Optimizing Dam Siting in the Paru River in Brazil Using a Multi-Objective Approach

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OPTIMIZING DAM SITING IN THE PARU RIVER IN BRAZIL USING A MULTI-OBJECTIVE APPROACH

by

Henrique Paiva de Paula

A report submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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ABSTRACT

Optimizing Dam Siting in the Paru River in Brazil
Using a Multi-objective Approach

by

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How should a decision-maker choose which hydropower plant to build in a given river? Hydropower plant expansion is a task that involves several stakeholders, objectives and resources. It requires that decision-makers use not only experience and previous knowledge to come up with their final decision, but also the use of tools to help them to decide, as well as to support their choices. The present project developed a computation model to optimize the choice of hydropower plants that can be built within a given river, considering three different objectives - energy generation, flooded surface area and river connectivity. The input data required to solve the mathematical problem was previously obtained from other sources. The mathematical model developed is classified as multi-objective linear integer problem and was solved using a the branch-and-cut method implemented by a commercial linear solver. In order to deal with the multi-objective approach, the constraint method was used. The main outputs of the model are the trade-off curves between objectives and the Pareto sets, which can be used by decision-makers to better understand the existing trade-offs imposed by the problem. The model was tested using the energy generated,
the flooded surface area and distance from mouth of each project studied in the hydropower inventory studies developed for the Paru River, a tributary of the left margin of the Amazon River, located in the state of Pará, Brazil.

The results showed that there is a trade-off between energy generation and surface flooded area, as well as energy generation and river connectivity, both a direct consequence of the fact that more projects will be necessary to meet energy requirements. Connectivity and surface flooded area, however, are not competing, since an improvement in both metrics will result in habitat quality improvement.

The results were also compared to the ones obtained in the inventory studies, showing that different methods (ranking methods x multi-objective optimization models) can yield different policies. The main reasons for these differences are related to the solution method used, since each one will take into account different management goals and performance metrics.
ACKNOWLEDGMENTS

"Feliz aquele que transfere o que sabe e aprende o que ensina"

Cora Coralina

Being an good example is the most efficient way of inspiring someone. For that, I have a lot to thank my parents and my sister: they keep showing me that dedication and hard work are the main keys to a happy and successful life. Thank you Mom, Dad and Lê.

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LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

\( B \) Total energy generated by the hydropower plants.

\( FR_{i,j} \) Decision to choose or not connected stream segments between non-adjacent plants \( i \) and \( j \).

\( HPP_i \) Decision to built or not Hydropower Plant \( i \).

\( I_{fa} \) total area flooded by reservoirs.

\( I_{sc} \) Maximum stream length unimpaired by dams.

\( N_{barriers} \) Number of barriers between sites \( i \) and \( j \).

\( a_i \) Coefficient representing the surface area flooded reservoir of plant \( i \).

\( b_{i,j,k} \) Coefficient matrix representing all possible combinations of connected stream segments.

\( d_{i,j} \) Coefficient matrix that represents the distance between plants.

\( e_i \) Coefficient representing the energy generated by plant \( i \).

\( i, j, k \) indexes for each plant/project.

\( op_{i,k} \) Coefficient matrix representing which projects \( i \) are overlapped by project \( k \).

\( sp_{i,j} \) Coefficient matrix representing which projects \( i \) exist for each site \( j \).

\textbf{ANEEL} Brazilian Electrical Energy Regulator.
GAMS  General Algebraic Moddeling System.

MOIP  Multi-Objective Integer Problem.

MOOM  Multi-Objective Optimization Model.

MOOP  Multi-Objective Optimization Problem.

RHS  Right-hand side.
CHAPTER 1
INTRODUCTION

1.1 Context

Hydropower still represents an important solution for the electricity generation expansion in the world. With the growing demand for water and energy, a concurrent rise in the need for water storage and hydropower projects may be expected, particularly in developing countries (Brown et al., 2008). An adequate plan to expand hydropower capacity in a given river or watershed requires the correct estimate of the benefits and the impacts generated by hydropower plants. Thus, optimization models that indicate the best alternative to be implemented can be an important tool for energy planners involved in hydropower expansion.

The elaboration of an inventory study, for example, requires the formulation of different alternatives, or policies, which will be further compared to each other using metrics previously defined in regulations. The hydropower plants that will be part of an alternative are usually chosen based on experience, preferences and even expectations of the team responsible for the task.

Furthermore, when analyzing hydropower expansion problems, decision-makers are often put in difficult situations. Energetic, economical, political, social and environmental issues are often part of the decision-making process, which is normally a complex task where different interests must be negotiated in order to reach a solution.

Thus, a Multi-Objective Optimization Model (MOOM) may be useful by generating a set of optimal solutions to the dam siting problem that can help technical teams to formulate different alternatives. In addition, by offering a visual solution to the problem - the Pareto front - it may also allow decision-makers to have an easier understanding of the trade-offs involved in each policy.
1.2 Research objectives

This project aims to develop a multi-objective approach to solve a hydropower plant expansion problem, also known as dam siting, using different metrics to measure the environmental impacts and the economic benefits, all based on field data, previous simulation results and geospatial analysis.

It is also part of the project to test the model using data obtained from an inventory study. The model performance and results obtained from the model developed in this project will be analyzed and compared to the results obtained in the inventory studies.

The first part of the model, developed using Excel/VBA®, deals with the input data formatting, so they can be read from another program. The second part, developed using General Algebraic Modeling System (GAMS), solves the optimization problem using input data previously obtained from the Excel/VBA® script outputs.

Finally, like in most mathematical programming problems, this project also intends to improve the understanding of the system under analysis, in order to guide the model users to identify and recommend better policies.

1.3 Scope and organization

This report consists of 6 chapters. Chapter 2 presents a literature review, previous studies and work developed in particular areas of energy planning, ecological impacts caused by hydropower plants and operations research. Chapter 3 discusses the model development. Chapter 4 describes the study case. Chapter 5 presents the model results and analysis, as well as a sensitivity analysis and a comparison with the inventory study results. Finally, Chapter 6 summarizes the results and presents the limitations, conclusions and future work.
CHAPTER 2
LITERATURE REVIEW

The development of a Multi-Objective Optimization Problem (MOOP) requires several different sources of scientific background information, due to the fact that we can have a variety of subjects related to each objective. The literature review in this report is organized by subject area.

2.1 Energy expansion planning

According to Chu and Majumdar (2012), energy consumption is expected to increase globally to 36,250 TW h in 2035. This represents an increase of approximately 81% when compared with the 2009 scenario. Although fossil fuels are likely to be the responsible for most part of this increase, "hydroelectricity can be an important contributor to meeting future energy needs, notably in developing countries where two billion people have no electricity supply" (Klimpt et al., 2002). Furthermore, dams can also provide other services, as "they can prevent or mitigate floods and droughts, they may provide irrigation, supply water for domestic, municipal and industrial use, as well as improve conditions for navigation, fishing, tourism or leisure activities" (Egré and Milewski, 2002). However, these improvements are controversial, since there may also be negative impacts regarding the same uses.

Hydropower is considered by a variety of authors a clean source of energy, even though recent findings show that hydropower plant reservoirs can emit CO₂ due to rotting vegetation and carbon inflows from the catchment (World Commission on Dams, 2000). As reported in IPCC (2007), "in the presence of climate change, dams may play an increasingly important role in protecting water resources. For example, areas affected by severe drought and those subject to high vulnerability from flooding
due to heavy precipitation will likely increase in coming decades" and dams can help ameliorate their negative consequences (Brown et al., 2008).

Considering these aspects, it is important to keep in mind that instead of trying to prevent new dams from being planned and build, the goal should be looking for the best portfolio of hydropower plants that can meet the energy demands while still accounting for other objectives. In fact, this is where an important alliance can be formed. Ecologists and engineers are meant to work together, if the goal is to pursue the path of sustainability. According to Mitsch and Jørgensen (2003), 'ecology as a science is not routinely integrated in engineering curricula, even in environmental engineering programs. Engineers are missing the one science that could help them the most in environmental matters. Likewise, environmental scientists and managers are missing a crucial need in their profession - problem solving'. Hence, models that involve both ecology and development issues should try to deal with the inherent conflicting objectives in an objective and multidisciplinary way.

2.2 Hydropower plants

Although hydroelectricity is still considered an important source of energy in the present and in the future, it still faces strong opposition. "Public expectations regarding the environmental and social performance of hydropower tend to increase over time" (Klimpt et al., 2002). Thus, it is important that hydropower projects consider not only the energy benefits, but also the social and environmental costs associated. In fact, not only hydropower, but all the other competing energy sources must also consider all their impacts. Otherwise, as noted by Klimpt et al. (2002), 'hydropower development will be confronted with an uneven playing field. Unbalanced regulations that favor fossil fuel power generation would increase air pollution and greenhouse gas emissions'.
2.2.1 Social and environmental costs

The social and environmental challenges posed by a hydropower plant project can be of different nature and magnitudes, depending on the project being developed. Biophysical impacts may be seen in water retention time, changes in natural flow regime, biodiversity distance of river left dry downstream of the dam, site stability and reservoir surface area, as well as in water quality, sediment transport, passage for migratory species, stranding of species and aquatic and riparian community composition. Social impacts may include downstream riparian population, downstream irrigation, political boundaries, existing dams, agreements and institutions, political participation, historical stability/tensions and displacement of traditional populations (Brown et al., 2008) (Hirsch et al., 2014).

