I\left(\frac{1 - \left(\frac{1 + r_t}{1 + r_w}\right)^{-t}}{\frac{1 + r_t}{1 + r_w} - 1}\right)$$
(4.11)

The resulting NPV is highly *epistatic*, meaning that the resulting value of each of the three terms (I,R, and M) is coupled to the others through the choice of H_g and Q_d . Thus, the use of an optimization algorithm which deals well with such functions is necessary. The GA is known to handle just such problems well [Haupt and Haupt, 2004].

The following sections cover the assumptions, necessary mathematical reformulation, and finally the results of the GA optimized RETScreen equation system. Previous works by Christos [2002] and Hreinsson and Eliasson [May 19-23 2002] have used similar approaches, but both opted to use detailed design considerations in dimensioning the individual components. This work attempts to get away from in-depth design for two reasons: The first is that the RETScreen costing formulation is only suitable for the prefeasibility stage, where detailed information is not available nor is it necessary. The second is that when the effects of the assumed interest (or discount) rate are considered, it can be found that using an objective function with a high level of design detail provides no real benefit to the engineer. This is because if the assumed interest rate changes slightly, its cumulative effect on the objective function will cancel out any benefit gained in obtaining costs from a detailed design analysis. It is this fundamental weakness of the previous two approaches which has lead to the work of this Thesis. The dominating assumption in this work's approach is that stochastic analysis compared to the costs resulting from optimized design parameters would serve as a superior and more robust indicator of project feasibility, at least economically.

4.4.1. Assumptions in Using the RETScreen Equations

It should be noted that in each of the costing reformulations, the same procedure was followed: the RETScreen power equation for "mini" plants was substituted into each individual RETScreen costing equation (full list provided in Appendix A), constants were determined based on data taken from the Case Study, and the equation was then rewritten and simplified to become a function of the variables Q_d and H_g . These two variables were then used as our chromosomes for optimization in the GA.

As previously mentioned, it is extremely important that the user first separate the input parameters into those taken from the Case Study and those for which assumptions needed to be made. For general application, the CS parameters can be taken as those which the design engineer has, i.e. the flow data, turbine efficiency curves. Assumed parameters are then those which are normally used as design parameters, i.e. the dam width, design flow, operational head, etc. Here it has to be assumed that the values obtained from the previous work are the "real" values, even though the project was never constructed. Any deviation in the RETScreen costing analysis is then also assumed to deviate from "reality", in only the sense that there are differences in the estimated costs. Preferably, a series of data sets consisting of small hydropower plants constructed in say, southern Germany could be applied to ascertain more accurate values of the adjustment factors. In the interests of time, only one in-depth case study could be found which possessed the necessary information, and thus the critical argument must be put forth that the exact values of the costing method should not be the focus of the reader, rather the methodology of application and its resulting uncertainty. Additionally, in applying the RETScreen formula-based costing method, two major items

Cost Category	Formula Number(s)	Applicable to Case Study?
Feasibility Study	1	No
Development	2	No
Engineering	3	Yes
Energy Equipment	4	Yes
Access Road	6	No
Transmission Line	7	No
Substation and Transformer	8	Yes
Penstock	11	Yes
Canal	13	No
Tunnel	14	No
Civil Works (other)	5+9+10+12	Yes
Miscellaneous	15	No

 Table 4.5.:
 RETScreen formula costing categories

need to be mentioned, the effects of currency and rounding:

Since the program is from Canada, the costs used to derive the formulas and accordingly the equations themselves are written in Canadian dollars. In order to convert the equations to the EUR currency, it was necessary to provide an exchange rate. This can be done simply in the program by inserting the appropriate rate directly into the Cost Analysis module of the program. For this study, the exchange rate was taken as the 215 day average beginning in January 2006 and ending with the submission of the Thesis in September of 2006. The average was taken because the costs in the Case Study were not taken all on one particular date, and the average should provide a reasonable assessment of the exchange rate for that period. For this time period, the exchange rate was 0.72 EUR to the Canadian Dollar Forex [13 July 2007], with a high of 0.739 and a low of 0.6925. The effects of the exchange rate were taken into account when calculating the rounding drift (discussed in the following paragraph) and implemented in the GA optimization by multiplying the NPV of the investment costs by 0.72 EUR/CAD.

The next issue addressed when using the RETScreen equations is that the reported cost values in the program are rounded to the nearest monetary unit. In order to have the

output of the rewritten equation system most closely match that of the program, the equation constants had to undergo an adjustment. This was accomplished in Excel by using a "drift correction". First, the RETScreen formula-based costing approach was considered by varying the values of H_g and Q_d from 0-5 in increments of 1 in the Energy Model module and recording the resulting costs. Next, the rewritten form of the equations were compared to the RETScreen output using a sum of error squared approach (RETScreen output - rewritten equation, squared). The equation constants were then optimized using the Solver package (Excel worksheet included on accompanying CD-ROM) such that they would minimize the sum of the errors squared. These drift corrected constants are the ones used in the following equations. Table 4.6 provides the error resulting before and after drift correction was applied for each of the rewritten component costing equations, and Figure 4.5 shows a graphical representation of the rounding drift and its correction. Although the differences are relatively small, this aided in removing most of what would otherwise result in a systematic error in the GA optimization's costing calculations.



Figure 4.5.: Rounding drift correction for costing equation reformulation - engineering costs

4.4.2. Reformulation of the RETScreen Equations

This section covers each of the individual costing equations used for the Matlab GA optimization, and provides an in-depth look at the assumptions made for each individual equation as they related to the Case Study data. At the end of this section, a brief summary of the final form of the equations can be found in Table 4.7.

Cost Category	Avg Error No Correction(%)	Avg Error w/ Correction (%)
Engineering	2.77	-0.35
Energy Equipment	2.98	-0.06
Substation and Transformer	2.57	2.57
Penstock	2.89	-0.02
Civil Works	5.37	0.18

Table 4.6.: RETScreen output and simplified equations with and without drift correction

The engineering costs after RETScreen can be calculated with the following formula

$$I_{eng} = 0.37n^{0.1} \left(\frac{MW}{H_g^{0.3}}\right)^{0.65} 10^6 \tag{4.12}$$

RETS creen calculates the power per turbine unit, (n) for "mini" plants with 12.8 $\geq 0.4m^3$ /s as

$$MW_u = 7.79Q_d H_q / 1000 \tag{4.13}$$

substituting this into the cost equation, multiplying out the constant values, and correcting for drift leaves (same formula used in subsection 4.3.1)

$$I_{eng} = 19,984Q_d^{0.54}H_g^{0.378} \tag{4.14}$$

Energy equipment costs consist of the sum of two costs, the generator and control (I_{gen}) and the cross flow turbine and governor (I_{tur}) .

$$I_{eqp} = I_{gen} + I_{tur} \tag{4.15}$$

The costs of the generator and control systems after RETScreen are

$$I_{gen} = 0.82n^{0.96} G_f C_g \left(\frac{MW}{H_g^{0.28}}\right)^{0.9} 10^6$$
(4.16)

where

 $G_f = grid factor, 0.9 \text{ if } MW \leq 1.5 \text{ and central-grid connected.}$

 $\rm C_g$ = low cost motor factor, equal to 0.75 if MW < 10 or 1.0 if MW ≥ 10. In this study, since the plant is much smaller than 10 MW, C_g was taken to be 0.75.

Inserting 4.13, multiplying out the constant values, and correcting for drift results in

$$I_{gen} = 5,033Q_d^{0.9}H_q^{0.648} \tag{4.17}$$

The cross flow turbine and governor cost equation after RETS creen is taken as 1/2 of the cost of the Pelton-Turgo equation cost

$$I_{tur} = 0.5(5.34n^{0.96} \left(\frac{MW}{H_g^{0.5}}\right)^{0.91} 10^6)$$
(4.18)

where

$$\frac{MW}{H_q^{0.5}} \le 0.4$$

Solving the equation by inserting 4.13, multiplying out the constant values, and correcting for drift gives

$$I_{tur} = 24,110Q_d^{0.91}H_q^{0.455} \tag{4.19}$$

This results in the total energy equipment equation becoming

$$I_{eqp} = 5,033Q_d^{0.9}H_g^{0.648} + 24,119Q_d^{0.91}H_g^{0.455}$$
(4.20)

Substation and transformer costs, although only making up a small part of the total investment costs, are also included and are accounted for using the following RETScreen formula

$$I_{sub} = \left(0.0025n^{0.95} + 0.002(n+1)\right) \left(\frac{MW}{0.95}\right)^{0.9} V^{0.3} 10^6$$
(4.21)

where

n = number of turbines

V = the transmission line voltage in kV (assumed to be 25)

Reformulating the equation by inserting 4.13, multiplying out the constant values, and correcting for drift results in

$$I_{sub} = 163Q_d^{0.9}H_q^{0.9} \tag{4.22}$$

Next, the penstock costs are calculated using the following RETScreen formulation

$$I_{pen} = 20n_p^{0.95} W^{0.88} \tag{4.23}$$

where

 $n_p =$ number of penstocks, (taken as 1 after the Case Study design)

W = weight (kg) of the penstock, which can be calculated as

$$W = 24.7d_p l_p t_{ave} \tag{4.24}$$

and

 $d_p^{-1} = \text{penstock diameter (m) is given as}$

$$d_p = 0.285 \left(\frac{Q_d}{n_p}\right)^{0.38} \left(\frac{l_p}{H_g k_{pen}}\right)^{0.19} \tag{4.25}$$

 l_p = penstock length (m) (in the Case Study 150m)

 k_{pen} = allowable penstock headloss (ratio to H_g)

 t_{ave} = average pipe thickness (mm), accounting for water hammer and given as

$$t_{ave} = d_p^{1.3} + 6 \tag{4.26}$$

This equation is derived for the case of using a steel penstock. In the Case Study, the penstock was a concrete pipe. This required that an additional correction factor be applied to relate the costing equation to that of a concrete pipe, using the local costing data as provided in Nguyen's Thesis. This relation was obtained by taking the cost per unit length of concrete pipe (50 EUR/m) and dividing it by the steel pipe cost (180 EUR/m), resulting in a conversion ratio of 0.3.

