Linear Power Discretization and Nonlinear Formulations
For
Optimizing Hydropower in a Pumped-Storage System

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(Abstract)

Operation of a pumped storage system is dictated by the time dependent price of electricity and capacity limitations of the generating plants. This thesis considers the optimization of the Smith Mountain Lake-Leesville Pumped Storage-Hydroelectric facility. The constraints include the upper and lower reservoir capacities, downstream channel capacity and flood stage, in-stream flow needs, efficiency and capacity of the generating and pumping units, storage-release relationships, and permissible fluctuation of the upper reservoir water surface elevation to provide a recreational environment for the lake shore property owners.

Two formulations are presented: (1) a nonlinear mixed integer program and (2) a discretized linear mixed integer program. These formulations optimize the operating procedure to generate maximum revenue from the facility. Both formulations are general and are applicable to any pumped storage system. The nonlinear program retains the physical aspects of the system as they are but suffers from non-convexity related issues. The linear formulation uses a discretization scheme to approximate the nonlinear efficiency, pump, turbine, spillway discharge, tailrace elevation-discharge, and storage-elevation relationships. Also, there are binary unit dispatch and either/or constraints accommodating spill and gated release.

Both formulations are applied to a simplified scheme of the Smith Mountain Lake and Leesville pumped storage system. The simplified scheme uses a reduced number of generating and pumping units at the upper reservoir to accommodate the software limitations. Various sensitivity analyses were performed to test the formulations. The linear formulation consistently performs better than the nonlinear. The nonlinear solution requires a good starting point for optimization. It is most useful as a verification tool for the solution from the linear program on all occasions. The formulations yield the best schedules for generating and pumping. A coarse time interval limits the use of all pumps in the presence of the spill constraint. A sufficiently large difference in the diurnal unit price encourages short-term pump back as opposed to a weekly cycle. The Leesville (downstream) reservoir affects the power production schedule with its large (approx. 9 ft) forebay rise for every foot drop at the Smith Mountain Lake. The linear formulation provides a valuable tool for studying the system under a wide range of conditions without having to worry about the computational difficulties associated with the nonlinear formulation.
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Chapter 1  Introduction

1.1  Problem Overview

Existing hydroelectric facilities have the ability to reduce air pollution, heat pollution, radioactive waste, and fly ash. Because of the ease with which water can be withdrawn or pumped up stream, hydropower facilities are used in conjunction with thermal plants, such as coal, oil, and nuclear. Pumped storage and hydroelectric plants are operated during peak power usage periods to make up for the shortfall that thermal power plants leave and during low power demand periods. The extra energy from thermal plants is used to pump water upstream to the upper reservoirs. This helps to run the thermal units in an efficient manner, as well as to prepare the hydropower plants for the next peak power demand.

The operating policy of a pumped storage hydropower system is composed of a profit maximizing function and a number of constraints. The profit function maximizes the revenue difference between production and consumption (pumping). Production yields a positive return, whereas, consumption results in a revenue loss. Pumping becomes a desirable alternative due to cost variations of electricity. The time dependent cost data clearly governs the operating policy of a pumped storage system. The practice of charging more money during peak demand periods has encouraged the production of power at the facility’s maximum capacity during peak hours and pumping water from the lower reservoir to the upper reservoir during non-peak hours. There are two broad categories of hydro-scheduling, namely long-range and short-range. The long-range hydro-scheduling problem includes the prediction of water inflows, water use (other than for power), power demand, and water releases. This thesis focuses on short-term hydro-scheduling. This type of problem assumes that the load, inflows, unit availability and
electric cost are all known. In this thesis, nonlinear and linear mixed integer program formulations are given for the optimization of the operation of a pumped storage system. The formulation is based on the Smith Mountain Lake-Leesville system. American Electric Power (AEP) is owner and operator of this system. See Figure 1-1 for a location of the hydroelectric facilities owned by AEP. The rest of this chapter is organized as follows. First, a brief history of the Smith Mountain Lake-Leesville system is presented. Next, this presentation helps to point out certain salient features of the pumped storage units as given in the section on problem description. Finally, the objectives and organization of the thesis are given.