Among these impacts, reservoir surface area is a relevant one. Not only it is widely use by energy planners as proxy to energy density efficiency calculations (e.g. energy/flooded area ratio), it is also related to important consequences of hydropower development. For instance, surface flooded area can be related to greenhouse gas emissions from reservoirs. In addition, population displacement is also a consequence of inundating a certain area to build a reservoir (World Comission on Dams, 2000).

Stream connectivity is another representative metric not only for ecological but also for negative economical impacts. According to Petts (2009), changes in "river hydrodynamics affect aquatic organisms in various ways". Among the affected organisms, fishes have considerable importance, as they can be source of food for riverine communities, as well as the basis of their economy (O’Hanley, 2011) (World Comission on Dams, 2000). Whether potamodrous (fishes that make migrate within freshwater) or diadromous (fishes that make migrate between marine and freshwate-ments) fishes, the construction of an artificial barrier will, in most cases, reduce the abundance and diversity of native species (O’Hanley, 2011).

In fact, to consider connectivity - or river length - as a significant and repre-
sentative metric for fish habitat is an assumption in this project, since this may not be
the case for all lotic ecosystems. As pointed out by Elmore et al. (2015), streamflows
and stream temperature may play an important role, depending on the ecosystem
and on the fish species under analysis. Nevertheless, measuring the consequences of
lost in connectivity is important to assess ecological and negative economical impacts
of installing new hydropower plants.

2.2.2 Energy benefits

The direct benefit obtained from a hydropower plant is energy, which is ob-
tained based on a simple process, using the kinetic energy provided by falling water.
This benefit can be translated into a monetary value, but it is not mandatory.

To obtain the energy that can be generated by a given hydropower plant, the
powerplant discharge, the hydraulic head and the efficiency of the turbine-generator
group are the main required input data (Harou et al., 2009). Head losses along
penstocks and the tailrace water elevation may also play a significant role in the
estimation of the energy that will be produced. A simulation model is usually used
to perform these calculations.

2.3 Multi-Objective Optimization

The development of hydropower plants is fundamentally a problem with several
objectives, since the goals of a given plant can go from energy generation to flood
control, going through irrigation and water supply, for example. These objectives
can be, and usually are, conflicting. Furthermore, the negative impacts related to
a new dam also affect a large number of stakeholders and natural environments.
Many authors highlight the importance of dealing with hydropower planning from a
multi-objective perspective. As pointed by Kareiva (2012), 'environmentalists and
development agencies alike commonly suffer from a certain myopia, whereby they
tend to come at problems from only one angle and one objective*. By using a multi-objective approach, it is possible to obtain a set of solutions that may also be used by decision-makers to identify and select objectives to better meet additional, unmodeled criteria (e.g., political factors) (Haight et al., 2000).

In order to deal with multi-objective problems, solution methods "can be classified as a priori, interactive, and a posteriori, according to the decision stage in which the decision maker expresses his/her preferences" (Mavrotas, 2009). Among these options, the a posteriori (or generation) methods can be more useful in decision processes involving different stakeholders, since they allow the decision maker to previously understand all the trade-offs involved in the problem (i.e. Pareto front).

Pareto efficiency is an economical concept that can be applied in resource allocation problems. A Pareto front can be defined as a set of nondominated solutions, or solutions that cannot be improved for one objective without a simultaneous detriment to at least one of the other objectives in the problem (Hwang and Masud, 1979).

Two of the most widely used generation methods are the weighting method and the ε-constraint method. Both methods can produce a Pareto front. However, the ε-constraint method has several advantages over the weighting method:

1. Uniform changes in the weight values do not necessarily represent a uniform coverage in the solution space;

2. The weighting method can only identify convex trade-off surfaces;

3. "The weighting method cannot produce unsupported efficient solutions in multi-objective integer and mixed integer programming problems, while the ε-constraint method does not suffer from this pitfall" (Mavrotas, 2009);

4. The weights may not have a physical meaning, which may be confusing for decision makers;
5. The \( \varepsilon \)-constraint method allows to control the number of generated efficient solutions by adjusting the number of desired points for the Pareto front.

The \( \varepsilon \)-constraint method solves the MOOP in different steps. First, each objective function is solved individually, ignoring the other ones, yielding the extreme points for each selected goal. Next, the model is solved for one of the objectives while the other ones are treated as constraints with right-hand side (RHS) target values which are varied parametrically throughout the solving process. As a result, a set of Pareto optimum solutions is obtained. An important aspect to the implementation of the \( \varepsilon \)-constraint method is to make sure that the range of the objective functions (extreme points) are defined within the feasible region of the problem.

Thus, by using the \( \varepsilon \)-constrained generation method, the decision maker can choose one of the policies that may be part of the Pareto front. However, MOOP does not recommend any particular noninferior solution over another (Kuby et al., 2005). For this, the decision maker must use, for example, higher level information, personal preferences or other additional criteria.
CHAPTER 3
MODEL DEVELOPMENT AND IMPLEMENTATION

According to Alminagorta et al. (2015), 'systems modeling offers a general framework to identify and connect interdependent system components, study interactions, and recommend management strategies to better achieve management goals'. This framework consists in 6 phases.

Phase 1 consists in describing the management goal(s). Phase 2 consists in identifying metrics which can be used to quantify how close (or far) from the goals identified in the previous phase we are. In Phase 3, the possible actions for the system’s managers must be identified. Phase 4 consists in mathematically relate actions and metrics and Phase 5, in identifying (also mathematically) the constraints that bound manager’s actions. Finally, Phase 6 is the implementation and search for the solution of the optimization model.

The development of this project followed, whenever possible, this framework. Each phase is described in the following sections.

3.1 Management Goals

The dam siting problem can be stated as: from a given set of hydropower plant projects, which ones should be built in a river in order to maximize benefits and minimize impacts? In this case, how to maximize energy production and to minimize flooded area and river fragmentation.

An important aspect of the management goals developed in this project is idea of multiple projects at a site. Thus, the problem is not only about choosing which projects to built along a river, but also which project to choose among a set of projects for the same site.
3.2 Performance Metrics

The literature review identified several key metrics that can be used to measure the impacts of building a dam. Based on the significance and the complexity of calculating their values, two indices were chosen: surface area flooded by the hydropower plant reservoir (in km$^2$) and pairs of river segment lengths unimpaired by dams (in km). The former can be calculated using geospatial analysis tools after developing the project of each plant, while the latter can be calculated as the sum of river segments bounded by dams (based on their location along the river). Each project developed holds several information that allows the geospatial analysis tools to calculate surface flooded area, such as dam height and area-stage-storage curves.

When evaluating river fragmentation, two different fishes’ life histories can be considered: *potadromous* or *diadromous*. Each one would require a different way of calculating this metric. The model developed in this project will be tested in a study case where the main stream discharges in another freshwater river and not into the ocean. As consequence, the *potadromous* application will be considered. In this case, the main concern is the ability of fishes to migrate regularly between patches (Cote et al., 2009).

The metric to be used for measuring the benefit is energy generated by each plant (in MW). Although a monetary equivalent for energy could also be used, this choice would lead to a time variable metric. In addition, it would also depend on market aspects and on how energy contracts and spot market purchases are made (Harou et al., 2009). Since the purpose of the model is to be used in different situations whenever and wherever necessary, energy was chosen as the performance metric. Besides, in order to have only one value of energy generation for each plant, they are considered, in this study, fixed head hydropower plants.
3.3 Management Actions

The main goal of the project is to help decide whether or not build a given hydropower plant, considering all the other projects and the associated benefits and impacts. Thus, a **Yes** or **No** type of decision is the most suited one, which can be accomplished by using binary decision variables for each project. A value of **1** indicates that the project should be built, while a **0** indicates that it should not.

3.4 Relation Between Actions and Metrics

Each one of the goals established in Phase 1 can be described as a relation between the management actions (build or not build) and the performance metrics (impacts and benefits). Mathematically, these relations can be described by equations 1 through 3:

\[ I_{fa} = \sum_i a_i \times HPP_i \]  
\[ B = \sum_i e_i \times HPP_i \]  
\[ I_{sc} = \sum_{i,j} d_{i,j} \times FR_{i,j} \]

Objective function in equation 1 is the total area flooded by reservoirs, \( I_{fa} \). In equation 2, the objective function is the total energy generated by the hydropower plants, \( B \). Equation 3 defines the objective function that represents the maximum stream length unimpaired by dams, \( I_{sc} \).

In equations 1 and 2, \( HPP_i \) are binary variables associated with the decisions to build or not build plant \( i \). Coefficients \( a_i \) in equation 1 represent the surface area flooded by reservoir of plant \( i \) and coefficients \( e_i \) in equation 2 represent the energy generated by plant \( i \). In equation 3, \( FR_{i,j} \) are binary variables associated with free reaches, or connected stream segments between non-adjacent plants \( i \) and
Coefficients $d_{i,j}$ represent the distance between plants $i$ and $j$. The units for each one of the coefficients are not pre-defined, but must be consistent.