The final form of the penstock costing equation, after correcting for drift, including the constant assumptions as taken from the Case Study, and applying the steel-to-concrete cost factor of 0.3 is

$$I_{pen} = 19,547 \frac{Q_d^{0.769}}{H_g^{0.385}} + 49,238 \frac{Q_d^{0.334}}{H_g^{0.167}}$$
(4.27)

¹this equation should be used in lieu of the penstock diameter equation found in Appendix A, as the original RETScreen equation contained an error and was confirmed by RETScreen staff through personal correspondence

The total civil works cost equation is represented by the sum of 4 individual RETScreen equations: civil works, installation of substation and transformer, installation of energy equipment, and the installation of penstock. The total civil works equation is then

$$I_{civ} = I_{cw} + I_{inst,sub} + I_{inst,eqp} + I_{inst,pen}$$

$$(4.28)$$

RETScreen calculates the installation costs (the last three terms of the total civil works equation) as fractional values of the original cost functions, resulting in

$$I_{civ} = I_{cw} + 0.15I_{sub} + 0.15I_{eqp} + 0.25I_{pen}$$
(4.29)

Although the following equation system for the total civil works cost will continue to include these last three terms, it should be noted that in applying the equation system in Matlab, factors of 1.15, 1.15, and 1.25 were applied to equations 4.22, 4.20, and 4.27 respectively. This was done to keep the resulting objective function as computationally simple as possible.

After RETScreen, the civil works cost component is

$$I_{cw} = 1.97n^{-0.04} CR\left(\frac{MW}{H_g^{0.3}}\right)^{0.82} \left(1 + 0.01l_b\right) \left(1 + 0.005\frac{l_d}{H_g}\right) 10^6$$
(4.30)

where

C = civil cost factor, taken as 0.44 if a dam exists, or 1.0 if no dam exists. For the Case Study, the dam was destroyed, and thus the Civil Cost Factor was 1.0

R = the rock factor, taken as 1.0 if there is rock at the dam site, and 1.05 if no rock. For the Case Study, it was assumed that rock would be present and thus the Rock Factor was taken as 1.0.

 l_b = distance to the borrow pit (km). Zero for the Case Study since the cut and lower method recommended by Nguyen in his Thesis uses the removed soil as the fill material.

 $l_d = dam$ crest length (m). It is fixed at 12m since this is the total width of the Wolfegger Ach, and is the same value used by Nguyen in his cost estimation. However, if other locations outside that of the Case Study were taken, this variable could also be included for optimization.

Equation 4.30 can be rewritten after correcting for drift and including the constant assumptions as taken from the Case Study to be

$$I_{cw} = 40,327Q_d^{0.82}H_g^{0.574}\left(1 + \frac{0.06}{H_g}\right)$$
(4.31)

resulting in the final form of the total civil cost equation

$$I_{civ} = 40,327Q_d^{0.82}H_g^{0.574}\left(1 + \frac{0.06}{H_g}\right) + 0.15I_{sub} + 0.15I_{eqp} + 0.25I_{pen}$$
(4.32)

Before going on to describe the second term of the NPV, it is a good idea to take a look at the final form of the investment cost term. Table 4.7 presents the constants and exponents for each of the equations and sub equations² used in rewriting the RETScreen equations. Since the investment cost term (see Equation 4.10 is the sum of each of the individual investment costs, looking at the values of constants and exponents allows for a quick, objective assessment of which terms will result in the largest contributions to the investment cost. It can be seen then that it should be expected that the turbine, penstock, and civil costs will have the largest effects on the investment cost term, with the substation and transformer having little effect at all.

Cost Category Equation Constant(s), C β α Engineering 4.14 19.984 0.540.378 Generator 4.175,0330.90.648Turbine & Governor 4.1924,110 0.910.455Substation & Transformer 1634.220.90.9Penstock 19,547 & 45,238 0.769 & 0.334 -0.385 & -0.167 4.27Civil Works 4.3240,327 0.820.574

Table 4.7.: Costing factors C, α , and β for the applied costing equations

 $^{^2\}mathrm{note}$ that the Civil Works equation includes more than one term

4.5. Optimized Design Results

Optimization was undertaken varying the population size and number of iterations to determine the global optimum. The maximum NPV found was 206,089 EUR with the combination of $Q_d=1.6$ and $H_g=5$. Nguyen's work had an NPV of 323,805 EUR using a design for $Q_d=3.0$ and $H_g=4.88$. Does this indicate that the absolute best design would occur using this combination? Certainly not. It has already been shown that the expected total initial investment cost variation ranges somewhere around 50%. However, the optimized design values were still not far off of Nguyen's and resulted in a far better NPV than in the previous chapter. The idea behind finding the optimum economic design for a small hydropower plant is that



Figure 4.6.: NPV optimized varying population size and max generations

the ideal design characteristics could be determined for a particular site with little effort. This implicitly assumes that the equations used represent the component costs with a reasonable level of accuracy, and that any assumptions made into choosing constants (such as the length of the penstock, weir width, etc.) are valid. Thus the optimization result itself carries some level of uncertainty and should only be viewed as a reasonable guess of what the best possible design shall look like. The problem remains that the engineer does not have any reference as to where this best solution lies with regard to component price uncertainty (the cost of steel has gone up dramatically in the last few years) or to uncertainty resulting from using the cost equations. If the optimized solution can be compared to an uncertainty analysis carried out including the ranges of costing equation error, then the engineer should have a better estimation of the expected cost breakdown. The final chapter of this Thesis deals with adding uncertainty into the cost estimation.

5. Including Uncertainty in Cost Estimation

This chapter finalizes the work of this Thesis. The first two chapters provided background information on why small hydropower costing may be important in the future, and which methods are available to use. Chapters 3 and 4 discussed using the RETScreen formulabased approach in the hopes that it would be able to provide accurate estimates for a given Case Study. The approach was validated, and then optimized in order to find the best design RETScreen could deliver. It was found that the NPV optimization recommended reducing the design flowrate Q_d , from 3 to 1.6 m³/s and increasing the operating head slightly from H_g 4.88 to 5 m. Important to consider is that the so-called optimized design leads to the best solution in terms of the NPV, where all other input variables (inflation rate, operating life, etc.) being equal, the optimum solution is a trade-off between the lowest total initial investment cost and annual energy production (and thus revenue). However, since it is known a priori that the RETScreen method has inherent errors for each costing catagory, it follows that consideration of the optimized design must therefore also include an accounting of these errors as well. Figure 5.1 shows the process flowchart for the cost optimized uncertainty analysis approach including the chapter number for which each step was carried out. This chapter proposes that the costs obtained for the optimum design can be utilized best when subjected to stochastic simulation taking into account the ranges of error for the individual costing equations.

5.1. Calculating and Implementing Costing Error Ranges

Chapter 2 provided an overview of several approaches for calculating small hydropower costs at the prefeasibility stage. The RETScreen method was chosen and tested in Chapter 3 against a Case Study. It was found that although the overall initial investment cost estimate was close to being within the expected cost variance of 50%, the costing accuracy of the individual equations varied greatly. Chapter 4 investigated the scenario in which the equations were assumed to be perfectly accurate in order to find the optimum prediction based on the costing equations alone. This optimized value is what the design engineer would be searching for if the RETScreen equation system was used without reference or any further review. Here, the values obtained through optimization for the individual cost catagories are subjected to a stochastic simulation applying the Monte Carlo method in order to determine useful ranges of cost uncertainty for the Case Study project.



Figure 5.1.: Process flowchart - cost optimized uncertainty, with chapter references

5.1.1. Determining Error Ranges

The calculation of error ranges is relatively straight-forward. From the original five costing catagories used in Chapter 3 (see Table 3.3), substation and transformer costs have been removed for further analysis, as they constituted less than one half of one percent of the total optimized initial investment cost. This leaves energy equipment, engineering and design, penstock, and civil works as the remaining cost catagories for analysis. When using the RETScreen method in Chapter 3, additional input variables (the FDC, turbine efficiency curve, etc.) were also considered. As long as all input variables are identical in application and value as those used in the observed case (the Case Study) then for the ith catagory with initial cost I_i , the error range can be calculated as the percent difference between the predicted and the observed cost as taken from Nguyen's Thesis. Thus, the values can be taken directly from Table 3.3 where it is considered to be equally undesirable for either low and high cost estimates. In order to remove possible negative costs, which are considered impossible, an *if* statement was incorporated into the calculation which set the minimum value of any cost catagory to ten percent of the optimized value. Note that this may also lead to an offset between the optimized and expected costs in the cost histogram for the case that the error range is greater than 100%. In this case, the Monte Carlo simulation will favor costs above the optimized total initial investment cost as can clearly be seen in Figure 5.2.

The error range applied was calculated as

$$Range_{I_i} = 100 \frac{I_{Obs,i} - I_{RETScreen,i}}{I_{Obs,i}}$$

$$(5.1)$$

where

 $I_{Obs,i}$ = observed initial cost for catagory i

 $I_{RETScreen,i}$ = calculated initial cost for catagory i

Table 5.1.:	Cost	catagories	and	their	calculated	error	ranges
-------------	-----------------------	------------	-----	-------	------------	-------	--------

Cost Catagory	$\operatorname{Range}(+/-)$
Energy Equipment	15
Engineering and Design	197
Penstock	277
Civil Works	54

As Table 5.1 shows, the error ranges for the engineering and design and the penstock are far outside what could be considered "good" estimations. Ideally, a larger set of case studies should be assessed using the RETScreen method in order to statistically determine the expected value of each equation's error range. In applying the error ranges in stochastic simulation, the user should be thinking about meeting or beating the worst-case scenario. The question is then, "are all of the simulated values within 50% of the optimized value?"