Figure 1-1. AEP Hydroelectric Plants
1.2 Project History

In the Operating Department Manual for the Smith Mountain Project, it states that the thought of constructing a dam along the Roanoke River originated in 1924. The property changed hands and AEP put forth an application in 1956 for a preliminary permit. The preliminary permit sought to place a conventional hydroelectric plant along the Roanoke River. The Roanoke River is a small river and could only provide a conventional hydropower potential of 40 to 60 MW (AEP, 1971). AEP revised the application to request the construction of a two-dam project. Figure 1-2 shows a detailed location of the Smith Mountain - Leesville pumped storage and hydroelectric facility. Approval of this application allowed AEP the opportunity to build a pumped storage facility. A hydropower study showed that the facility would have a generating capacity of 580 MW between two dams. Construction began in 1960, was completed in 1965, and the plant has been running ever since (AEP, 1971).
1.3 Smith Mountain Lake

The Smith Mountain-Leesville pumped storage hydroelectric facility is used to generate electricity for AEP. The facility consists of two dams and corresponding reservoirs. The upper reservoir, Smith Mountain Lake, is 40 miles (64 km) long and has 400 miles (645 km) of shoreline. Water storage for Smith Mountain Lake is 1.14 million Ac-ft (1844 million m$^3$) with an upper operating level of 795.00 ft (242.32 m) above sea level. The power pool fluctuation is limited to approximately 2 ft (0.61 m) because of the maximum storage available in the lower reservoir. The Smith Mountain dam is an arch concrete dam 235 ft (71.6 m) high and 816 ft (249 m) long. The dam houses five power-generating units, each of which has a Francis-type turbine. Units 1 and 5 can produce 70
megawatts of electricity each with 6,000 cfs (156 m3/s) of water passing through each penstock; units 2 and 4 can produce 160 megawatts each, passing 11,000 cfs (425 m3/s) through each penstock; and unit 3 can produce 100 megawatts, passing 8000 cfs (227 m3/s) through the penstock. In addition to power generation, units 1, 3, and 5 are used to pump water from the lower reservoir back into the Smith Mountain Lake. Shown in Figure 1-3 are the penstocks for units 2, 3, and 4. Units 2 and 4 are designed as turbines only. Units 1, 3, and 5 are reversible units, acting as pumps or turbines, depending on the need (AEP, 1971).

![Smith Mountain Dam](image)

**Figure 1-3. Smith Mountain Dam**

### 1.4 Leesville Lake

Leesville Lake is the lower reservoir and is 17 miles (27 km) long with 100 miles (161 km) of shoreline. The water storage capacity in the Leesville Lake is 95,000 Ac-ft (117 million m³) and the reservoir level can fluctuate by as much as 13 ft (3.96 m).
Releasing one foot (0.3 m) of the water at Smith Mountain Lake can raise the Leesville Lake level by 6 ft (1.83 m). The Leesville Dam is 90 ft (27.4 m) high and 980 ft (299 m) long. The dam houses two fixed blade propeller power generating units, each with a capacity of 20 megawatts. The primary function of this reservoir is to provide a holding pool of water that can be pumped back into Smith Mountain Lake (AEP, 1971).

1.5 Problem Description

An important aspect of hydropower operation is the load curve. The load curve represents the power demand as a function of time. Quick fluctuations in the load curve and slow response of thermal units can create serious problems with the stability of the electrical system. Because electricity cannot be stored, the demand has to be met with simultaneous production that results in slight excess and deficit. By current regulations, the area control error must cross zero every ten minutes (see section 0). This error must be minimized within a selected time duration. For this reason, pumped storage provides an exceptional benefit to power companies. The pumped storage facility, or any hydroelectric facility, can begin to produce power in less than 15 minutes. Another advantage of a pumped storage facility is its ability to consume power. The pumped storage and hydroelectric facility can be producing power, along with the thermal units, for peak demands. When the demand decreases dramatically the thermal units will take time to reduce their output, but the pumped storage facility can reduce its output almost instantaneously, then reverse the units and begin consuming power. AEP does not divide the load between its plants such that a particular plant is required to produce a percentage of the total load. Instead, AEP optimizes the usage of thermal units and adjusts the hydroelectric plants to meet the overall system load. Therefore, Smith Mountain Lake is brought online only to meet peak demands or sudden increases in load. When there is a
surplus of electrical energy in AEP’s region, Smith Mountain Lake is used to meet the area control error requirement through the use of the pumps. Smith Mountain Lake can provide a net difference of 900 MW on the grid in about 15 minutes. This can be done by switching from pumping, which uses 300MW of energy, to producing 600 MW of energy in less than 15 minutes.