### 3.5 Constraints

Equations 4 through 8 mathematically define the constraints present in the model.

\[
\sum_i sp_{i,j} \times HPP_i = 1, \forall j \tag{4}
\]

\[
\sum_i op_{i,k} \times HPP_i = 1, \forall k \tag{5}
\]

\[
FR_{i,j} \leq \sum_k \frac{(1 - HPP_k)}{N_{barriers_{i,j}}} \times b_{i,j,k} \tag{6}
\]

\[
\sum_{i,j} FR_{i,j} \leq 1 \tag{7}
\]

\[
HPP_i, FR_{i,j} \in 0, 1 \tag{8}
\]

Equation 4 states that if there is more than one project in a given site, only one can be built, and coefficients $sp_{i,j}$ represent which projects $i$ can be built on each site $j$. Equation 5 does not allow projects to be simultaneously built if they interfere with another one, and coefficients $op_{i,k}$ represent which projects $i$ can interfere with project $k$. Equation 6 defines a free reach, which is any pair of stream segment unimpaired by dams, regardless of its length. In this equation, $N_{barriers}$ represents the number of barriers between plants $i$ and $j$ and $b_{i,j,k}$ represents all possible combinations of connected stream segments. Equation 7 forces the model to only choose one free reach. Finally, equation 8 defines $HPP_i$ and $FR_{i,j}$ as binary variables.
3.6 Model Implementation

The mathematical formulation for the complete problem can be described by the following model:

Minimize \( I_{fa} = \sum_i a_i \times HPP_i \)  \hspace{1cm} (9)

Subject to \( B = \sum_i e_i \times HPP_i \)  \hspace{1cm} (10)

\( I_{sc} = \sum_{i,j} d_{i,j} \times FR_{i,j} \)  \hspace{1cm} (11)

\( \sum_i sp_{i,j} \times HPP_i = 1, \forall j \)  \hspace{1cm} (12)

\( \sum_i op_{i,k} \times HPP_i = 1, \forall k \)  \hspace{1cm} (13)

\( \sum_k FR_{i,j} \leq \frac{-HPP_k}{\text{Nbarriers}_{i,j}} \times b_{i,j,k} \)  \hspace{1cm} (14)

\( \sum i,j FR_{i,j} \leq 1 \)  \hspace{1cm} (15)

\( HPP_i, FR_{i,j} \in 0, 1 \)  \hspace{1cm} (16)

The computation model was developed in two different environments. In the first one, a set of Excel/VBA® scripts were used to deal with the input data formatting. The second part, developed using GAMS, solves the optimization problem using CPLEX solver, which is part of GAMS basic installation package.

3.6.1 Input data setup

The input data for the model consists of a table with \( n \) rows and 7 columns, where \( n \) is the number of projects available for the system under analysis. The columns refer to site name, project name (there can be more than one per site), total area flooded by each reservoir, total energy generated by each project, the distance of each project in relation to the river mouth, and the upstream and downstream
Based on this table, the scripts developed in Excel/VBA® format a set of worksheets that are read by GAMS and used by the model as coefficients in the objective functions and constraints. The model is then solved, yielding a set of objective function values that can later be analyzed by the decision-maker.

The Excel/VBA® codes developed in this project are reproduced in Appendix B.

3.6.2 Mathematical programming setup

Having the mathematical model defined in phases 4 and 5 (equations 1 to 8), the next step is to obtain solutions to the problem. As discussed in Chapter 2, the constraint method was chosen to solve the multi-objective problem. Furthermore, all the objective functions and constraints are linear, whereas the decision variables are binary. Thus, the model can be defined as a linear Multi-Objective Integer Problem (MOIP), which can be solved by GAMS/CPLEX.

The code implemented in GAMS solves the problem in two steps. The first one solves the optimization problem for each objective function, ignoring the other ones, which yields the extreme points. The second one solves the problem considering one objective function as the goal and the other two as constraints. In this step, several right-hand side values for the objectives treated as constraints are used.

To obtain a set of objective function values large enough to be properly analyzed, the model can be run separately treating each of three objectives as the main goal.

The GAMS code developed for this project is reproduced in Appendix C.

Figure 1 illustrates the steps required to run the model and further analyze the results.
Figure 1: Model flowchart
CHAPTER 4

STUDY CASE ANALYSIS AND MODEL RUN

To examine its performance and analyze its effectiveness, the model was tested using data available in the first review of the Paru River Watershed Hydropower Inventory Studies (Omega Energia Renovavel and Grupo Energia Consult, 2012).

4.1 Study region

The Paru River, located in the state of Para, Brazil, is a tributary of the left margin of the Amazon River. With approximately 785 km of extension, it still preserves its natural course undammed, mainly due to its remote location. The long-term mean discharge 100 km upstream from its mouth is around $677 \, m^3/s$ (measured from 1931 until 2010) and the elevation difference is approximately 450 km from head to mouth. The Paru River shows a different hydrologic behaviour when compared to most of the rivers in Brazil used for hydropower generation. Its historical wet period goes from June until August, while the other rivers where most hydropower plants are located in the country have a wet period going from November until March. Therefore, it may be interesting to explore this hydrological behaviour for power generation purposes. At the same time, the river is located in a very remote and unexplored area, where several national and state parks, as well as natural reserves, are located. This poses a challenge for its hydropower development, since many social and environmental aspects will impact the choice of the best alternative.

As mentioned in Chapter 2, the impact of connectivity in fish population will be used as one metric in the model. The Paru River presents high diversity of species. Omega Energia Renovavel and Grupo Energia Consult (2012) identified, in the inventory studies, approximately 95 different species. Ferreira (1993) conducted
a species assessment in the region close to the Paru River watershed, identifying 342 species.

Both studies documented that characiform fishes have relevant migratory patterns in the region. Omega Energia Renovavel and Grupo Energia Consult (2012) identified *Piaractus brachypomus* and *Prochilodus spp.* as potamodrous species with relevant migratory behaviour and commercial value.

Figure 2 shows the location of the Paru River Watershed. The Paru River profile is illustrated in Figure 3. From this figure, it is possible to divide the main stream into three segments:

**Downstream:** flat region influenced by the Amazon River backwater.

**Midstream:** steeper regions in the beginning and at the end of this segment, with flat surface in between.

**Upstream:** flat region close to headwaters.
Figure 2: Paru River watershed. Source: Author.
4.2 Inventory studies

A hydropower inventory study is one of the first steps in hydropower planning not only in Brazil, but in other countries as well. Its primary goal is to optimize the choice of the available alternatives of river partitioning by analyzing the costs, the benefits and the social and environmental impacts of each alternative. An alternative can comprise one or more hydropower plants. Through field data collection and analysis, literature reviews, simulations, budgets and economical analysis, they aim to obtain the best cost/benefit alternative and the minimal social and environmental impacts.

In Brazil, inventory studies can be prepared by any citizen or company interested in developing hydropower plants, upon authorization from the Brazilian Electrical Energy Regulator (ANEEL). These studies are analyzed by the same Regulator and, after approval, are made available to the general public. Anyone has access to the studies and can start elaborating the feasibility studies or basic designs of each hydropower plant, which is the next step in the hydropower expansion process.

The Paru River Inventory Study, selected to be the study case in this project, was elaborated during 31 months, from 2009 to 2012, and approved in 2014.
4.3 Input data from the inventory studies

According to the mathematical model described in Chapter 3, the following data are necessary in the model:

- Name of each site;
- Name of each plant (also called projects);
- Energy generated by each hydropower plant;
- Surface area flooded by the reservoir of each hydropower plant;
- Distance of each hydropower plant from the river mouth;
- Upstream elevation of each hydropower plant;
- Downstream elevation of each hydropower plant.

The elaboration of any inventory study also requires these data. Thus, all necessary data for this project can be obtained directly from these studies.

In this study case there are 25 different sites and 34 different projects. There are sites with more than one possible project. Table 1 contains the sites, projects and their technical characteristics used as input data in this project.
Table 1: Input data for the model

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<thead>
<tr>
<th>Site name</th>
<th>Project name</th>
<th>Surface flooded area [km²]</th>
<th>Energy generated [MW]</th>
<th>Distance from mouth [km]</th>
<th>Upstream elevation [m]</th>
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<td>304.36</td>
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</table>
4.4 Model run

As explained in Chapter 3, the model first solves for the extreme points the first objective - area, uses these points to solve the problem for the second objective - energy - having the first objective treated as a constraint. Next, the model uses the extreme points for this second step as right-hand side values to constraint the second objective while solving for the third one - segment. In order to obtain a meaningful set of objective function values, several right-hand side levels are required for each objective. This is achieved by using nested loops, as illustrated in Figure 1.

The model, solved as explained above, resulted in the following model statistics:

- For the extreme points:
  - 1,220 single equations
  - 1,194 single variables

- For the intermediate points:
  - 1,222 single equations
  - 1,190 discrete variables
  - 1,194 single variables

A licensed version of GAMS was used to run the model. To solve the model CPLEX solver was used, which is part of GAMS basic installation package.

In terms of computation effort, it took 10 min and 50 s to solve the problem, considering 20 right-hand side levels and 20 steps per objective. All results were obtained using a Lenovo laptop computer equipped with an Intel® Core™ i5 processor with 2.40 GHz and 8 MB of RAM.
5.1 Model results

The first results obtained from the model run are the extreme points for each objective function. For area, the minimum value is zero, which means that no projects are selected. The extreme point for maximizing energy, considering all physical constraints, yields 1065.95 MW, distributed in 13 hydropower plants. These plants would flood total surface area of 653.20 km$^2$, which is the maximum flooded surface area. Lastly, maximizing stream connectivity results in a maximum connected stream length of 195.98 km, which is the largest possible segment between the first and the last site. Although the river length is larger than this value, in the model the maximum stream length is considered as the distance between the most upstream and the most downstream sites.