5.1.2. Applying Error Ranges

Now that the error ranges have been defined for the Case Study costing catagories, they can be implemented into a Monte Carlo simulation. This was carried out by creating an Excel spreadsheet (found on the accompanying CD-ROM), **MCTotalCost.xls** where the user inputs the optimized RETScreen cost value for up to four costing catagories and the cost error in percent as calculated in the previous section. The Monte Carlo simulation assumes a uniform distribution for each of the cost catagories, and carries out a total of 10,000 simulations per run. This is more than sufficient, since calculations with an estimated 2% error need only around 800 simulations (see spreadsheet for calculation). Since the simulation uses the sum of random variables, the resulting distribution is normal (as dictated by the Central Limit Theorem). Figure 5.2 shows the resulting histogram of the total initial investment cost using optimized costs taken from the previous chapter, and the cost error ranges from the previous section. The probabilities of falling within ± 10 , 25, and 50% of the optimized cost (*they are not confidence intervals!*) are provided and the corresponding regions are shaded. Probabilities are calculated by summing the total number of simulation results within 10, 25, or 50% of the RETScreen total initial investment cost, and dividing by

the total number of simulations. Minimum performance is defined such that all simulated costs should fall within 50% of the optimized value. The associated probability range is shown in red in the case that minimum performance is not met.

The shaded ranges can be best understood if one reads them as "there is a probability of 0.505 that the actual cost falls within a range of 25% of the optimized cost". It is recommended that when the engineer "sees red", they should think about reconsidering the cost optimized uncertainty approach, as minimum performance is not satisfied. For example, Figure 5.2 shows that there is a probability of 0.156 that the optimized cost might not only be dead wrong but that it may be considerably higher (see the red area in Figure 5.2) than the optimized value.



Figure 5.2.: Monte Carlo simulation - total initial investment cost

The results in Figure 5.2 are quite interesting, in that even with two of the four cost equations performing miserably, the probability of the optimized cost being within 50% (the goal is to beat or equal this) is still relatively high, at 0.844. However, the presence of red indicates that use of the approach is not recommended. In this case, Appendix D provides a quick overview of the various small hydro costing methods, along with their strengths and weaknesses. Furthermore, the optimized cost is well below the expected value indicating the presence of large error ranges, with a probability of 0.156 that the actual cost will not fall within the minimum performance criteria.

Though the method has essentially failed to meet the minimum performance criteria, there is still hope for the Case Study, especially if one recalls the results of Chapter 3. There it was found that treating the concrete pipe as a canal rather than using the RETScreen steel penstock equation with a correction factor provided a more reasonable estimate of the penstock cost. Assuming all other factors equal, the GA optimization was run once again this time substituting in a canal for the penstock. Revised values for the error ranges are taken from Chapter 3 (also see Table 3.4) and Figure 5.3 provides the results.

Table 5.2.: Cost catagories and their calculated error ranges - canal instead of penstock

Cost Catagory	Range%(+/-)
Energy Equipment	15
Engineering and Design	197
Canal	26
Civil Works	17



Figure 5.3.: Monte Carlo simulation with canal - total initial investment cost

The results are much improved over the previous case, with all simulated values meeting minimum performance criteria and a probability of 0.881 that the actual cost will now fall within 25% of the optimized cost. What changed to make the results so much more favorable? First off, using the penstock equation provided a grossly overestimated cost estimate. Secondly, an increase in the canal equation's costing accuracy also carried over to improving the accuracy of the civil works costs as well. Furthermore, the optimal design values after using the canal equation were also closer to Nguyen's, with $Q_d = 2 \text{ m}^3/\text{s}$ and $H_g = 5 \text{ m}$. Thus, it is extremely important that the engineer has experience in applying the costing equations. First, to make sure that they are able to estimate costs reasonably well by validating them under local conditions. And second, to understand in which cases the equations can be best applied. This section should serve to point out one major finding

in using the cost optimized uncertainty approach - *costing equations need to be from the onset as accurate as possible*, as they affect the analysis twice: once through their overall contribution to the optimized cost, and again by influencing the Monte Carlo simulation results through their error range.

Before moving on to the final comments, one intriguing question still begs to be answered: What minimum error range would the costing equations need to have if one wanted to halve the minimum prefeasibility cost estimate accuracy requirement from 50 to 25%. Figure 5.4 provides the answer for the Case Study's situation. Here it can be seen that if the error range for the energy equipment and canal equations is 30%, and for engineering and design and civil works is 25%, the expected probability of all cost estimates within 25% of the optimized cost is 1.0. This reinforces the importance of validating and choosing the costing equations which produce as accurate initial estimates as possible.



Figure 5.4.: Monte Carlo simulation for 25% costing accuracy - total initial investment cost

5.2. Final Remarks

It was shown in Chapter 2 that small hydro costing can be estimated at the prefeasibility stage using a set of equations representing costing catagories for items such as engineering design, electromechanical equipment, civil works, etc. Additionally, a variety of small hydro costing and assessment methods were investigated in order to determine which method would be the most suitable for prefeasibility stage cost estimates. The RETScreen formula-based costing method was chosen, and validated in Chapter 3. It was also shown that although the overall performance was mediocre when compared to the Case Study, the accuracy of individual costing equations varied greatly. Next, Chapter 4 applied a GA optimization in terms of Q_d and H_g using the RETScreen method to maximize the NPV assuming that the applied costing equations were completely correct. Here it was found that the best design characteristics chosen were underestimated for Q_d (1.6 vs. 3.0 m³/s) and very close for H_g (5 vs 4.88 m). Furthermore, as the penstock design in the Case Study was a low pressure concrete pipe, it was found that substituting the canal equation in RETScreen yielded better optimized results, both in terms of the costing catagories, and for Q_d (2.0 vs. 3.0 m³/s), while H_g once again remained at 5 m for both cases. This chapter proposed including the error range of each of the individual costing catagories into a stochastic simulation, and determined both that the choice of costing equations as well as their corresponding error ranges is paramount in increasing the accuracy of prefeasibily cost estimation.

As previously mentioned a major improvement to the approach can still be made: Average error range values can be obtained for the individual equations if the RETScreen method can be further validated against a larger set of case studies. This would not only aid in defining region-specific trends in the accuracy of the individual equations, but would also allow for a more systematic assessment of using the proposed cost optimized uncertainty method.

It is also worth mentioning that the cost optimized uncertainty approach can be applied for any engineered system, and thus the author hopes that the reader does not come away believing that the method proposed here can only be used for small hydropower. If the reader is interested in applying the basic concepts as layed out in this work, they are heartily encouraged in doing so, it is the author's promise that they will enjoy the effort!

A. Complete List of RETScreen Equations

FRANCIS, KAPLAN AND PROPELLOR TURBINES (REACTION TURBINES):		
ITEM	FORMULA	
Reaction turbine runner size	$d = kQ_d^{0.473}$	
(<i>d</i>)	where: $d =$ runner throat diameter in m	
	k = 0.46 for d < 1.8	
	= 0.41 for $a \ge 1.8$ O_{a} = design flow (flow at rated head and full gate opening in m ³ /c).	
	Q_d = design now (now at rated near and run gate opening in in 75)	
Specific speed (n_q)	$n_q = kh^{-0.5}$	
	where: n_q = specific speed based on flow	
	κ = 800 for propetter and Kaplan turbines = 600 for Francis turbines	
	h = rated head on turbine in m	
	(gross head less maximum hydraulic losses)	

FRANCIS TURBINES:	
ITEM	FORMULA
Specific speed adjustment to peak efficiency $(^{e}e_{nq})$	$^{n_{q}} = \{(n_{q} - 56)/256\}^{2}$
Runner size adjustment to peak efficiency (^{e}d)	$^{n}e_{d} = (0.081 + ^{n}e_{nq})(1 - 0.789d^{-0.2})$
Turbine peak efficiency (e_p)	$e_p = (0.919 - {}^{\circ}e_{nq} + {}^{\circ}e_d) - 0.0305 + 0.005 R_m$ where: R_m = turbine manufacture/design coefficient (2.8 to 6.1; default = 4.5). Refer to online manual.
Peak efficiency flow (Q_p)	$Q_p = 0.65 \ Q_d \ n_q^{0.05}$
Efficiencies at flows below peak efficiency flow (e_q)	$e_q = \left\{ 1 - \left[1.25 \left(\frac{(Q_p - Q)}{Q_p} \right)^{(3.94 - 0.0195n_q)} \right] \right\} e_p$
Drop in efficiency at full load $(^{\wedge}e_{p})$	$^{n}e_{p} = 0.0072 n_{q}^{0.4}$
Efficiency at full load (e_r)	$e_r = \left(1 - e_p\right) e_p$
Efficiencies at flows above peak efficiency flow (e_q)	$e_{q} = e_{p} - \left[\left(\frac{Q - Q_{p}}{Q_{d} - Q_{p}} \right)^{2} \left(e_{p} - e_{r} \right) \right]$

KAPLAN AND PROPELLOR TURBINES:		
ITEM	FORMULA	
Specific speed adjustment to peak efficiency $(^{e}e_{nq})$	$^{n_{q}} = \left\{ \left(n_{q} - 170 \right) / 700 \right\}^{2}$	
Runner size adjustment to peak efficiency $(^{A}e_{d})$	$^{e_{d}} = (0.095 + ^{e_{nq}})(1 - 0.789d^{-0.2})$	
Turbine peak efficiency (e_p)	$e_p = (0.905 - {}^{\wedge}e_{nq} + {}^{\wedge}e_d) - 0.0305 + 0.005 R_m$ where: R_m = Turbine manufacture/design coefficient (2.8 to 6.1; default 4.5). Refer to online manual.	