1.6 Objectives

The general objective of this thesis is to mathematically formulate the workings of a pumped storage system to obtain an optimal operating procedure. The specific objectives are as follows:

1. Formulate a mathematical non-linear model for the best operation of pumped storage systems.
2. Obtain an efficient linear formulation from the nonlinear formulation
3. Solve both formulations with reduced data from the Smith Mountain Lake-Leesville system.

The remainder of the thesis is organized as follows. Chapter 2 presents an overview of the electrical system. Chapter 3 contains the nonlinear formulation. Chapter 4 has the efficient linear formulation. Chapter 5 contains the results and summary. Chapter 6 presents the conclusions and recommendations.
Chapter 2  Electrical System

2.1  Introduction

The electrical system of the United States consists of many different parts and subsystems. Three important parts of the system are the source, demand, and the grid. The source is made up of different generating facilities. The demand consists of industrial, commercial, municipal, agricultural, and residential loads that extract energy through the grid from the source. The grid is a network of transmission lines, distribution lines, and interconnections with other utility companies. The grid contains substations and other devices, which are used to regulate the voltage and distribute the power to the demand. For more information on power systems, refer to Wood and Wollenberg (1984).

Electricity must be used the moment it is produced. It cannot be stored in large quantities for a long time. Also, there is nothing similar to a valve to alter the flow; the flow must be controlled by generation. This process is like synchronizing several pumps to satisfy the time varying demand of water without the benefit of valves and storage tanks. From the power plant, the electricity is transmitted at nearly the speed of light over transmission lines, which are normally supported by tall steel towers. Transmission lines are operated at a high voltage, which reduces energy losses due to resistance. On transmission lines, the neutral wire is located above the current carrying wires. The neutral wire serves as a lightning arrester and in some cases houses optical fibers for use by the utility owner or may be leased out to other companies. The destination of a transmission line is a substation. There, the voltage is reduced by a step down transformer and transferred to smaller lines called distribution lines. They are typically carried on wooden poles, which distribute electricity to neighborhoods, commercial areas and farms. On distribution lines, the neutral wire is located below the current carrying wires, for safety reasons. The neutral wire, ideally, should not carry any electrical flow because it is grounded every few poles. The neutral wire is grounded by connecting it to the ground with a copper wire. This
serves to carry any extra electricity into the ground where it cannot cause harm (Randy Agnew, personal interview, 1997).

All parts of an electrical system work together. Consider this analogy of water to the electrical system. Given a bucket (grid), consider that person A (source or generation) begins to pour water into the bucket while person E (demand) starts to withdraw water from the bucket. This event ensures person E that the water being withdrawn from the bucket is from person A. Another situation is when person A (source 1), person B (source 2), and person C (source 3) all have their own water to fill the same bucket. Person E (demand 1) begins to withdraw water from the bucket. This water may have come from person A, B, C, or any combination. Now another person F (demand 2) joins person E at the bucket. Person F begins to withdraw water from the bucket. This final situation makes it difficult to determine from whom the water is coming, other than the fact that person A knows how much they have added to the bucket, person B knows how much they have added to the bucket, and the same for person C. On the other end, person E and person F know how much each has withdrawn. The exact beginning and the exact destination of a drop of water is undeterminable, but the quantities of the supply and demand are measurable. Thus each person A, B, and C will get paid according to the amount each supplied and each person E and F will pay the amount withdrawn. This analogy of a bucket of water to an electrical system is a simplification of the electrical system, but it helps one to understand better. The previous cases have ignored the possibility of water overflow from the bucket or the bucket going dry. The water level in the bucket can be used to describe the system frequency and voltage. Consider the first situation with only one source and one demand; A and E. If person A (source) is adding water at the rate of $S_A$ and person E is withdrawing at the rate of $D_E$, where $S_A > D_E$ then the volume in the bucket will begin to rise. This is like too much electricity generation, which causes the frequency and voltage to increase. Frequency is measured in cycles per second. One complete revolution of an electric device is considered one
cycle. Now add person F to this same situation, withdrawing water at the rate of \(D_F\), where \(D_E + D_F > S_A\). The volume in the bucket will begin to decrease also causing the outlet pressure to decrease. A similar effect happens when the power demand is greater than generation. The frequency and voltage will start to decrease causing motors and clocks to run slower. For more details on how frequency and voltage are affected as the result of load variation the reader should consult the books by Faulkenberry and Coffer (1996) and Elgerd (1982).