In order to have an initial visual idea of the trade-offs between the objectives, a 3D trade-off surface was generated. Another 3D plot was also generated using colors to represent connected segment length (where blue represents a healthy, functioning river while red represents a highly segmented stream). Figures 4 and 5 illustrate these plots, respectively. To obtain the plots, DiscoveryDV, a multi-dimensional data visualization software, was used.
Figure 4: 3D plot considering all three objectives simultaneously
Figure 5: 3D plot using colors to represent connected stream segment
5.2 Discussion of results

The multi-objective approach used in this project is well suited to perform trade-off analysis among the different objectives. This type of analysis will be the main focus in this Chapter.

Figure 4 simultaneously shows the trade-offs among the three objectives. This chart holds all the necessary information that the model can possibly yield to decision-makers. Analyzing this plot, it can be seen that area and energy are conflicting objectives, since an increase in energy generation will increase the surface flooded area by adding more plants or by choosing plants with larger flooded areas. In the same way, energy generation and river connectivity are also competing. Maximizing energy causes a decrease in the length of connected stream segments. Finally, comparing area and river connectivity, it is possible to verify that the smaller the flooded area, the longer the segments. This behaviour is also expected, since less flooded area is a direct result of not choosing projects to build, which leads to longer connected stream segments.

The same information can be seen in a 2D plot in which the third dimension is shown in a different color palette, as illustrated in Figure 5. The color bar scale indicates where the largest connected stream segments are. This information, associated with the 2D relationship between area and energy, can be a useful tool for decision-makers when analyzing the trade-offs between all objectives at once. It may also be a good way to communicate the model results and eventual decisions in a clear and easy way for a non-technical audience.

An important observation is that the area flooded by a given hydropower plant is not necessarily directly correlated to the amount of energy it will generate. In other words, while it may seem intuitive, it does not always mean that a more energy producing plant will have a larger lake. The relationship between reservoir
area and energy is not always a direct correlation, it depends on other variables, such as dam height. This point must be observed when analyzing this type of problem.

Furthermore, it is also possible to analyze the individual solution obtained from the model. Each point in the trade-off curves represents a different policy, or a different set of objective function values. These values are dependent on the decision variable values (i.e. whether or not to build hydropower plant \( HPP_i \)). For example, the decision-maker may decide for a policy that tries to generates more energy without flooding a large portion of land and keeping a reasonably long stream segment unimpaired. Thus, he chooses the point marked in Figure 6, where the total flooded surface area is 111.12 km\(^2\), the total energy generated is 782 MW and the maximum connected stream segment equals 57.37 km. This policy yields the recommendations illustrated in Table 2.

**Figure 6:** Policy example in the trade-off curve
### Table 2: Policy example for the study case

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<thead>
<tr>
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<th>Build?</th>
<th>Project name</th>
<th>Build?</th>
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It is important to notice that modelling more right-hand side objective values will produce a more dense Pareto front.

Another way to express the obtained results is by using parallel coordinate plots. They allow the accommodation of larger dimensions by using axes in parallel (Rosenberg, 2012). In parallel plots, each point is represented by a polyline with vertices on the parallel axes. Thus, a point in 4 will be represented by a line in an equivalent parallel plot. The position of the polyline on each axis corresponds to the coordinate of the point.

Parallel plots also provide a good way to visualize the correlations between variables. According to Li et al. (2008), "positive correlation leads to a pattern with parallel line segments; negative correlation gives a diabolo-like pattern, with line segments intersecting in one point". Intermediate correlation can be estimated by judging how close these patterns approximates with available data, and the strength of correlation will be given by how close this approximation is.
The parallel plots generated in this project used a "minmax" scale, which means that, for continuous variables, the minimum value is zero, and the maximum is one (dividing the variable value by the its maximum). For binary variables, it makes no difference to adopt such scaling.

In Figure 7, it is possible to notice a positive correlation between objectives Area and Energy. The correlation is not very strong, since lines are not all parallel to each other, but it is present. Energy and Segment Length, on the other hand, show a weak negative correlation, since a few lines cross each other in a spread region in between their axes.

To assess the correlation between Area and Segment Length, Figure 8 was generated, showing axes in a different order. Here, it is also possible to observe a weak negative correlation between Area and Segment.
5.3 Sensitivity Analysis

Sensitivity analysis can be defined as the analysis of changes of an optimal solution caused by change of data in the model. These changes can happen in the objectives function coefficients or in the right-hand side constraint values. This analysis can be performed in GAMS by assessing the marginal values in the equation solution report and in the variable solution report. The former informs the shadow values, or how much the objective function value would change for a unit change in the right-hand side value of a binding constraint. The latter indicates the reduced costs, or the change in the objective function value for a unit change in the decision variable values, considering all other data fixed.

In this project, the robustness to the model in the face of changes in the parameters was assessed by analyzing parallel coordinate plots, where the axes represent the three objective functions. For each decision variable $HPP_i$, a different plot was generated, grouping the objective function values by decision variable values. Although the grouping legend is continuous, $HPP_i$ can only assume 0 or 1. Thus, dark
Figure 9: Parallel plot of the decision space including the decision variable related to project A03PA008.

Blue means 0, while light blue means 1, except on plots with only one binary value - in these plots, blue means 0. The "minmax" scaling was also used here.

For example, Figure 12 shows how frequent this project was selected by the model. Each light blue line represents an alternative in which project A03PA008 was selected. Figure 10, on the other hand, shows that project A21PA158 was never selected for any alternative, showing the same color for every line.

In addition, the parallel plots can show the impact of a given project in each objective function performance. Figure 11, for example, shows that Project A12PA108, when chosen, does not lead to a large variation in the Area objective function performance. Project A3PA008, illustrated in Figure 12, performs the exact opposite way for the same objective.

Finally, Figure 13 summarizes the frequency each project was selected as part of an alternative. It can be seen that projects A03PA008, A29PA208, A32PA240 and A34PA250 were the most frequent model choices.

The parallel plots were generated for all decision variables $HPP_i$ and are presented in Appendix A.
Figure 10: Parallel plot of the decision space including the decision variable related to project A21PA158

Figure 11: Parallel plot of the decision space including the decision variable related to project A12PA108
Figure 12: Parallel plot of the decision space including the decision variable related to project A03PA008

Figure 13: Number of times each project was selected for any alternative
5.4 Comparison with inventory study results

The results obtained in the Paru River Inventory Studies recommended the policy illustrated in Table 3, which yields a total of 448.47 km$^2$ of flooded area, generates 911.45 MW and results in 96.81 km of connected stream segment. It was obtained using the procedures recommended in the Manual for Hydropower Inventory Studies of River Basins (Minister of Mines and Energy/CEPEL, 2010), a mandatory reference anyone interested in developing hydropower inventory studies in Brazil.

The method adopted in the manual consists in ranking cost-benefit and social and environmental impact indexes for each alternative, allowing the user to choose the best one in terms of construction and operation and maintenance (O& M) costs, energy generation and negative/positive social and environmental impacts, which are mainly related to aquatic and terrestrial environments, ways of life, territorial organization and economic basis, as well as traditional and indigenous communities around the plants. The construction costs are evaluated using pre-defined tables and charts from typical designs. O& M costs are a function of energy generation. The energetic benefits are based on reservoir operation simulations. Finally, the social and environmental impacts are based on expert opinion and geospatial analysis.

Even though no identical policy was obtained by using the model hereby developed, it is possible to compare results from both methods. For example, one policy illustrated in Table 3 results in 369.17 km$^2$ of flooded area, generates 1009.70 MW and leads to 96.81 km of connectivity. Thus, the use of different performance metrics can yield close, but not identical results. In this comparison, the only projects common to both methods are the ones shown in bold in Table 3. A dynamic method such as the one developed in this project, even though considered fewer metrics when compared to scoring method used in the inventory studies, solves the problem in a more efficient way, obtaining a larger set of possible policies.
### Table 3: Policy comparisons

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CHAPTER 6
SUMMARY AND CONCLUSIONS

In analyzing alternative dam sites for the present project, the following questions arise: would the task of a decision-maker responsible for choosing which plants to build in the Paru River be more or less complex after having the results yielded by the model as described in Chapter 4? What if this decision-maker had to choose one policy using only the input data available and intuition? What if the decision had to be made in a political environment, with different stakeholders pushing for their particular interests? The use of a MOOP will surely be an important tool to analyze the possible policies contained in the Pareto set, allowing the decision-maker to support his choice based on reliable data and previously knowing the trade-offs between all possible outcomes. Furthermore, if in a political environment, the use of a MOOP can be even more relevant, allowing the policy makers involved in the process to know what would mean to indulge one objective over another. As stated by Polasky and Binder (2012), "reporting a set of results has the advantage of letting decision-makers see important distributional consequences by reporting benefits and costs to different groups".

6.1 Limitations

The model developed in this project has important limitations that must be considered when running it and when analyzing the results. Firstly, the model has the ability to generate the input data to be solved by the MOOP for a single stream only. To handle more than one stream or a stream network, a few modifications would have to be made to the Excel/VBA® scripts. Mainly, the scripts would have to be able to identify the name of the river from the input data table and build the
auxiliary worksheets considering new upstream-downstream relationships, as well as more than one distance between sites, since the same barrier can, in a stream network, have more than one adjacent connected stream segment.

Secondly, it is assumed that projects developed upstream in the river will not affect energy generation from downstream plants. This assumption was based on the data available in the inventory studies developed for the Paru River, which showed that there would be no upstream energetic benefits from storage. Hence, this assumption is adequate for the study case. For a different scenario, it would be necessary to modify the model, probably including built-in simulation capabilities, allowing the user to verify if, by depleting the reservoir and losing total head, it would still be energetically interesting, not only for one particular plant, but for the whole cascade.