KAPLAN TURBINES:		
ITEM	FORMULA	
Peak efficiency flow (Q_p)	$Q_p = 0.75 \ Q_d$	
Efficiency at flows above and below peak efficiency flow (e_q)	$e_q = \left[1 - 3.5 \left(\frac{Q_p - Q}{Q_p}\right)^6\right] e_p$	

PROPELLOR TURBINES:		
ITEM	FORMULA	
Peak efficiency flow (Q_p)	$Q_p = Q_d$	
Efficiencies at flows below peak efficiency flow (e_q)	$e_q = \left[1 - 1.25 \left(\frac{Q_p - Q}{Q_p}\right)^{1.13}\right] e_p$	
PELTON TURBINE	S:	
--	---	
ITEM	FORMULA	
Rotational speed (n)	$n = 31 \left(h \frac{Q_d}{j} \right)^{0.5}$ where: j = Number of jets (user-selected value from 1 to 6)	
Outside diameter of runner (<i>d</i>)	$d = \frac{49.4 \ h^{0.5} j^{0.02}}{n}$	
Turbine peak efficiency (e_p)	$e_p = 0.864 \ d^{0.04}$	
Peak efficiency flow (Q_p)	$Q_p = (0.662 + 0.001j) Q_d$	
Efficiency at flows above and below peak efficiency flow (e_q)	$e_{q} = \left[1 - \left\{(1.31 + 0.025j) \left \left(\frac{Q_{p} - Q}{Q_{p}}\right) \right ^{(5.6 + 0.4j)} \right\}\right] e_{p}$	

TURGO TURBINES	<u>5:</u>
ITEM	FORMULA
Efficiency (e_q)	Pelton efficiency minus 0.03

CROSS-FLOW TU	RBINES:
ITEM	FORMULA
Peak efficiency flow (Q_p)	$Q_p = Q_d$
Efficiency (e_q)	$e_q = 0.79 - 0.15 \left(\frac{Q_d - Q}{Q_p}\right) - 1.37 \left(\frac{Q_d - Q}{Q_p}\right)^{14}$

VARI	ABLES LISTED ALPHABETICALLY					
А	Access road difficulty factor	Jt	Higher cost vertical axis turbine factor	n	Number of penstocks	
в	Foreign costs civil works factor	¥	Allowable tunnel headloss (ratio to H_g)	Ъ	Transmission line wood pole vs. steel tower factor	
ပ	Civil cost factor	×	User-defined equipment manufacture cost coefficient to account for country of manufacture	ð	Flow under consideration (m^{3}/s)	
లి	Lower cost generator factor	K	Lower cost small horizontal axis turbine factor	۵	Design flow (m^3/s)	
°	Tunnel volume of concrete lining (m ³)	l _a	Access road length (km)	Q	Flow per unit (m³/s)	
p	Runner diameter (m)	l _b	Distance to borrow pits (km)	R	Rock factor	
D	Transmission line difficulty factor	L.c	Ratio of the cost of local labour costs compared to Canadian cost expressed as a decimal	R,	Tunnel volume of rock excavation (m^3)	
dp	Diameter of penstock(s) (m)	I _{cr}	Canal length in rock (m)	Sr	Side slope of rock terrain through which canal will be built (degrees)	· · · · · · · · · · · · · · · · · · ·
ш	Engineering cost factor	_cs	Canal length in impervious soil (m)	S	Side slope of soil terrain through which canal will be built (degrees)	
Ë	Ratio of the cost of local construction equipment costs compared to Canadian costs expressed as a decimal	Id	Dam crest length (m)	Т	Tote road factor	
Ŧ	Frost days at site	I _p	Penstock length (m)	t _{ave}	Average penstock thickness (mm)	
щ	Frost days factor	Ιτ	Transmission line length (km)	\mathbf{t}_{b}	Penstock thickness at turbine (mm)	
ъ	Ratio of the cost of local fuel costs compared to Canadian costs expressed as a decimal	lt	Tunnel length (m)	٦°	Tunnel lining length ratio	
9	Grid connected factor	MM	Total capacity (MW)	ţ	Penstock thickness at intake (mm)	
H	Gross head (m)	ΜW	Capacity per unit (MW)	>	Transmission line voltage (kV)	
	Interest rate (%)	Е	Number of turbines	≥	Penstock weight (steel) (kg)	

BASIC PARAMETERS			
ITEM	SMALL	MINI	MICRO
Design flow (maximum flow used by generating station) in $\mathfrak{m}^3/\mathfrak{s}$ (Q_d)		User-defined value	
Recommended classification	$Q_d > 12.8$	$12.8 \ge Q_d > 0.4$	$Q_d \leq 0.4$
Selected classification	User-defined value based on	acceptable risk (flood, etc.).	$Q_d \leq 0.4$
Number of turbines (n)	User-defir	ned value	1
Flow per turbine in $\mathfrak{m}^3/\mathfrak{s}$ (Q_u)	$= Q_{a}$	<i>u/^p</i>	$=Q_d$
Approx. turbine runner diameter in m (d)		$= 0.482 Q_{u}^{0.45}$	
Gross head in m $(H_{_{\cal S}})$		User-defined value	
MW/unit in MW (hidden) (MW_u)	$= 8.22 \ Q_u H_g / 1000$	$= 7.79 \ Q_u H_g / 1000$	$= 7.53 Q_{u} H_{g} / 1000$
Total Capacity in MW (hidden) (MW)	1W =	$u^n n$	$=MW_u$

OTHER VARIABLES AND COSTING FAC	TORS (IN ORDER OF USE IN FO SMALL	RMULAE) MINI = 0.67 if existing dam
Engineering cost factor (hidden) (E)		= 1.0 if no dam as specified by yes/no selection
Grid-connected factor to account for the use of induction generators (hidden) (G)	Π	0.9 if MW < 1.5 and central-grid co
Factor to account for use of lower-cost motors as generators for projects below 10 MW (hidden) (C_g)		= 0.75 if MW < 10 = 1.0 if MW > 10
Factor to account for cost increase with vertical axis Kaplan, Francis and Propeller units at heads above 25 m (hidden) (J_i)		= 1 if $H_g \le 25$ = 1.1 if $H_g > 25$
Factor to account for cost decrease with small horizontal Kaplan, Francis and Propeller axis units (hidden) (K_i)		$= 0.9 \text{ if } d < 1.8$ $= 1.0 \text{ if } d \ge 1.8$
-actor to adjust access road costs to reflect lower-cost tote road construction (hidden) (T)		= 0.25 if tote road = 1.0 otherwise as specified by yes/no selection
Access road difficulty of terrain factor (A)	User-	defined factor with recommended rang
Length of access road in m (1 _,)		User-defined value

î Factors (in order of use in formulae)	SMALL MINI MICRO	ctor User-defined factor with recommended range of 1 to 2	User-defined value	User-defined value	= 0.85 if V < 69 = 1.0 if V ≥ 69	= 0.44 if existing dam $= 1.0 if no dam$ as specified by yes/no selection	= 1 if rock at dam site $= 1.05 if no rock$ as specified by yes/no selection	User-defined value	User-defined value	User-defined value	Calculated value (penstock cost formula)	Calculated value (penstock cost formula)	User-defined value
OTHER VARIABLES AND COSTING	ITEM	ransmission line difficulty of terrain fact (D)	Length of transmission line in km $(l_{\rm i})$	Transmission line voltage in kV (V)	Factor to reflect cost of wood pole vs. ste tower construction (hidden) (P)	Civil cost factor (hidden) (C)	Rock factor (hidden) (R)	Distance to a borrow pit in km (l_b)	Length of dam crest in m $({\rm l_d})$	Number of identical penstocks $(n_{\rm p})$	Weight of penstock(s) in kg (hidden) (W)	Diameter of penstock(s) in m (d_p)	Length of penstock(s) in m $\binom{1}{p}$

OTHER VARIABLES AND COSTING FAO	CTORS (IN ORDER OF USE IN FOI	RMULAE)	
ITEM	SMALL	MINI	MICRO
Average pipe wall thickness of penstock(s) in mm $(t_{\rm ave})$		Calculated value (penstock cost formula)	
Penstock pipe wall thickness at intake in mm (hidden) (t _i)		Calculated value (penstock cost formula)	
Penstock pipe wall thickness at turbine in mm (hidden) (t_b)		Calculated value (penstock cost formula)	
Terrain side slope of soil through which canal is to be constructed in degrees $(S_{\rm s})$		User-defined value	
Length of canal to be constructed in soil in m $(I_{\rm cs})$		User-defined value	
Terrain side slope of rock through which canal is to be constructed in degrees $(S_{\rm r})$		User-defined value	
Length of canal to be constructed in rock in m (1 _{cr})		User-defined value	
Tunnel rock excavation volume in m^{a} (hidden) (R_{\rm v})	Calculated value (tr	umel cost formula)	N/A
Tunnel concrete lining volume in m^{a} (hidden) ($C_{\rm v}$)	Calculated value (tr	unnel cost formula)	N/A
Length of tunnel in m (I,)	User-defit	ned value	N/A

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	MICRO	N/A	N/A	ie	re	6	ie	re	re	$\left(egin{array}{c} F_c \ F_c \end{array} ight) \ L_c \ $	cd range of 0.5 to 1.0
ICTORS (IN ORDER OF USE IN FORMULAE)	SMALL MINI	User-defined value	User-defined value with recommended range of 15% (excellent rock) to 100% (poor rock)	User-defined val	User-defined val	$=\frac{110}{(365-f)^0}$	User-defined val	User-defined val	User-defined val	$= \left(0.3335E_{c} + 0.3333\right) \times \frac{1}{\left(\frac{E_{c}}{L_{c}}\right)^{0.5}} + 0.3333 \left(\frac{1}{L_{c}}\right)$	User-defined value with recommend
OTHER VARIABLES AND COSTING FA	ITEM	Allowable tunnel headloss expressed as a ratio to the gross head (k)	Percent length of tunnel that is lined factor $(T_{\rm c})$	Interest rate (i)	Number of days with frost at site (f)	Frost-days factor (hidden) (F)	Local vs. Canadian equipment costs ratio $(E_{\rm c})$	Local vs. Canadian fuel costs ratio $(F_{\rm c})$	Local vs. Canadian labour costs ratio $(\mathrm{L_{c}})$	Civil works foreign cost factor (hidden). Used in program to determine local cost of the civil works components of foreign projects (B)	Equipment manufacture cost coefficient (K)