### 2.2 Power Generation

There are three main types of generating units: thermal (steam), gas combustion, and hydroelectric. These systems have different operating procedures. A thermal unit has a slow start-up and shutdown process and therefore, is unable to quickly adapt for large increases or decreases in demand. A hydroelectric unit can be engaged or disengaged in two minutes. This is why hydropower is primarily used during peak demand periods. For multiple thermal and hydropower units to be connected to the grid, they must be synchronized. It is critical that the generating units be in synchronization with the system. This synchronization ensures that the unit is operating at the correct frequency.

For synchronization to take place, Elgerd (1982) states that the following conditions must be satisfied: (1) the generator and network frequencies be equal, (2) the phase sequence of the generator match that of the network, (3) the generator emf and network voltage be equal in magnitude, and (4) the emf and network voltage have equal phase. The unit can then produce or consume power. Because alternate current and voltage are sinusoidal in nature, the power varies both positively and negatively with time as opposed to DC power, which is always positive. The power generated is obtained as the product of sinusoidal voltage and the current, called the apparent power (expressed in Volt-Amps, VA), which is the power sent to a device. The apparent power is also used to calculate heat generation by the equipment, and for sizing wires and circuit breakers. Apparent power is the amount of power drawn out of the generator.
However, the power utilized by the device is only the positive portion of the power (the cosine component) called the real power measured in watts (W). The difference between the apparent power and the real power is known as the reactive power, which is both positive and negative with an average of zero power. The ratio of real power to the apparent power is called the power factor. Therefore, the generator or any power supply must provide the actual load divided by the power factor as the apparent power to support the device. The power factor is determined based on the phase angle between the voltage and the current.

Some large utility companies depend on steam units for the majority of their generation. There are two major types of steam units; those fired by coal and those run by nuclear fuel. If the unit is off-line (cold), then there is a significant time lag to bring the unit in to synchronization. If the unit is in synchronization then it takes approximately 20-30 minutes to bring one unit up to a generating capacity of 100 MW. Therefore, if a utility company notices their demand increasing by a significant amount in a short period of time, multiple plants will increase their power production with units already on-line. For example, if demand requires an increase of 100 MW in power production, five plants will each be raised 20MW; thus the time required to produce 100MW will only be 10 minutes, as opposed to 20-30 minutes for one plant. The units have a narrow band of high efficiency, which is near full capacity. Typically, the units are kept running close to full capacity because of the efficiency curve. The units are only brought on-line when there is a definite need to produce more power for a long period of time. Also, the units are only taken off-line when there is no other way to reduce the power output or there is a long period of expected power surplus (Agnew, personal interview, 1997).

Run-of-the river hydropower generating facilities can be used both for peak and base loads. These facilities are typically constrained by reservoir levels and downstream minimum and maximum flow. They may be utilized for other water resources, such as irrigation, flood control, and recreation. For base loads, the turbine units are typically set to an automated mode.
This automated mode will vary the discharge through the unit depending upon the power output required and the minimum stream flow required.