When it comes to hydropower plant development, a much larger set of objectives are involved and they may not be easily expressed mathematically. In this project, a three-objective optimization problem was formulated, which clearly holds a smaller number of management goals when compared to a real life situation. Although part of the model limitations, this feature is present in any multi-objective model which deals with real life problems and this is the main reason why decision-makers will still be the most important part of the policy making procedure: model results are just another input for them throughout the whole process.

Regarding the model running process, two manual tasks are still necessary after obtaining the outputs. First, the plots have to be manually generated using DiscoveryDV (scatter plots) and R (parallel plots), which requires manipulation of GAMS output files. Secondly, even though GAMS output files are dumped into an Excel® workbook in order to make it easier to find which projects belong to a given policy, a manual query still has to be performed. These deficiencies can be overcome by developing Excel/VBA® scripts to analyze the final results and by developing
automated functions to obtain the plots.

Finally, a few inferior points were generated by the model, which required a sorting post-processing step. The reason for it seems to be the iterations over small ranges of right-hand side values. Logic to prevent that is an improvement that can also be implemented into the GAMS coding.

6.2 Conclusions

In order to support decision-makers to choose between several alternatives of sets of hydropower plants to be implemented in a given river, the Manual for Hydropower Inventory Studies of River Basins (Minister of Mines and Energy/CEPEL, 2010) recommends the use of a ranking method, described in 5. This method generates a small set of alternatives, which may not be in the Pareto front. The method proposed in this project, based on the development of a multi-objective optimization model, generates the Pareto front for a proposed problem, allowing the decision maker to better choose, from a larger set of Pareto-optimal alternatives, the one to implement.

The model was developed for the the Paru River, in Brazil and was able to generate the Pareto front for the problem. One of the Pareto-optimal policies was compared with the recommended policy obtained using the Manual for Hydropower method, showing that different metrics and different models may result in different policies for the same problem.

Furthermore, the following conclusions were drawn from this project:

- Energy generation and surface flooded area are competing objectives;
- Energy generation and river connectivity are also competing objectives;
- Flooded area and river connectivity are not competing objectives - an improvement in both will improve habitat quality by reducing flooded area and increas-
ing river connectivity;

- Each project affects the management goals in different ways:
  
  - Projects A3PA008, A7PA050, A15PA120, A22PA160, A29PA208, A32PA240 and A34PA250 have a wide influence over the performance of all three objectives;
  
  - Projects A6PA04, A10PA096, A11PA096, A12PA108, A13PA110 and A20PA150 have little influence over all three objectives;
  
  - The remaining projects have moderate influence over one or more than one objectives. For example, project A18PA128 can affect the Area objective performance in more than 50%, but will affect the Energy objective performance in less than 30%.

The resulting model plots showed that an increase in energy generation will increase the surface flooded area, since more reservoirs will be formed. It will also lead to a decrease in river connectivity, due to the fact that more projects will be necessary, decreasing the connected stream segment lengths. It also showed that there is a positive correlation between objectives Area and Energy and a weak negative correlation between Energy and Segment and Segment and Area.

The sensitivity analysis showed that each project will have a different degree of impact to each objective function. Furthermore, a frequency analysis showed that projects A03PA008, A29PA208, A32PA240 and A34PA250 were the most frequent model choices.

Another important aspect of the model developed in this project is that, notwithstanding the complexity involved in a MOOP, the simplicity of the objective functions can be understood by decision-makers, even if they are not technically oriented. As stated by Geoffrion (1976), in order to persuade a managerial or political figure to use a model as problem-solving aid, it must be intuitive for them why
the results are as they are. By having simple objective functions, this can be easily achieved.

Finally, when comparing the results obtained using the model developed in this project with the results from the inventory studies, it was possible to notice that different performance metrics can yield similar, but slightly different results. Consequently, the use of a dynamic model like the one developed in this project may be useful for technicians involved in the elaboration of inventory studies when defining possible alternatives to be further assessed by other criteria.

6.3 Future Work

The limitations hereby described suggest that the model can be improved by adding three functionalities: the ability to deal with stream networks, the ability to consider energetic benefits from upstream storage and the use of other automated tasks to deal with GAMS output files and to generate the plots.

Further research may also include assessing if the performance metrics chosen for this project could be improved, either by using a different mathematical formulation or by choosing different metrics. The latter option would, in fact, lead to a different model that could be used along with the present one, improving the quantity and quality of information available to decision-makers to better perform their tasks.


Appendices
Appendix A

PARALLEL PLOTS OBTAINED FOR EACH PROJECT

Figure 14: Parallel plots 1-4
Figure 15: Parallel plots 5-8
Figure 16: Parallel plots 9-12
Figure 17: Parallel plots 13-16
Figure 18: Parallel plots 17-20
Figure 19: Parallel plots 21-24
Figure 20: Parallel plots 25-28
Figure 21: Parallel plots 29-32
Figure 22: Parallel plots 33-34
Appendix B

EXCEL/VBA® SCRIPT CODES

Attribute VB_Name = "Module2"

Option Explicit

Sub Build_Sites_Projects()
    ' Build Sites_Projects worksheet from Design_Data worksheet

    ' Defining variables
    Dim nrow As Integer, ncol As Integer, row As Integer, col As Integer
    Dim String1 As String, String2 As String

    ' Clear destination worksheet
    Call Clear_Sites_Projects

    ' Copy column of sites
    Sheets("Design_data").Select
    Range("A1").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("Sites_Projects").Select
    Range("A100").Select
    ActiveSheet.Paste
    nrow = Application.CountA(Selection)
' Copy and transpose column of designs

Sheets('Design_data').Select
Range('B2').Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets('Sites_Projects').Select
Range('B100').Select
ncol = Application.CountA(Selection)

' Fill in cells based on correspondence between sites and designs

For row = 2 To nrow
    String1 = Sheets('Design_data').Cells(row, 1).Value &
              Sheets('Design_data').Cells(row, 2).Value
    For col = 2 To ncol + 1
        String2 = Sheets('Sites_Projects').Cells(99 + row, 1).Value &
                  Sheets('Sites_Projects').Cells(100, col).Value
        If String1 = String2 Then
            Sheets('Sites_Projects').Cells(99 + row, col).Value = 1
        Else
            Sheets('Sites_Projects').Cells(99 + row, col).Value = 0
        End If
    Next col
Next row
'Consolidating duplicated sites

Sheets("Sites_Projects").Range("A100").Select
Range(Selection, Selection.End(xlDown)).Select
Range(Selection, Selection.End(xlToLeft)).Select
ActiveSheet.Names.Add Name:="ConsolBySite", RefersToR1C1 :=Selection
Range("A1").Select
Selection.Consolidate Sources:= _
'Sites_Projects!ConsolBySite', Function:= _
xlSum, TopRow:=True, LeftColumn:=True, CreateLinks:=
False

'Format output table

Range("A1").Select
Selection.Resize(nrow + 1, ncol + 1).Select
With Selection
  .HorizontalAlignment = xlCenter
  .VerticalAlignment = xlCenter
  .WrapText = True
  .Orientation = 0
  .AddIndent = False
  .IndentLevel = 0
  .ShrinkToFit = False
  .ReadingOrder = xlContext
.MergeCells = False

End With

' Returning to Design_data worksheet
Range('A1').Select
Sheets('Design_data').Select
Range('A1').Select
Application.CutCopyMode = False

End Sub

Sub Build_Objectives_coef()

' Transpose values of area and energy from worksheet "
Design_data" to worksheet Objectives_coef

' Clear destination worksheet
   Call Clear_Objectives_coef

' Copy and transpose data
Sheets('Design_data').Select
Range('B1').Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Resize(, 3).Select
Selection.Copy
Sheets('Objectives_coef').Select
' Returning to Design_data worksheet
Range("A1").Select
Sheets("Design_data").Select
Range("A1").Select
Application.CutCopyMode = False

End Sub

Sub Build_Overlapping_Projects()

' Build Overlapping_Projects worksheet from Design_Data worksheet

' Defining variables
Dim nrow As Integer, ncol As Integer, row As Integer, col As Integer, Count As Integer
Dim elevup As Double, elevdown As Double
Dim cell As Range

' Clear destination worksheet
Call Clear_Overlapping_Projects

' Copy column of designs
Sheets("Design_data").Select
Range("B2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets("Overlapping_Projects").Select
Range("A2").Select
ActiveSheet.Paste

nrow = Application.CountA(Selection)

' Copy and transpose column of designs
Sheets("Design_data").Select
Range("B2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets("Overlapping_Projects").Select
Range("B1").Select

ncol = Application.CountA(Selection)

' Fill in cells based on upstream and downstream levels
For row = 2 To nrow + 1
    Count = 1
    elevup = Sheets("Design_data").Cells(row, 6).Value
    Sheets("Overlapping_Projects").Select
    ActiveSheet.Cells(row, row + 1).Select
    If ncol - row + 1 > 0 Then
        Selection.Resize(1, ncol - row + 1).Select
        For Each cell In Selection
            elevdown = Sheets("Design_data").Cells(row + Count, 7).Value
            If elevup > elevdown Then
                cell.Value = 1
            End If
        Next cell
    End If
Next row
Else
    cell.Value = 0
End If
Count = Count + 1
Next
End If
ActiveSheet.Cells(row, row).Value = 1
Next

' Fill in the empty cells with zeros
Range("A2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Resize(, ncol + 1).Select
For Each cell In Selection
    If IsEmpty(cell) Then
        cell.Value = 0
    End If
Next