BASIC COSTING FORM	AULAE		
ITEM	SMALL	MINI	MICRO
Feasibility study (Eq.#1)	$= 0.032 \sum (Eq.\#2) t$	to (Eq.#15)	$= 0.031 \sum (Eq. #2) \ to \ (Eq. #15)$
Development (Eq.#2)		$= 0.04 \sum (Eq.\#3) \ to \ (Eq.\#14)$	
Engineering (Eq.#3)	$= 0.37 \ n^{0.1} \ E\left(\frac{M}{H}\right)$	$\frac{AW}{I_s^{0.34}} \right)^{0.54} \times 10^6$	$= 0.04 \left(\frac{MW}{H_g^{0.3}} \right)^{0.54} \times 10^6$
Energy equipment (Eq.#4)	Generator and Control: (all turbine types)	$= 0.82 \ n^{0.96} \ G \ C_g \left(\frac{MW}{H_g^{0.28}}\right)^{0.9} > $	<10 ⁶
	Kaplan turbine and governor:	$= 0.27 \ n^{0.96} J_t K_t d^{1.47} \left(1.17 \right)$	$H_g^{0.12} + 2 \times 10^6$
	Francis turbine and governor:	$= 0.17 \ n^{0.96} \ J_i \ K_i \ d^{1.47} \left\{ \left(13 + 0.0 \right)^{1.47} \right\} $	$1 H_g^{0.3} + 3 > 10^6$
	Propeller turbine and governor:	$= 0.125 \ n^{0.96} \ J_i \ K_i \ d^{1.47} \left(1.17 \right)^{1.17}$	$H_{g}^{0.12} + 4$)×10 ⁶
	Delton/Duridini opridine	$= 3.47 \ n^{0.96} \left(\frac{MW_u}{H_g^{0.5}} \right)^{0.44} \times 10^6 \ n$	here $\frac{MW_u}{H_g^{0.5}} > 0.4$
		$=5.34 \ n^{0.96} \left(\frac{MW_u}{H_g^{0.5}}\right)^{0.91} \times 10^6 \ n$	here $\frac{MW_u}{H_g^{0.5}} \le 0.4$
	Cross-flow turbine and governor:	Cost of Pelton/Turgo ×0.5	
Installation of energy equipment (Eq.#5)		= 0.15 (Eq.#4)	
Access road (Eq.#6)		$= 0.025 T A^2 l_a^{0.9} \times 10^6$	
Transmission line (Eq.#7)		$= 0.0011 D P l_T^{0.95} V \times 10^6$	

BASIC COSTING FORM	NULAE		
ITEM	SMALL	INIM	MICRO
Substation, and transformer (Eq.#8)	=(0	$(0025 \ n^{0.95} + 0.002 \ (n+1) \times \left(\frac{MW}{0.95}\right)^{0.9} \times V^{0.3}$	<10 ⁶
Installation of substation and transformer (Eq.#9)		= 0.15 (Eq. #8)	
Civil works (Eq.#10)	$= 3.54 \ n^{-0.04} C R$ $\times \left(\frac{MW}{H_g^{0.3}}\right)^{0.82}$ $\times (1+0.01 \ l_b)$ $\times \left(1+0.005 \frac{l_d}{H_g}\right)$ $\times 10^6$	$= 1.97 n^{-0.04} C R$ $\times \left(\frac{MW}{H_g^{0.53}}\right)^{0.82}$ $\times (1+0.01 l_b)$ $\times \left(1+0.005 \frac{l_d}{H_g}\right)$ $\times 10^6$	$= 1.97 \ n^{-0.04} \ C$ $\times \left(\frac{MW_u}{H_g^{0.82}}\right)^{0.82}$ $\times \left(\frac{1+0.005 \ H_d}{H_g}\right)$ $\times 10^6$
Penstock (Eq.#11)		$= 20 \ n_{p}^{0.95} W^{0.88}$ where: $W = (24.7 \ d_{p} \ l_{p} \ t_{owe})$ where: where: $d_{p} = \frac{\left(\frac{Q_{d}}{n}\right)^{0.43}}{H_{g}^{0.14}}$ $t_{r} = d_{p}^{1.3} + 6$ $t_{b} = 0.0375 \ d_{p} \ H_{g}$ $t_{owe} = 0.5(t_{r} + t_{b})$ if	$t_b \ge t_t$

 $\times 1.1\sum (Eq.#2)$ to (Eq.#14) $+0.1\sum(Eq.#2)$ to (Eq.#14)MICRO N/A = 0.17 i $= 20 \times \left[\left(1.5 + 0.01 S_s^{1.5} \right) Q_d I_{cs}^{0.9} \right]^{0.9}$ (for soil conditions) $=100\times\left[\left(1.5+0.016S_{r}^{2}\right)Q_{d}l_{or}^{-1}\right]^{0.9}$ $=\sum (Eq.\#1) \ to \ (Eq.\#15)$ (for rock conditions) $C_{v} = 0.185 \ l_{t}^{1.375} \left(\frac{Q_{d}^{2}}{k H_{g}} \right)^{0.375}$ $C_{v} = 0.306 \ R_{v} \ T_{c}$ $=5 W^{0.88}$ MIN $\times 1.1\sum (Eq.\#2) \ to \ (Eq.\#14)$ $+0.1\sum (Eq.#2) to (Eq.#14)$ $= 400 \ R_{\nu}^{0.88} + 4000 \ C_{\nu}^{0.88}$ $= 0.25 \ i \ Q_d^{0.35}$ where: SMALL **BASIC PARAMETERS** Installation of penstock (Eq.#12) Miscellaneous (Eq.#15) Initial Costs – Total (Formula Method) Tunnel (Eq.#14) Canal (Eq.#13) ITEM

CANADIAN AND NON-CA	NADIAN PROJECTS - Canadian Projects	APPLICATION OF "F	;" "B," AND "K" FAC Non-Canad	<i>CTORS</i> tan Projects	
Costing Category	Apply "F" Factor	% Local Component	Apply "F" to Local	Apply "B" to Loca	-
Feasibility study (Eq.#1)		15%			
Development (Eq.#2)		50%			
Engineering (Eq.#3)	Yes	40%	Yes		
Energy equipment (Eq.#4)		%0			
Installation of energy equipment (Eq.#5)	Yes	100%	Yes	Yes	
Access (Eq.#6)	Yes	100%	Yes	Yes	
Transmission line (Eq.#7)	Yes	60% if V < 69 40% if V ≥ 69	Yes	Yes	
Substation and transformer (Eq.#8)		%0			
Installation of substation and transformer (Eq.#9)	Yes	100%	Yes	Yes	
Civil works (Eq.#10)	Yes	85%	Yes	Yes	
Penstock (Eq.#11)		%0			
Installation of penstock (Eq.#12)	Yes	100%	Yes	Yes	
Canal (Eq.#13)	Yes	100%	Yes	Yes	
Tunnel (Eq.#14)	Yes	85%	Yes	Yes	
Miscellaneous (Eq.#15)					

B. Additional Results from Example GA Optimization

This appendix provides both brief descriptions and the graphical output of several GA optimization runs using the engineering cost example from Chapter 4. The hope is that the future user of such an optimization will get a better feeling for what the paramters do, and their relative importance in obtaining the global optimum. All values used here are referenced to those used in Table 4.1.

But first, a few comments:

The reader is well-advised to keep the following in mind at all times: *nothing effects the outcome of an optimization more than the choice and definition of the objective function itself.* This Thesis used an extremely simple, bivariate state optimization with known, highly restrictive constraints.

GA optimization using a vast array of variables increase exponentially in time, and thus a further considertion of applying any metaheuristic should be "how can I simplify my system?" Additionally, the use of internal loops may also increase computational time, and should be avoided when applying the GA.

B.1. Number of Generations - G

The number of generations (G) used is a good overall test of an applied objective function performance. Since each run of the algoritm should get closer to the optimum, obtaining a stabile solution after with increasing G can be a good indication of the optimum solution. Computational time for runs with an increasingly large G depends on the complexity of the objective function, and on the population size, and is highly situation dependent. For example, calculating with G = 1,000 for this example case required only a few seconds (roughly 300 generations per second), whereas including the entire NPV objective function resulted in a calculation time of around 15 minutes (roughly 1 generation per second). The following two examples indicate the results of increasing population size. Figures B.1 and B.2 show that the best state for this example (**the global optimum is exactly 87,566**) was found somewhere around 100 generations even when G = 1,000 and thus the rest of the computational effort went to waste. An idea of what the search space surface might look like (how bumpy) can often give clue to whether or not such an extensive searh needs to be undertaken. In this case, further optimizations will stick with G = 1,000 even though it is highly likely that the optimum value will be found earlier on.

B.2. Mutation Rate - M

As previously mentioned in Chapter 4, the priciple use of including the mutation rate (M) is to keep the algorithm out of local optima by adding a "freak" to the population which allows for a broader investigation of the search space. The effects of M = 0.9 can be seen in Figure B.3 where the average population values deviate far from the best solution. This means there is no "royal family" of states which keep their variable values generation after generation. At the same time, Figure B.4 shows that a certain amount of elitism occurs when M = 0.1, so the population averages tend to investigation of the search space more closely around the best state.

B.3. Selection Ratio - S

The selection rato, S plays a more minor role compared to G, M, and P. It is more useful as a fine-tuning parameter when the performance of a GA is important for real-time applications. It's main function can be seen as keeping the population searching close (high S) or further out (low S) from the best performing states. Additionally, it can be seen in Figures B.5 and B.6 that the tuning parameters M and S dictate the algorithm's ability to investigate the search space in a broader fashion. Note that in the application of the MATLAB algorithm used, the minimum selection ration is fixed at 0.5.