Pumped storage plays an important role in the generation, demand, and control aspects of the system. The pumped storage idea works because the selling price of electricity is dependent on time. Typically, pumped storage is used in conjunction with thermal power. Pumped storage systems store electricity in the form of potential energy (water). The facility will operate the turbines during the peak hours of the day when the cost of electricity is the highest. Thus, the utility company will receive a larger profit for the same water than if it was released through the turbines during non-peak hours. The cost of electricity is cheapest when the demand is the lowest. This idle time during the non-peak hours allows the electric company to use excess power to reverse the turbines and pump water up stream. If the company does not have excess electricity, then it will purchase the power from an adjacent utility company at the lower non-peak cost. This allows a pumped storage system to be economically feasible. The downstream channel constraints can be dictated by an environmental, political, or recreational consideration or by a regulatory agency. The maximum allowable flow for the channel may be set to reduce erosion or prevent flooding downstream of the reservoir. For small channels, the minimum allowable flow for the channel may be set to ensure a healthy aquatic life system, or to allow fishing and recreational boating. However, meeting this minimum water level may require water to be released through control gates, by-passing the turbines. Koebbe (1993) has stated that pumped storage has been proven, to date, to be the most efficient and cost-effective energy storage. There are more than 180 plants worldwide with a combined capacity greater than 70,000 MW (Koebbe, 1993).
2.3 *Transmission and Distribution*

The transmission network is the backbone of the electrical system. What makes a system more reliable is the ability to interconnect many generating units and other electric companies. As mentioned previously, when one generating unit cannot supply adequate power, another generating unit connected to the same grid can increase production and supply the needed power. A map of AEP’s transmission line layout is shown in Figure 2-1 and the transmission network linking the Smith Mountain – Leesville system is shown in Figure 2-2).

Transmission lines transport power at a high voltage and low current. This allows the power to be transmitted with less resistance and therefore, less waste in the form of heat. Typical transmission voltages are 34.5kV to 765kV (Faulkenberry and Coffer, 1996).

The ability to transmit large quantities of electricity from the generating plant to a local system (distribution network) is a vital part of delivering reliable electricity. To get from a transmission line to a distribution line, the power must go through a substation. A substation is the link between a power company and the residential and commercial electricity users. Distribution lines are operated at a lower voltage level for safety reasons. Generally, the distribution system has voltage levels with in a range of 11.6 to 34.5 kV (Faulkenberry and Coffer, 1996).

The voltage along the distribution line will decrease because of consumers withdrawing electrical power and line losses. For this reason there is a range of voltages, 110 to 125 volts, which a consumer may receive. The voltage that a consumer receives is dependent upon the overall load and their distance from the substation. Because of this phenomenon, the voltage leveling at the substation is set higher than the nominal voltage and the voltage will decrease the further the consumer is from the substation.

The United States is divided into two major electrical grids; the eastern grid and the western grid. These grids are not completely isolated, but are only connected in a few locations.
These connections between the east and west are considered a weak link because they will “trip” before allowing too much power to be drawn across the connection. The eastern grid is very strong with many interconnections between utility companies in the eastern U.S. These interconnections bring added stability to the system (Agnew, personal interview, 1998).

Interconnections between utility companies create a balance between generation and demand. The benefit comes when looking at the fluctuation in peak demand periods. While one electric company may be experiencing a peak demand, another company may have electricity to spare. The company with extra power supplies the grid and is, in effect, selling their extra power to the company that needs it. Another factor that is affected by the grid is the system inertia. The interconnections create a larger grid, which increases the inertia. Therefore, small fluctuations in generation and demand are less noticeable.
Figure 2-1. AEP Southern Transmission System Map (AEP, 1999)
2.4 System Control