' Format output table
Range("A1").Select
Selection.Resize(nrow + 1, ncol + 1).Select
With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = True
    .Orientation = 0
End With

' Returning to Design_data worksheet
Range("A1").Select
Sheets("Design_data").Select
Range("A1").Select
Application.CutCopyMode = False

End Sub

Sub Build_Segments()

' Build Segments worksheet from Design_Data worksheet

' Defining variables
Dim nrow As Integer, ncol As Integer, row As Integer, col As Integer, Count As Integer
Dim Location1 As Double, Location2 As Double
Dim cell As Range

' Clear destination worksheet
Call Clear_Segments

' Copy column of designs
Sheets("Design_data").Select
Range("B2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets("Segments").Select
Range("A2").Select
ActiveSheet.Paste
nrow = Application.CountA(Selection)

' Copy and transpose column of designs
Sheets("Design_data").Select
Range("B2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets("Segments").Select
Range("B1").Select
ncol = Application.CountA(Selection)

' Calculate every possible reach length
For row = 2 To nrow + 1
  Location1 = Sheets("Design_data").Cells(row, 5).Value
  Count = 0
  For col = 2 To ncol + 1
    Location2 = Sheets("Design_data").Cells(2 + Count, 5).Value
    ' Perform calculations with Location1 and Location2
  Next col
Next row
If Location1 < Location2 Then
    Sheets("Segments").Cells(row, col).Value = Location2 - Location1
Else
    Sheets("Segments").Cells(row, col).Value = 0
End If
Count = Count + 1
Next
Next

' Format output table
Range("A1").Select
Selection.Resize(nrow + 1, ncol + 1).Select
With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = True
    .Orientation = 0
    .AddIndent = False
    .IndentLevel = 0
    .ShrinkToFit = False
    .ReadingOrder = xlContext
    .MergeCells = False
End With

' Returning to Design_data worksheet
Range("A1").Select
Sheets('Design_data').Select
Range('A1').Select
Application.CutCopyMode = False

End Sub

Sub Build_Barrriers()

' Build Barriers worksheet from Segments worksheet

' Defining variables
Dim nrow As Integer, ncol As Integer, finalnrow As Integer, row As Integer, col As Integer, Count1 As Integer, Count2 As Integer
Dim Position1 As Double, Position2 As Double
Dim cell As Range, coef As Range

' Clear destination worksheet
Call Clear_Barriers

' Copy column of designs
Sheets('Design_data').Select
Range('B2').Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
nrow = Application.CountA(Selection)
Sheets('Barriers').Select
Cells(3, 3).Select
ActiveSheet.Paste
For Count1 = 1 To nrow – 1
    Cells(3 + nrow * Count1, 3).Select
    ActiveSheet.Paste
Next

For Count1 = 1 To nrow
    Sheets("Design_data").Select
    Cells(1 + Count1, 2).Select
    Selection.Copy
    Sheets("Barriers").Select
    For Count2 = 0 To nrow – 1
        Cells(3 + (Count1 – 1) * nrow + Count2, 1).Select
        ActiveSheet.Paste
    Next
Next

' Copy column of ranks
Sheets("Design_data").Select
Range("H2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
nrow = Application.CountA(Selection)
Sheets("Barriers").Select
Cells(3, 4).Select
ActiveSheet.Paste
For Count1 = 1 To nrow – 1
    Cells(3 + nrow * Count1, 4).Select
    ActiveSheet.Paste
Next
For Count1 = 1 To nrow
    Sheets("Design_data").Select
    Cells(1 + Count1, 8).Select
    Selection.Copy
    Sheets("Barriers").Select
    For Count2 = 0 To nrow - 1
        Cells(3 + (Count1 - 1) * nrow + Count2, 2).Select
        ActiveSheet.Paste
    Next
Next

' Copy and transpose column of designs
Sheets("Design_data").Select
Range("B2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets("Barriers").Select
Range("E1").Select
ncol = Application.CountA(Selection)

' Copy and transpose column of ranks
Sheets("Design_data").Select
Range("H2").Select
Range(Selection, Selection.End(xlDown)).Select
'Define barriers between designs

Range("A3").Select
Range(Selection, Selection.End(xlDown)).Select
finalnrow = Application.CountA(Selection)
For Count1 = 0 To finalnrow - 1
    Cells(3 + Count1, 5).Select
    Selection.Resize(, ncol).Select
    Count2 = 0
    For Each cell In Selection
        If Cells(2, 5 + Count2).Value > Cells(3 + Count1, 2).Value And _
            Cells(2, 5 + Count2).Value < Cells(3 + Count1, 4).Value Then
            cell.Value = 1
        Else
            cell.Value = 0
        End If
        Count2 = Count2 + 1
    Next
Next
Deleting rank columns and row

Columns("B:B") . Select
Selection . Delete Shift:=xlToLeft
Columns("C:C") . Select
Selection . Delete Shift:=xlToLeft
Rows("2:2") . Select
Selection . Delete Shift:=xlUp

Format output tables

Range("A1") . Select
Selection . Resize(finalnrow + 1, ncol + 1) . Select
With Selection
  . HorizontalAlignment = xlCenter
  . VerticalAlignment = xlCenter
  . WrapText = True
  . Orientation = 0
  . AddIndent = False
  . IndentLevel = 0
  . ShrinkToFit = False
  . ReadingOrder = xlContext
  . MergeCells = False
End With

Returning to Design_data worksheet

Range("A1") . Select
Sheets("Design_data") . Select
Range("A1") . Select
Application.CutCopyMode = False

End Sub

Sub Invert_Sign()
' Invert the signs of the objective function coefficients
  that will be minimized

' Defining variables
  Dim coef As Range, column As Integer

' Obtaining the number of columns to be selected before
  transposing (depends on the number of objectives)
  column = InputBox("Enter the column number in which the
                  objective function is to be minimized:")

' Selecting the column that will have the coefficient signs
  inverted
  Cells(2, column).Select
  Range(Selection, Selection.End(xlDown)).Select

' Looping through the range in the column to invert the signs
  For Each coef In Selection
    coef.Value = -coef.Value
  Next

  Range("A1").Select
End Sub

Sub Calculate_ranks()

'Calculate the distance rank column

'Defining variables

    Dim rngSource As Range
    Dim rngCell As Range

'Defining the range from which ranks will be calculated

    Sheets("Design_data").Select
    Range("E2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Set rngSource = Selection

'Clear destination column

    Range("H2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Clear
    Application.CutCopyMode = False

'Calculate the ranks

    For Each rngCell In rngSource
        rngCell.offset(, 3).Value = WorksheetFunction.Rank(
            rngCell.Value, rngSource, 1)
    Next rngCell
    Set rngSource = Nothing
    Set rngCell = Nothing
'Format rank column

Range('H2').Select

Range(Selection, Selection.End(xlDown)).Select

With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = True
    .Orientation = 0
    .AddIndent = False
    .IndentLevel = 0
    .ShrinkToFit = False
    .ReadingOrder = xlContext
    .MergeCells = False
End With

With Selection.Font
    .Name = 'Calibri'
    .Size = 11
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ThemeColor = xlThemeColorLight1
.TintAndShade = 0
.ThemeFont = xlThemeFontMinor

End With

Range("A1").Select

End Sub

Sub Gen_RHS_values()
' Generate right hand side values to build the Pareto front
Dim first As Double, last As Double, step As Double
Dim row As Integer, nlevels As Integer

' Ask the user how many levels he wants
nlevels = InputBox("How many levels do you want? (between 3 and 1000)") + 1

' Clear destination cells
Sheets("RHS_Values").Select
ActiveSheet.Range(Cells(2, 1), Cells(1000, 4)).ClearContents

' Fill in Level column
Range("A2").Value = 1
Range("A3").Value = 2
Range("A2:A3").Select
Selection.AutoFill Destination:=Range(Cells(2, 1), Cells(nlevels, 1)), Type:=xlFillDefault
Range(Cells(2, 1), Cells(nlevels, 1)).Select
With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .NumberFormat = ""
End With

' Evenly fill in Minimum Area column
Range("B2").Value = 0
Cells(nlevels, 2).Value = Range("G2").Value * (-1)
first = ActiveSheet.Range("B2").Value
last = ActiveSheet.Cells(nlevels, 2).Value
step = (last - first) / (nlevels - 2)
ActiveSheet.Range("H2").Value = step
Range("B3").Select
For row = 3 To nlevels - 1
    ActiveSheet.Cells(row, 2).Value = ActiveSheet.Cells(row - 1, 2).Value + step
Next

' Evenly fill in Maximum Segment column
Range("C2").Value = 0
Cells(nlevels, 3).Value = Range("G3").Value
first = ActiveSheet.Range("C2").Value
last = ActiveSheet.Cells(nlevels, 3).Value
step = (last - first) / (nlevels - 2)
ActiveSheet.Range("H3").Value = step
Range("C3").Select

For row = 3 To nlevels - 1
    ActiveSheet.Cells(row, 3).Value = ActiveSheet.Cells(row - 1, 3).Value + step
Next

' Evenly fill in Maximum Energy column
Range("D2").Value = 0
Cells(nlevels, 4).Value = Range("G4").Value
first = ActiveSheet.Range("D2").Value
last = ActiveSheet.Cells(nlevels, 4).Value
step = (last - first) / (nlevels - 2)
ActiveSheet.Range("H4").Value = step
Range("D3").Select

For row = 3 To nlevels - 1
Next

' Format table
Range(Cells(2, 2), Cells(nlevels, 4)).Select
With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = True
    .Orientation = 0
    .AddIndent = False
End With