B.4. Population Size - P

The population size, P (see Figures B.7 and B.8) and G are by far the most useful tuning parameters when using the GA as it was applied in this work. Essentially, the user will find no great difference in applying P and G, since both result directly in the algorithm applying more states in order to find the optimum. Regarding computational time, the same applies here as well, increase P and the result is an exponential growth in run time. Thus, there is no trick in choosing a small number of generations, and then trying to optimize the problem quickly with a huge population (the author of course, did try this anyhow). One hint about P: it was found very useful to get a first glance at the search space by setting P to a high number for a small number of generations. The state variable outputs can serve to create preliminary map of the search space so that if constraints are at first unknown, the user is able to direct their attention to those regions which look the most promising.



Figure B.1.: G = 100, M = 0.2, S = 0.5, P = 10, Cost = 88,223.66



Figure B.2.: G = 1,000, M = 0.2, S = 0.5, P = 10, Cost = 87,653.04



Figure B.3.: G = 1,000, M = 0.9, S = 0.5, P = 10, Cost = 87,575.75



Figure B.4.: G = 1,000, M = 0.1, S = 0.5, P = 10, Cost = 87,589.68



Figure B.5.: G = 1,000, M = 0.2, S = 0.9, P = 10, Cost = 87,580.83



Figure B.6.: G = 1,000, M = 0.2, S = 0.5, P = 1,000, Cost = 87,619.27



Figure B.7.: G = 1,000, M = 0.2, S = 0.5, P = 10, Cost = 87,612.15



Figure B.8.: G = 1,000, M = 0.2, S = 0.5, P = 1,000, Cost = 87,567.63

C. MATLAB Code for GA Optimization

The first three pages of this appendix include the source code for the continuous GA itself.

The last five pages contain the code for applying the objective function for both the NPV optimization (function 1), and the example used in Chapter 4 for the engineering cost optimization (function 2).

Comments are provided throughout, but if you have questions, please feel free to contact me at **jtuhtan@gmail.com**.

And above all, have fun!

```
%
           Continuous Genetic Algorithm
Ŷ
% minimizes the objective function designated in ff
% Before beginning, set all the parameters in parts I, II, and III
% Haupt & Haupt
8 2003
÷
Ŷ
                       I Setup the GA
ff='testfunction';
                          % objective function
                  % number of optimization variables used in the test function
npar=2;
varhi=5; varlo=0;
                         % variable limits
Ŷ
                      II Stopping criteria
8
maxit=1000;
                       % max number of iterations
mincost=-9999999999;
                     % minimum cost
Ŷ
ŝ
                       III GA parameters
popsize=20;
                    % set population size
mutrate=0.4;
                    % set mutation rate
                    % fraction of population kept
selection=0.5;
                    % continuous parameter GA Nt=#variables
Nt=npar;
keep=floor(selection*popsize);% #population members that survive
nmut=ceil((popsize-1)*Nt*mutrate); % total number of mutations
M=ceil((popsize-keep)/2); % number of matings
%_
%
               Create the initial population
iga=0;
                  % generation counter initialized
par=(varhi-varlo)*rand(popsize,npar)+varlo; % random
cost=feval(ff,par);
                          % calculates population cost using ff
                           % min cost in element 1
[cost,ind]=sort(cost);
par=par(ind,:);
                       % sort continuous
minc(1)=min(cost);
                       % minc contains min of
meanc(1)=mean(cost);
                           % meanc contains mean of population
8_
Ŷ
               Iterate through generations
while iga<maxit
  iga=iga+1;
                           % increments generation counter
%_
Ŷ
                       Pair and mate
M=ceil((popsize-keep)/2);
                            % number of matings
prob=flipud([1:keep]'/sum([1:keep])); % weights chromosomes
odds=[0 cumsum(prob(1:keep))']; % probability distribution function
pick1=rand(1,M);
                                       % mate #1
```

```
pick2=rand(1,M);
                                        % mate #2
% ma and pa contain the indicies of the chromosomes that will mate
ic=1;
while ic<=M
  for id=2:keep+1
   if pick1(ic)<=odds(id) & pick1(ic)>odds(id-1)
     ma(ic)=id-1;
    end
    if pick2(ic)<=odds(id) & pick2(ic)>odds(id-1)
     pa(ic)=id-1;
    end
  end
  ic=ic+1;
end
°
           Performs mating using single point crossover
°
ix=1:2:keep;
                                    % index of mate #1
xp=ceil(rand(1,M)*Nt);
                                    % crossover point
r=rand(1,M);
                                    % mixing parameter
for ic=1:M
    xy=par(ma(ic),xp(ic))-par(pa(ic),xp(ic)); % ma and pa mate
    par(keep+ix(ic),:)=par(ma(ic),:);
                                               % 1st offspring
                                              % 2nd offspring
    par(keep+ix(ic)+1,:)=par(pa(ic),:);
   par(keep+ix(ic),xp(ic))=par(ma(ic),xp(ic))-r(ic).*xy; % 1st
    par(keep+ix(ic)+1,xp(ic))=par(pa(ic),xp(ic))+r(ic).*xy; % 2nd
        if xp(ic)<npar % crossover when last variable not selected
            par(keep+ix(ic),:)=[par(keep+ix(ic),1:xp(ic)) par(keep+ix(ic)+1,xp(ic)+1:
npar)];
           par(keep+ix(ic)+1,:)=[par(keep+ix(ic)+1,1:xp(ic)) par(keep+ix(ic),xp(ic)+1:
npar)];
        end % if
end
÷
                       Mutate the population
%
mrow=sort(ceil(rand(1,nmut)*(popsize-1))+1);
mcol=ceil(rand(1,nmut)*Nt);
for ii=1:nmut
   par(mrow(ii),mcol(ii))=(varhi-varlo)*rand+varlo; % mutation
end % ii
÷
% The new offspring and mutated chromosomes are evaluated
cost=feval(ff,par);
8
Ŷ
            Sort the costs and associated parameters
[cost, ind]=sort(cost);
```

par=par(ind,:);

```
8
°
            Do statistics for a single nonaveraging run
  minc(iga+1)=min(cost);
   meanc(iga+1)=mean(cost);
%_
                        Stopping criteria
°
if iga>maxit | cost(1)<mincost
   break
end
[iga cost(1)]
end %iga
%_
Ŷ
                       Displays the output
day=clock;
disp(datestr(datenum(day(1), day(2), day(3), day(4), day(5), day(6)), 0))
disp(['optimized function is ' ff])
format short g
disp(['popsize = ' num2str(popsize) ' mutrate = ' num2str(mutrate) ' # par = ' num2str ¥
(npar)])
disp(['#generations=' num2str(iga) ' best cost=' num2str(cost(1))])
disp(['best solution'])
disp([num2str(par(1,:))])
disp('continuous genetic algorithm')
figure(1)
iters=0:length(minc)-1;
plot(iters,minc,'-b',iters,meanc,'-r');
xlabel('No. of Generations', 'FontSize',12);
ylabel('Cost','FontSize',12);
text(0,minc(1), 'best', 'FontSize',12);text(1,minc(2), 'population average', 'FontSize',12)
```

```
% Test functions for optimization of a small hydropower scheme (1-10 MW)
% Set funnum to the function you want to use.
% Haupt & Haupt
% 2003
% file modified for Master's Thesis "Cost Optimization of Small Hydropower"
% by Jeffrey Tuhtan, Universitaet Stuttgart - WAREM
% September 2007
function f=testfunction(x)
funnum=1;
if funnum==1
                %F1
     x(:,1) is Qd - constrained by the Qmax term in front of the sin value, here it is m{arksymp}
14
        % using abs(sin()) converts the Q value to a 0-1 distribution
     \ x(:,2) is Hg - constrained by the 'varhi' and 'varlo' parameters in
        % the GAcontinuous.m file used to run the optimization
Qmax = 14.1
Qd = abs(Qmax*sin(x(:,1)))
Qd = 1.87
Sr = 45 %!!! side slope in degrees, use when considering canal in soil!!!
Lcs = 150 % canal length in meters
Hg = x(:,2)
 %%% These are the 6 costing equations, as functions of Qd and Hg only
 Ceng = 19984*(Qd.^0.54).*(Hg.^0.378)
 Cgen = 5033*(Qd.^0.9).*(Hg.^0.648)
 Ctur = 24110*(Qd.^0.91).*(Hg.^0.455)
 Csub = 163*(Qd.^{0.9}).*(Hg.^{0.9})
 Cpen = 20*[(1.5+0.01*Sr^1.5)*Qd.*Lcs].^0.9% use when considering canal...
 %Cpen = 0.3*(65157*(Qd.^0.769).*(Hg.^-0.385)+ 164127*(Qd.^0.334).*(Hg.^-0.167))
 Cciv = 40327*(Qd.^0.82).*(Hg.^0.574)
 %%% I is the total investment cost, taken as the sum of the 6 costing equations
 \$ The coefficients are all set to 1.00, but the user can play around with
    % the results by changing them to see what happens, it gets interesting!
 I = 1.00*Ceng+1.00*Cgen+1.00*Ctur+1.00*Csub+1.00*Cpen+Cciv
 %%% Efficiency caculation - this is a function of the Qd and Qmax over
    % the flow duration curve which is input by the user and used by the
    % program. The resulting efficiency is based on an efficiency curve
    % for a cross flow turbine
 % Alternately, the hidden value (%) of n may be used instead if the user wants
    % to define a fixed value of the efficiency - but then the calculations
    % will not reflect a decrease in annual energy production as a result of
    % changing efficiencies over the whole flow duration curve
 % Qmax is the maximum Q possible for a given flow duration curve
    % (user-defined)
```

```
\ n_other is the base electrical efficiency of the whole system, not depending on the
    % flowrate, such as the transmission system
%n = n_other.*(0.79 + 0.055.*((Qd − min(Q5-Qlow, Qd))./Qd) − 0.22.*(((Qd − min(Q5-Qlow, ビ
Qd))./Qd).^14))
%%% R, the energy calculation divides up the flow duration curve into 20 segments, each 5% m arepsilon
of one year or 18.25 days
    % if the user wishes to use another segmentation, then the time factor, tf
    % needs to be changed to reflect the number of days
 The min(A,B) function makes sure that the chosen Q,H combination by the
    % optimization algorithm results in a interval power calculation which is
    % not greater than the maximum theoretical power calculation. The max
    % theoretical calc is based upon the flow duration curve:
    \ "fee" is the price of sold energy in EUR/kWh,
    \ "tf" is the number of days per segment of the FDC,
    % "t_optday" is number of hours per day at which the plant is operational,
    % "rho" is the density of water in kg/m3,
    % "g" is the gravitational constant in m/s2,
    % "n" is input as per above,
    \ "0.001" is the conversion factor for power in Watts to kW,
    % "Qlow" is the low flow req. which is subtracted from the FDC curve in m/s3,
    % (note: the hydropower scheme is inherently diversionary)
    \ "FkWh" is the total income per segment not including Hg or Qd.
% In order to change the given flow duration curve, the user needs to split
    % the annual values into 20 equal segments, and manually input the values
    % into 'QXX = Q_user_inputXX' for its appropriate range
fee = 0.0967
tf = 18.25
t_optday = 24
rho = 1000
g = 9.81
Qlow = 0.4
Q5 = 14.1
Q10 = 6.1
Q15 = 4.5
Q20 = 3.8
Q25 = 3.2
030 = 2.8
Q35 = 2.5
Q40 = 2.3
Q45 = 2.0
Q50 = 1.8
Q55 = 1.7
Q60 = 1.6
Q65 = 1.5
```