The fluctuations that occur because of load changes present the system operator with the complex task of balancing generation with demand. As the load changes so does frequency (f), voltage (V), phase angles (ϕ), current (I), torque (T), power (P) and kinetic energy (W_{kin}). Elgerd (1982) puts it as follows. The electromechanical air-gap torque that is developed within the generator forms the basic link between the mechanical turbine power, and the electrical power transmitted from the generator terminals. The physical law that controls this phenomenon is the force on the current carrying conductor placed in a magnetic field, which is the vector product of the magnetic field strength and the current. If this law is applied to the rotor based magnetic field wave and stator based current wave, the stator is subject to a force (and torque) acting in the direction of rotation. The rotor is subject to an equal and opposite reaction force and torque. This torque tends to decelerate the rotor, but is prevented from doing so by the turbine torque. Therefore, there is an intimate connection between the magnetic field - current induced torque and the mechanical torque of the turbine. If the system experiences a drop in load
(excess generation), then there will be an imbalance and the frequency increases. This frequency increase will cause motors, clocks, etc. to run faster. As the frequency increases the motors will realize a higher load torque. The increases in the load torque will withdraw more power from the grid. This withdrawal of power will deplete the excess supply, which will allow the system to reach equilibrium. The cost for this equilibrium is a higher frequency, along with changes in voltage, phase angles, current, torque, power, and kinetic energy. These changes can cause severe damage to the generating unit and to the electricity users if not controlled. For example, a thermal unit requires a specific angular velocity for the turborotor. If this angular velocity is not maintained, the resonance within the turborotor may reach a critical rate and cause cracks or complete failure (Elgerd, 1982).

The Automatic Load-Frequency Control (ALFC) provides compensation for small variations in the load and frequency. The ALFC provides generator control of power output and frequency. The ALFC has the ability to make small adjustments by changing the position of the valve on a thermal unit or the wicket gates on a hydro unit. These changes are used to increase or decrease the power output to coincide with the small and quick fluctuations in demand. The ALFC has a response time of one to several seconds. A second function of the ALFC is to provide extended frequency control. This portion of the ALFC is non-responsive to the quick changes; instead, it balances the frequency and power over several minutes. The Automatic Voltage Regulator (AVR) provides system stability through regulation of DC power supplied to the generator field. This DC power is supplied through an exciter. An exciter is either a DC generator, or a brushless or static type generator. The exciter energizes the generator field windings which controls
the voltage (Elgerd, 1982). For more information on AC electrical machines refer to Hambley (1997).

Depending upon the system demand, power companies have a certain range of power production that must be maintained. Over a given period, a power company may produce more than or less than the required power demand; however, this excess and deficiency must equal zero when summed for this time period. This condition can be considered a curve function, and when integrated computes a positive and negative area. This area is called the area control error (see Figure 2-3) and is regulated by North American Electric Reliability Council (NERC) in accordance with East Central Area Reliability Coordinate Agreement (ECAR). See Figure 2-4 for the states affected by ECAR. NERC requires that all power companies maintain these criteria, or else the inadvertent energy will increase or decrease beyond the acceptable levels. This increase or decrease in energy will affect the overall performance of the system (Randy Agnew, personal interview, 1998; Don Benjamin, personal communication, 1999; and NERC, 1996).
**Area Control Error (ACE)**

- **ACE = Actual Interchange - Schedule Interchange**
- **NERC Operating Standards:**
  - ACE must be zero once at least every ten minutes.
  - Average deviation must be within specified limits.

**Figure 2-3. Area Control Error (Walton, 1999)**

---

**East Central Area Reliability Coordination Agreement (ECAR)**

(Illinois, Indiana, Kentucky, Michigan, Maryland, Ohio, Pennsylvania, Virginia, West Virginia)

**Figure 2-4. ECAR region, to which AEP belongs. (NERC)**
When the demand starts to drop quicker than the utility company can reduce its production, the company can divert it to its pumped storage facility to pump (use electrical power) water into the upper reservoir. The increase in power demand created by the pumps will help to balance the supply and demand curves. This balance of supply and demand allows the area control error to cross zero (see Figure 2-3). This method of increasing the load through “energy storage” is preferred because fluctuating the production of the steam plants is expensive and inefficient. In the next chapter an optimization for the efficient operation of a pumped storage system is given. The formulation yields both the generating and pumping schedules while maximizing revenue.
Chapter 3  Formulation of Pumped Storage Optimization
Problem