With Selection.Font
    .Name = "Calibri"
    .Size = 11
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ThemeColor = xlThemeColorLight1
    .TintAndShade = 0
    .ThemeFont = xlThemeFontMinor
End With

Range("A1").Select

End Sub

Sub Read_Original_Data()
    ' Read original data from the first worksheet
' Clear destination area
Sheets('Design_Data').Select
Range('A2').Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Resize(, 8).Select
Selection.Clear

' Read and copy data from Original_Data worksheet
Sheets('Original_Data').Select
Range('A2').Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Resize(, 2).Select
Selection.Copy
Sheets('Design_Data').Select
Range('A2').Select

Sheets('Original_Data').Select
Range('B2').Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Copy
Sheets('Design_Data').Select
Range('B2').Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
Sheets('Original_Data').Select
Range("C2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Resize(, 2).Select
Selection.Copy
Sheets('Design_Data').Select
Range("F2").Select
:=False, Transpose:=False

Sheets('Original_Data').Select
Range("G2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Resize(, 3).Select
Selection.Copy
Sheets('Design_Data').Select
Range("C2").Select
:=False, Transpose:=False

'Returning to Design_data worksheet
Sheets('Original_Data').Select
Range("A1").Select
Application.CutCopyMode = False
Sheets("Design_data").Select
Range("A1").Select
Application.CutCopyMode = False

' Format table
   Call Format_Input_data

End Sub

Sub Format_Input_data()
   ' Format the input data table

   ' Format fonts and centralize values
   Range("A1").Select
   Range(Selection, Selection.End(xlDown)).Select
   Range(Selection, Selection.End(xlToRight)).Select
   With Selection
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlCenter
      .WrapText = True
      .Orientation = 0
      .AddIndent = False
      .IndentLevel = 0
      .ShrinkToFit = False
      .ReadingOrder = xlContext
      .MergeCells = False
   End With
With Selection.Font
    .Name = "Calibri"
    .Size = 11
    .Strikethrough = False
    .Superscript = False
    .Subscript = False
    .OutlineFont = False
    .Shadow = False
    .Underline = xlUnderlineStyleNone
    .ThemeColor = xlThemeColorLight1
    .TintAndShade = 0
    .ThemeFont = xlThemeFontMinor
End With

With Selection.Interior
    .Pattern = xlSolid
    .PatternColorIndex = xlAutomatic
    .ThemeColor = xlThemeColorDark1
    .TintAndShade = 0
    .PatternTintAndShade = 0
End With

' Format headers
Range("A1").Select
Range(Selection, Selection.End(xlToRight)).Select
Selection.Font.Bold = True
With Selection.Interior
    .Pattern = xlSolid
    .PatternColorIndex = xlAutomatic
    .ThemeColor = xlThemeColorAccent2
    .TintAndShade = 0.399975585192419
    .PatternTintAndShade = 0
End With

Range('A1').Select
Sheets('Design_data').Select
Range('A1').Select

End Sub

Sub Generate_All()
    ' Generate all destination worksheets

    Call Invert_Sign
    Call Calculate_ranks
    Call Build_Sites_Projects
    Call Build_Objectives_coef
    Call Build_Overlapping_Projects
    Call Build_Segments
    Call Build_Barriers

End Sub

Sub Clear_Sites_Projects()
    ' Clear Sites_Projects worksheet
Sub Clear_Objectives_coef()
    ' Clear Objectives_coef worksheet
    Sheets("Objectives_coef").Cells.Clear
    Sheets("Objectives_coef").Select
    Range("A1").Select
    Sheets("Design_Data").Select
    Range("A1").Select
End Sub

Sub Clear_Overlapping_Projects()
    ' Clear Overlapping_Projects worksheet
    Sheets("Overlapping_Projects").Cells.Clear
    Sheets("Overlapping_Projects").Select
    Range("A1").Select
    Sheets("Design_Data").Select
    Range("A1").Select
End Sub
End Sub

Sub Clear_Segments()

' Clear Segments worksheet

Sheets("Segments").Cells.Clear
Sheets("Segments").Select
Range("A1").Select
Sheets("Design_Data").Select
Range("A1").Select

End Sub

Sub Clear_Barriers()

' Clear Barriers worksheet

Sheets("Barriers").Cells.Clear
Sheets("Barriers").Select
Range("A1").Select
Sheets("Design_Data").Select
Range("A1").Select

End Sub

Sub Clear_All_Dest()

' Clear all destination sheets

Call Clear_Sites_Projects
Call Clear_Objectives_coef
Call Clear_Overlapping_Projects
Call Clear_Segments
Call Clear_Barriers

Sheets('Design_data').Select
Range('A1').Select

End Sub

Sub Copy_Obj_Names()

' Copy the names of the objectives from the Design_Data worksheet

' Copy names from Design_Data worksheet
Sheets('Design_Data').Select
Range('C1').Select
Selection.Resize(. , 3).Select
Selection.Copy
Range('A1').Select

' Copy and transpose names
Sheets('RHS_level').Select
Range('A1').Select
Selection.PasteSpecial Paste:=xlPasteAll, Operation:=
    xlNone, SkipBlanks:=False, Transpose:=True
End With
End Sub

With Selection.Font
    .Bold = False
End With
Range('A1').Select
End Sub
Appendix C
GAMS CODE DEVELOPED FOR THIS PROJECT

scalar starttime; starttime = jnow;
$offlisting

*****************************************************************************

* Options to reduce the size of the listing file
$offsymxref
$offsymlist

* Formatting solution report output format
Option solprint = silent;

*****************************************************************************

*****************************************************************************

$ontext
Hydropower Plant Siting using a multiobjective approach

Script developed as part of the author’s Master’s Degree in Civil and Environmental Engineering at Utah State University – 2016
*Problem statement*

− Management goals
The problem is stated as maximize the energy generated by hydropower plants, minimize the surface area flooded by the reservoirs and minimize river fragmentation by maximizing river segments’ lengths not impaired by dams.

− Management actions
The decision variables are the choices of whether or not to build a given plant in a given site along a river (binary decision variables, 1 being "build" and 0 being "do not build") and the choices of whether or not consider a stream segment as fragmented or not (binary decision variables, 0 being "fragmented" and 1 being "not fragmented").

− Constraints
The first set of constraints limits the possibility to build more than one project in sites that may have more than one. The second set of constraints guarantees that the projects do not overlap each
other.

The third set of constraints defines a free reach, which is a segment between two projects in different sites that does not have any barriers in between.

The fourth constraint forces the model to choose only one segment.

**General model formulation**

\[
\text{Min. Goal Area} = \text{Sum}(i) \{ \text{flooded area}_i \times \text{HPP}_i \}
\]

\[
\text{Max. Goal Energy} = \text{Sum}(i) \{ \text{energy generation}_i \times \text{HPP}_i \}
\]

\[
\text{Max. Goal Length} = \text{Sum}(i, j) \{ \text{free reach}_i, j \times \text{seg coef}_i, j \}
\]

s.t.: \text{Sum}(i) \{ \text{site project}_m, i \times \text{X}_i \} \leq 1 \text{ for all } m

\text{Sum}(i) \{ \text{overlap project}_j, i \times \text{X}_i \} \leq 1 \text{ for all } j

\text{FR}(i, j) \leq \text{Sum}(k) \{ ((1 - \text{HPP}_i) / N\text{barriers}_i, j) \} \times \text{barriers}_i, j, k \text{ for all } i, j

\text{Sum}(i, j) \{ \text{FR}_i, j \} \leq 1

**Model formulation for the constraint method**

\[
\text{Min. Sum}(i) \{ \text{flooded area}_i \times \text{HPP}_i \} \leq \text{Level1}
\]

s.t.: \text{Sum}(i) \{ \text{energy generation}_i \times \text{HPP}_i \} \geq \text{Level2}

\text{Sum}(i, j) \{ \text{free reach}_i, j \times \text{seg coef}_i, j \}

\text{Sum}(i) \{ \text{site project}_m, i \times \text{X}_i \} \leq 1 \text{ for all } m

\text{Sum}(i) \{ \text{overlap project}_j, i \times \text{X}_i \} \leq 1 \text{ for all } j

\text{FR}(i, j) \leq \text{Sum}(k) \{ ((1 - \text{HPP}_i) / N\text{barriers}_i, j) \} \times \text{barriers}_i, j, k \text{ for all } i, j

\text{Sum}(i, j) \{ \text{FR}_i, j \} \leq 1
barriers_{i,j,k} \forall \text{all } i,j
\sum_{i,j} \{FR_{i,j}\} \leq 1

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1–5–2017

Defining the sets and the parameters which will be used to read data
Defining the set for the objectives
SET_{objective, objective} functions
/Area, Energy, Length /

Defining a duplicate name for the set 'objective'
ALIAS (objective, objective2);

Defining the direction for each objective
Here, we define which objectives are maximized and which are
\[ \text{minimized} \]
\[ $set\_\text{min} - 1 \]
\[ $set\_\text{max} + 1 \]

PARAMETER dir (objective) direction of the objective functions
\[ \text{Area}_{\text{min}}, \text{Energy}_{\text{max}}, \text{Length}_{\text{max}} /; \]

Defining the sets for sites and projects
SETS site sites
\[ \text{project} \text{ projects} ; \]

Defining a duplicate name for the set 'project'
ALIAS (project, project2, project3);