Q70 = 1.4

96

Q75 = 1.4Q80 = 1.3085 = 1.2Q90 = 1.1095 = 1.0Q100 = 0.9 $n = \min(14.1 - 0 \log 0 d)$ $n_{other} = 1$ n5 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q5-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q5-**¥** Qlow, Qd))./Qd).^14))) n10 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q10-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q10-¥ Qlow, Qd))./Qd).^14))) Qlow, Qd))./Qd).^14))) n20 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q20-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q20-**K** Qlow, Qd))./Qd).^14))) n25 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q25-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q25-¥ Qlow, Qd))./Qd).^14))) n30 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q30-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q30-**¥** Qlow, Qd))./Qd).^14))) n35 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q35-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q35-4 Qlow, Qd))./Qd).^14))) n40 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q40-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q40-**k** Qlow, Qd))./Qd).^14))) n45 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q45-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q45-Qlow, Qd))./Qd).^14))) n50 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q50-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q50-K Qlow, Qd))./Qd).^14))) n55 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q55-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q55-∠ Qlow, Qd))./Qd).^14))) n60 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q60-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q60-**K** Qlow, Qd))./Qd).^14))) n65 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q65-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q65-Qlow, Qd))./Qd).^14))) n70 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q70-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q70-**k** Qlow, Qd))./Qd).^14))) n75 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q75-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q75-Qlow, Qd))./Qd).^14))) Qlow, Qd))./Qd).^14))) n85 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q85-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q85-¥ Qlow, Qd))./Qd).^14))) n90 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q90-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q90-K Qlow, Qd))./Qd).^14))) n95 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q95-Qlow, Qd))./Qd) - 3.*(((Qd - min(Q95-**k** Qlow, Qd))./Qd).^14))) n100 = max(0, n_other.*(0.79 - 0.055.*((Qd - min(Q100-Qlow, Qd))./Qd) - 3.*(((Qd - min ¥ (Q100-Qlow, Qd))./Qd).^14)))

```
%%%MW_ann = Annuual energy production, in MWh
  M5
            = min(Q5-Qlow, Qd).*Hg.*rho.*g.*n5.*0.000001.*tf.*t_optday
            = min(Q10-Qlow, Qd).*Hg.*rho.*g.*n10.*0.000001.*tf.*t_optday
  M10
            = min(Q15-Qlow, Qd).*Hg.*rho.*g.*n15.*0.000001.*tf.*t_optday
   M15
   M20
            = min(Q20-Qlow, Qd).*Hg.*rho.*g.*n20.*0.000001.*tf.*t_optday
   M25
             = min(Q25-Qlow, Qd).*Hg.*rho.*g.*n25.*0.000001.*tf.*t_optday
            = min(Q30-Qlow, Qd).*Hg.*rho.*g.*n30.*0.000001.*tf.*t_optday
   M30
            = min(Q35-Qlow, Qd).*Hg.*rho.*g.*n35.*0.000001.*tf.*t_optday
   M35
            = min(Q40-Qlow, Qd).*Hg.*rho.*g.*n40.*0.000001.*tf.*t_optday
   M40
            = min(Q45-Qlow, Qd).*Hg.*rho.*g.*n45.*0.000001.*tf.*t_optday
   M45
   M50
            = min(Q50-Qlow, Qd).*Hg.*rho.*g.*n50.*0.000001.*tf.*t_optday
            = min(Q55-Qlow, Qd).*Hg.*rho.*g.*n55.*0.000001.*tf.*t_optday
   M55
            = min(Q60-Qlow, Qd).*Hg.*rho.*g.*n60.*0.000001.*tf.*t_optday
   M60
            = min(Q65-Qlow, Qd).*Hg.*rho.*g.*n65.*0.000001.*tf.*t_optday
   M65
   M70
            = min(Q70-Qlow, Qd).*Hg.*rho.*g.*n70.*0.000001.*tf.*t_optday
            = min(Q75-Qlow, Qd).*Hg.*rho.*g.*n75.*0.000001.*tf.*t_optday
   M75
            = min(Q80-Qlow, Qd).*Hg.*rho.*g.*n80.*0.000001.*tf.*t_optday
   M80
   M85
            = min(Q85-Qlow, Qd).*Hg.*rho.*g.*n85.*0.000001.*tf.*t_optday
            = min(Q90-Qlow, Qd).*Hg.*rho.*g.*n90.*0.000001.*tf.*t_optday
   M90
   M95
             = min(Q95-Qlow, Qd).*Hg.*rho.*g.*n95.*0.000001.*tf.*t_optday
   M100 = min(Q100-Qlow, Qd).*Hg.*rho.*g.*n100.*0.000001.*tf.*t_optday
   MWh_ann = M5 + M10 + M15 + M20 + M25 + M30 + M35 + M40 + M45 + M50 + M55 + M60 + M65 + 🕊
M70 + M75 + M80 + M85 + M90 + M95 + M100
 %%%R = Annual revenues, in September 2007 EURO as the sum of each of the interval ∠
revenues
   R = MWh_ann.*fee.*1000
 %%% Objective function - NPV over 30 years
      (user must change the function 'f' manually to adjust the time span over which the <math>m k
NPV is to be calculated)

m \% sorry in not using a loop for (i=1 to n=30 years etc.), but the algorithm runs much 
m \varkappa
faster this way!
 r = 0.015
 i= 1+.045
 %%% The Net Present Value, including a 1% annual increase in the O&M
      $costs, the below function can also be used, as it does not include the
      %annual increase in O&M
 EUR_kWh = (1+30*r).*I./(1000.*MWh_ann.*30)
 f=I-(R-(r*I))/i-(R-(r*1.01*I))/i^2-(R-(r*1.02*I))/i^3-(R-(r*1.03*I))/i^4-(R-(r*1.04*I)) \varkappa
/i^5-(R-(r*1.05*I))/i^6-(R-(r*1.06*I))/i^7-(R-(r*1.07*I))/i^8-(R-(r*1.08*I))/i^9-(R-(r*1.≰
09*I))/i^10-(R-(r*1.10*I))/i^11-(R-(r*1.11*I))/i^12-(R-(r*1.12*I))/i^13-(R-(r*1.13*I)) ∠
/i^14-(R-(r*1.14*I))/i^15-(R-(r*1.15*I))/i^16-(R-(r*1.16*I))/i^17-(R-(r*1.17*I))/i^18-(R- 𝒴
(r*1.18*I))/i<sup>1</sup>9-(R-(r*1.19*I))/i<sup>2</sup>0-(R-(r*1.20*I))/i<sup>2</sup>1-(R-(r*1.21*I))/i<sup>2</sup>2-(R-(r*1.⊀
22*1))/i^{23-(R-(r*1.23*1))/i^{24-(R-(r*1.24*1))/i^{25-(R-(r*1.25*1))/i^{26-(R-(r*1.26*1))} \varkappa})
/i^27-(R-(r*1.27*I))/i^28-(R-(r*1.28*I))/i^29-(R-(r*1.29*I))/i^30
 %f=I-(R-(r*I))/i-(R-(r*I))/i^2-(R-(r*I))/i^3-(R-(r*I))/i^4-(R-(r*I))/i^5-(R-(r*I))/i^6- ∠
(R-(r*I))/i^7-(R-(r*I))/i^8-(R-(r*I))/i^9-(R-(r*I))/i^10-(R-(r*I))/i^11-(R-(r*I))/i^12-(R- 𝒴)/i^12-(R- 𝔅)/i^12-(R- 𝔅)/
```

(r*I))/i^13-(R-(r*I))/i^14-(R-(r*I))/i^15-(R-(r*I))/i^16-(R-(r*I))/i^17-(R-(r*I))/i^18-(R-𝒴))/i^18-(R-𝒴)/i^18-(R-𝔅)/i^18-(R-𝔅)/i^18-(R-𝔅)/i^18-(R-𝔅)/i^18-(R-𝔅)/i^18-(R-𝔅)/i^18-(R-𝔅)/i^18-(

```
 (r*I))/i^{19-(R-(r*I))/i^{20-(R-(r*I))/i^{21-(R-(r*I))/i^{22-(R-(r*I))/i^{23-(R-(r*I))/i^{24-(R- \varkappa (r*I))/i^{25-(R-(r*I))/i^{26-(R-(r*I))/i^{26-(R-(r*I))/i^{30})}} (r*I))/i^{29-(R-(r*I))/i^{30}}
```

elseif funnum==2

funnum==2 %Test function 2, engineering costs

Qd = x(:,1) Hg = x(:,2) f = 19984*(Qd.^0.54).*(Hg.^0.378)

end

D. Small Hydro Costing Approaches, Their Advantages and Disadvantages

Approach	Advantages	Disadvantages
Formula- Based	Fast and easy to apply. Numer- ous national studies using such approaches are available for com- parison. Can be updated easily using producer price indexes or locally-obtained information. Al- low for quick cost estimation.	Not sensitive to many local site conditions. Often grossly over/underestimate costs. No un- certainty in costing analysis is included.
Computer- Based	Can take into account ecologi- cal, hydrological, and economic conditions of a particular site. Detailed, site-specific information can be included in the cost esti- mation. Parameters can be varied to determine their influence for a given site with little inconvience. Allows for fast comparison of al- ternatives.	Requires information which may not be available at the prefeasi- bility stage. Time consuming and in many cases may not give a bet- ter result than a simple formula- based approach.
Optimized Uncertainty	Includes detailed, site-specific in- formation. Allows the user to create a prefeasibility design with economically-optimized de- sign parameters. Uncertainty analysis can provide ranges of costs and their corresponding probability of occurance for a wide range of scenarios.	Time consuming process requir- ing many assumptions and input data. The user must be famil- iar with computer-based meth- ods, basic optimization theory, and uncertainty analysis to make the approach useful. Costing equations used should be val- idated and adjusted to match local conditions for reliable re- sults. Due to the many assump- tions made, the end result may still vary greatly from the NPV optimum.
Detailed Itemized	Most likely method to produce accurate results. Small changes in the design can be taken into ac- count. Alternative scenarios can be compared with a high level of accuracy and detail. Site-specific conditions can be taken into ac- count directly without having to use factors, averaged values, or equations.	Does not provide any indication as to whether the chosen design is optimum. Requires a great deal of information often not found at the prefeasibility level. The most time consuming of all approaches, with high data requirements.

Bibliography

- Ibidun O. Adelekan and Afeikhena T. Jerome. Dynamics of household energy consumption in a traditional african city, ibadan. *Environmentalist*, 26:99–110, 2006.
- Francois Avellan. Hydropower rehabilitation, from large to mini-hydro plants. In Conference and Exhibition: Small and medium hydropower projects, Baden, Switzerland, 10-13 June 1997. Schweizerischer Wasserwirtschaftsberband.
- Christoph Böhringer, Klaus Conrad, and Andreas Löschel. Carbon taxes and joint implementation. *Environmental and Resource Economics*, 24:49–76, 2003.
- Christoph Böhringer and Thomas F. Rutherford. Carbon abatement and international spillovers: A decomposition of general equilibrium effects. *Environmental and Resource Economics*, 22:391–417, 2002.
- James Burke. The Pinball Effect. Litte, Brown & Company. London, 1996.
- Zelalem Hailu G. Christos. Optimization of Small Hydropower Sites for Rural Electrification. PhD thesis, Universität Dresden, 2002. Wasserbauliche Mittelungen Heft 22.
- CIA. CIA World Factbook 2007. Technical report, US CIA, Arlington, Virginia, 2007.
- K Conrad. Energy tax and competition in energy efficiency: The case of consumer durables. Environmental and Resource Economics, 15:159–177, 2000.
- Adam Curtis. Pandora's box, 1992. BBC Television Dist.
- Marco Dorigo and Thomas Stützle. Ant Colony Optimizaton. MIT Press, Cambridge, Massachusetts, 2004.
- Catallin Dragu, Tom Sells, and Ronnie J.M. Belmans. Small hydro power state of the art applications. In *International conference Power Generation and Sustainable Development* (AIM), Liege, Belgium, 2001. IEEE.
- E. M. Wilson. Assessment Methods for Small-hydro Projects. Technical report, International Energy Agency, April 2000.
- Dominique Egre and Joseph C. Milewski. The diversity of hydropower projects. *Energy Policy*, 30:1225–1230, 2002.

- Jonas Eliasson, Gudmundur Ludvigsson, Eduard Doujak, Agnar Olsen, and H.-B. Matthias. A proposal to exploit optimally the hydropower potential of fljotsdalur iceland july 7-9. Las Vegas, Nevada, 1999. ASCE. Proceedings of the Waterpower'99 Conference.
- For ex. Canadian Forex, 13 July 2007. For eign Exchange Services < http://www.chartflow.com/canadianforex/charts.asp >.
- James E. Francfort, Scott D. Matthews, B. N. Rinehart, and Jennifer L. Zane. Hydropower Evaluation Software (HES) User's Manual. U.S. Department of Energy, Idaho Operations Office, June 2002.
- Mitsuo Gen and Runwei Chen. *Genetic Algorithms and Engineering Design*. John Wiley and Sons, Inc. New York, 1997.
- J. Giesecke, W. Marx, R. Soyeaux, H. Bellebna, and S. Bellebna. Möglichkeiten der Umstrukturierung der Energieversorgung Baden Württenbergs unter besonderer Berücksichtigung der Stromversorgung, Teilgutachten - Nutzung der Wasserkraft. Technical report, Institut für Wasserbau, Universität Stuttgart, Stuttgart, Germany, 1987.
- J.L. Gordon. Black boxing hydro costs. In Invited presentation for World Bank staff at the hydropower cost seminar organized by Independent Project Analysis Inc., Washington, D.C., USA, 28 September 1989. World Bank.
- J.L. Gordon and A.C. Penman. Quick estimating techniques for small hydro potential. *Water* and Dam Construction, 31(10), 1979.
- GTZ. Laufwasserenergie Kleinwasserkraftanlagen, Statusbericht. Technical report, Deustche Gesellschaft für technische Zusammenarbeit, Frankfurt, 1980.
- John S. Gulliver and Roger E.A. Arndt. *Hydropower Engineering Handbook*. McGraw-Hill Educaton Inc., New York, 1991.
- Douglas G. Hall, Richard T. Hunt, Kelly S. Reeves, and Greg R. Carroll. Estimation of Economic Parameters of U.S. Hydropower Resources. Technical report, Idaho National Engineering and Environmental Laboratory INEEL/EXT-03-00662, Idaho Falls, ID, 2003.
- Adam Harvey. Micro-Hydro Design Manual. Intermediate Technology Publications, Ltd, Warwickshire, UK, 1993.
- Randy L. Haupt and Sue Ellen Haupt. *Practical Genetic Algorithms*. John Wiley & Sons, Inc., Hoboken, New Jersey, 2nd Edition edition, 2004.
- H.-B. Horlacher and M. Kaltschmitt. Potentiale, Kosten und Nutzungsgrenzen regenerativer Energiequellen zur Stromerzeugung in Deutschland. *Wasserwirtschaft*, 84:80–84, 1994.
- Egill B. Hreinsson and Jonas Eliasson. Optimal design and cost/benefit analysis of hydroelectric power systems by genetic algorithms. Brasilia, Brasil, May 19-23 2002. SEPOPE. Proceedings of the VII Symposium of Specialists in Electrical Operations and Expansion Planning.

- IEA. World Energy Outlook 2005. Technical report, International Energy Agency/OECD, Paris, France, 2005.
- Lars Jenssen, Kare Mauring, and Tor Gjermundsen. Economic Risk- and Sensitivity Analyses for Small Scale Hydropower Projects. Technical report, International Energy Agency, March 2000.
- Peter Klingeman. Streamflow Evaluations for Watershed Restoration Planning and Design, 19 August 2007. Analysis Techniques: Flow Duration Analysis < http: //www.water.oregaonstate.edu/streamflow/analysis/flow/>.
- Frans H. Koch. Hydropower-the politics of water and energy: Introduction and overview. Energy Policy, 30:1207–1213, 2002.
- Edward W. Merrow and Ralph F. Shangraw. Understanding the cost and schedules of world bank supported hydroelectric projects. Technical report, The World Bank Industry and Energy Department, PRE, Washington, DC, 1990.
- Erling Mork. Emergence of financial markets for electricity: a european perspective. *Energy Policy*, 29:7–15, 2001.
- NRC. RETScreen International, 26 June 2007. Natural Resources Canada < http://retscreen.net/ang/centre.php >.
- OECD. Statistics, policy and knowledge. In Keynote speech at the First World Forum on Key Indicators by OECD Chief Statistician Enrico Giovannini, Paris, France, 2005. OECD.
- Alan E. Pisarski and Niels DeTerra. American and european transportation responses to the 1973-74 oil embargo. *Transportation*, 4:291–312, 1975.
- Singiresu S. Rao. Engineering Optimization, Theory and Practice. John Wiley & Sons, Inc., New York, 1996.
- Steven S. Skiena. The Algorithm Design Manual. Springer Science+Business Media, Inc. New York, 1997.
- Thomas Staubli. Technische Innovation und Entwicklung im Bereich der Kleinturbinen. In Conference and Exhibition: Small and medium hydropower projects, Baden, Switzerland, 10-13 June 1997. Schweizerischer Wasserwirtschaftsberband.
- Rangarajan K. Sundaram. A First Course in Optimization Theory. Cambridge University Press, New York, 1996.
- Olli Tahvonen. International CO₂ Taxation and the Dynamics of Fossil Fuel Markets. *International Tax and Public Finance*, 2:261–278, 1995.
- US DOE. International Energy Outlook 2006. Technical report, US Dept of Energy, DOE/EIA-0484(2006), Washington, DC, 2006.

David H. Wolpert and William G. Macready. no free lunch theorems for optimization. *IEEE Transactions on Evolutionary Computation*, 1(1):67–82, 1997.