Defining the parameters for the objective functions
PARAMETERS ae_coef (project, objective) \text{objective function} coefficients for area and energy
seg_coef (project, project2) \text{objective function} coefficients for distances between projects;

Defining the parameters for the constraints
PARAMETERS site proj (site, project) relationship between sites and projects
overl proj (project, project2) relationship between overlapping projects
Nbarriers (project, project2) \# of barriers between projects
barriers (project, project2, project3) barriers
between projects;

* Creating GDX file from the Excel file
$CALL GDXXRW.EXE data_input_revision.xls MaxDupeErrors=1000
set=site rng=Design_data!A2 rdim=1 set=project rng=
  Design_data!B2 rdim=1 par=ae_coef rng=Objectives_Coef!A1
  par=seg_coef rng=Segments!A1 par=site_proj rng=
  Sites_Projects!A1 par=overl_proj rng=Overlapping_Projects!
  A1 par=barriers rng=Barriers!A1 rdim=2 cdim=1

* Reading the GDX file
$gdxin data_input_revision.gdx

* Importing data structure values from GDX file
$load site
$load project
$load ae_coef
$load seg_coef
$load site_proj
$load overl_proj
$load barriers

*****************************************************************************

*****************************************************************************
Calculating number of barriers between projects

\[ \text{NBarriers}(\text{project}, \text{project2}) = \text{sum}(\text{project3}, \text{barriers}(\text{project}, \text{project2}, \text{project3})) ; \]

Defining sets parameters used to build and solve the model using the eps-constraint method

Defining the ordered sets for the eps-constraint method

\[ \text{SETS}_{\text{obj}_\text{goal}(\text{objective})} \quad \text{The objective treated as goal in the objective set} \]

\[ \text{Number of levels} / 1*20 / ; \]

Defining a duplicate name for the set "level"

\[ \text{ALIAS}_{(\text{level}, \text{level2})} ; \]

Parameters to store values

\[ \text{PARAMETERS}_{\text{obj}_\text{val}(\text{objective})} \quad \text{Objective function value} \]

\[ \text{min}_\text{val}(\text{objective}) \quad \text{Minimum value for the objective} \]

\[ \text{max}_\text{val}(\text{objective}) \quad \text{Maximum value} \]
for the objective

Solution point in the Pareto front;

Parameters and scalars to use in the loops
PARAMETERS step(objective) Define the number of steps for each objective /Area 20, Energy 20, Length 0/

obj_val_inc(objective) Value by which each objective will be incremented in each step;

SCALAR obj_index Index number of the current objective /1/;

Parameters to use in the eps–constraint method
PARAMETERS rhs(objective) Right–hand side values of constraint objective (arb. units);

Defining the variables
VARIABLES HPP(project) decision variable levels for Goal Area and Goal Energy – Build or not built each project

FR(project, project2) decision variable levels for
Goal_Length: Consider segment as fragmented or not

\( Z(\text{objective}) \) \( \text{objective function values} \) (arb units)

\( \text{CURROBJ} \) \( \text{objective function value of} \) selected \( \text{objective function} \) (arb units);

* Defining the binary variables \((0=\text{Do not build/fragmented}, 1=\text{Build/not fragmented})\)

\( \text{BINARY VARIABLES} \) \( \text{HPP}, \text{FR}; \)

******************************************************************************

******************************************************************************

* Combining variables and data in equations
* Equations for the problem

\( \text{EQUATIONS Goal Area} \) \( \text{Objective function Area} \)

\( \text{Goal Energy} \) \( \text{Objective function Energy} \)

\( \text{Goal Length} \) \( \text{Objective function Length} \)

\( \text{ExclusivityCons (site)} \) \( \text{Constraints to allow only one project per site} \)

\( \text{NoOverlapCons (project2)} \) \( \text{Constraints to prevent projects overlapping each other} \)

\( \text{FreeReach (project, project2)} \) \( \text{Constraints that define} \)
OnlyOneSeg Constraints to allow only one segment per run;

Goal_Area .. \sum\limits_{\text{project}} \text{ae_coef}(\text{project},'Area') \times \text{HPP}(\text{project}) = \sum\limits_{\text{project}} \text{Z}(\text{Area});

Goal_Energy .. \sum\limits_{\text{project}} \text{ae_coef}(\text{project},'Energy') \times \text{HPP}(\text{project}) = \sum\limits_{\text{project}} \text{Z}(\text{Energy});

Goal_Length .. \sum\limits_{\text{project}, \text{project2}} \text{seg_coef}(\text{project}, \text{project2}) \times \text{FR}(\text{project}, \text{project2}) = \sum\limits_{\text{project}, \text{project2}} \text{Z}(\text{Length});

* Constraints

ExclusivityCons(\text{site}) .. \sum\limits_{\text{project}} \text{site_proj(\text{site},\text{project})} \times \text{HPP}(\text{project}) = 1;

NoOverlapCons(\text{project2}) .. \sum\limits_{\text{project}} \text{overl_proj(\text{project2},\text{project})} \times \text{HPP}(\text{project}) = 1;

FreeReach(\text{project}, \text{project2}) .. \text{FR}(\text{project}, \text{project2}) = \sum\limits_{\text{project3}} ((1 - \text{HPP}(\text{project3}))/\text{Nbarriers(\text{project}, \text{project2})) \times \text{barriers(\text{project}, \text{project2}, \text{project3})});

OnlyOneSeg .. \sum\limits_{\text{project}, \text{project2}} \text{FR}(\text{project}, \text{project2}) = 1;

* Defining the model for the problem

MODEL Mod_DamSiting Dam_siting_problem formulation / All /;

* Equations for the eps-constraint method

EQUATIONS MainObj Objective function treated as
goal

ConstObj(objective).Objective.functions as constraints;

* Equations for the objectives as main goal or as constraint
MainObj.. CURROBJ=E=sum(obj_goal,Z(obj_goal));
ConstObj(objective)$(ord(objective)<obj_index).. dir(objective)*Z(objective)=G=dir(objective)*rhs(objective);

* Defining the models for the eps-constraint method
MODEL Mod_Extreme To calculate the extreme points /
    Mod_DamSiting, MainObj/;
MODEL Mod_Intermediate To calculate the intermediate points /
    Mod_DamSiting, MainObj, ConstObj/;

******************************************************************************************************************************************

******************************************************************************************************************************************

* Creating the file to store the intermediate points
File Results/Results.csv/;
Results.pc=5;
Put Results;
Loop(objective, Put, objective.tl);
Put/;

******************************************************************************************************************************************
Solving the model

Solving for extreme points of 1st objective

Defining the first objective — Area as goal

Solving the model for the first objective function — Area

Bear in mind that the goal is to minimize Area

Calculating the increment between steps and defining the first value for obj_val(Area)
step ("Area") - 1;
obj_val ("Area") <= max_val ("Area") + obj_val_inc ("Area");

********** Solve for intermediate points of 2nd objective at different **********

********** rhs values bounded by the extreme points of 1st objective **********

First loop - find extreme values for 2nd objective
Loop (level$ (ord (level$) <= step ("Area") ),

Defining the initial value for the RHS to constraint the 1st objective
obj_val ("Area") = obj_val ("Area") - obj_val_inc ("Area");

Defining the 2nd objective - Energy as goal
obj_goal (objective) = no;
obj_goal ("Energy") = yes;

Assigning values for the RHS term
rhs ("Area") = obj_val ("Area");

Defining which objectives to use as constraint in this case, Area
obj_index = 2;

Solving the model to obtain the maximum and minimum values
for the 2nd objective

Solve Mod Intermediate USING MIP MAXIMIZING CURROBJ;
max_val("Energy") := Z.L("Energy");
Solve Mod Intermediate USING MIP MINIMIZING CURROBJ;
min_val("Energy") := Z.L("Energy");

* Calculating the increment between steps and defining the first value for obj_val(Energy)
obj_val_inc("Energy") := (max_val("Energy") - min_val("Energy"))/(step("Energy") - 1);
obj_val("Energy") := min_val("Energy") - obj_val_inc("Energy");

* Second loop — Solve the problem having the 1st and 2nd objectives bounded by constraints
Loop(level2$ (ord(level2) <= step("Energy")),

* Defining the initial value for the RHS to constraint the 2nd objective
obj_val("Energy") := obj_val("Energy") + obj_val_inc("Energy");

* Defining the 3rd objective — Length as goal
obj_goal(objective) := no;
obj_goal("Length") := yes;

* Assigning values for the RHS term
\[ \text{rhs} ("\text{Energy}") = \text{obj\_val} ('\text{Energy}') ; \]

\[ \text{∗ Defining which objectives to use as constraints in this case, Area and Energy} \]
\[ \text{obj\_index} = 3 ; \]

\[ \text{∗ Solving the model to obtain the maximum and minimum values for the 3rd objective} \]
\[ \text{Solve\_Mod\_Intermediate USING\_MIP\_MAXIMIZING\_CURROBJ;} \]

\[ \text{∗ Recording the solutions} \]
\[ \text{sol\_point (objective , level2) = Z.L (objective);} \]

\[ \text{∗ Writing the solution points in the output file} \]
\[ \text{Loop (objective , Put\_sol\_point (objective , level2 ));} \]
\[ \text{Put ; /;} \]

\[ \text{∗ End of second loop} \]
\[ \text{);} \]

\[ \text{∗ End of first loop} \]
\[ \text{);} \]

\[ \text{∗ Close the output file} \]
\[ \text{putclose Results ;} \]

\[ \text{scalar elapsed ; elapsed = (jnow - starttime) * 24 * 3600 ;} \]
display elapsed;