3.1 Introduction

Because electricity cannot be stored as is, it must be delivered as soon as it is produced. However, there have been attempts to store electricity by indirect means including pumped hydro storage, compressed air storage, and battery storage, as well as, super conducting magnetic field storage and demand side management (Paula, 1990; Henry and Graeser, 1985). In pumped storage, the water is pumped back to an upper reservoir during the weekend and withdrawn during the week to satisfy the peak load. Compressed air energy storage involves compressing air into a container. When needed, the compressed air is heated with a fuel and the expanding air does work on a turbine. Batteries are recharged with an AC current inducing a chemical reaction among the constituents of the battery. Typically, the reverse reaction results in discharging the battery. Super conducting magnetic energy storage provides a means of directly maintaining the energy in the magnetic field. Demand side management, as opposed to the (energy) supplier’s storage schemes, aims to utilize electrical energy efficiently on the users’ end. A general feature of demand side management is to use electricity the previous night to heat or cool a storage medium such as bricks or chilled water. The next day utilize the heat from the bricks or circulate the chilled water to cool the building. In this thesis, the focus is on the pumped storage units.

Pumping is a desirable alternative due to the variations in the cost of electricity. The practice of charging more money during peak demands has encouraged the production of power at the facility’s maximum capacity during peak hours and pumping water from the lower reservoir to the upper reservoir during non-peak hours.

Velz (1971) discusses the environmental impacts of the pumped storage systems. These include flooding of large areas, alteration of the hydrology, changes to aquatic biology and fish, danger from possible failure of dams, and overhead high voltage transmission lines. However,
the approval of such projects clearly indicates their benefits over the environmental impacts. Also, many of these effects can be minimized. Another important fact is the ever-growing demand for electrical energy. Hydro units have little to no polluting effects on the environment, whereas, all other major modes of power generation have serious effects.

An important issue in hydropower operation is the load curve. Quick fluctuations in the load curve and the slow response of thermal units can create serious problems with the voltage and area control error. Because demand must be met with simultaneous production and thermal units cannot quickly respond to increases and decreases in demand, pumped storage units provide an exceptional benefit to power companies. The pumped storage facility can produce power in less than 15 minutes, and can be used along with the thermal units for peak demand periods. When the demand decreases the hydro unit can consume the excess power from the thermal units by pumping water to the upper reservoir. Eriksen and Pedersen (1997) and Giles and Wunderlich (1991) have formulated criteria related to the value of hydropower. They consider the exponential growth in the thermal unit costs above certain threshold power to satisfy the peak demand, as well as, the costs involved in chasing the peaks and valleys of the load curve. Cohen and Wan (1985) group the optimization models related to pumped storage as marginal cost models, linear/nonlinear, and dynamic programming (DP) models. They also provide a DP formulation to a basic pumped storage problem. Gorenstin et al. (1992) point out the curse of dimensionality associated with the DP formulation. In addition, DP does not have such general purpose software, as does the linear programming (LP) and nonlinear programming (NLP). However, Lee and Chen (1992) provide good details related to the constraints involved in a pumped storage system within a DP framework (also, see Lee et al. 1987). Li et al. (1992) apply a network model for a hydrothermal coordination problem. From the literature survey, the following points emerge. No detailed explicit formulation is readily available. The non-convex nature of the NLP formulation is not discussed in detail, and solutions to overcome multiple local
optima are not offered. Linearization schemes have not been suggested. In this thesis a well
detailed formulation with sufficient explanation is presented. Because of the non-convex nature
of the NLP problem, a suitable linearized version is also presented.

AEP does not divide the load between its plants such that a particular plant is required to
produce a percentage of the total load. Instead, AEP optimizes the usage of thermal units and
adjusts the hydroelectric plants to meet the remaining system load. Therefore, Smith Mountain
Lake is brought online only to meet the peak demands or sudden increases in load. When there
is a surplus of electrical energy in AEP’s region, Smith Mountain Lake is used to meet the area
control error requirement by running the pumps. Smith Mountain Lake can provide a net
difference of 900 MW on the grid in about 15 minutes. The three turbines, that also pump, can
use 300 MW of energy to pump, and then switch to producing 600 MW in less than 15 minutes.

In the following pages, a mathematical formulation based on this real system is
presented. A schematic of the system is shown in Figure 3-1. The formulation results in a
nonlinear integer program. The solution space is non-convex because of the need for binary
variables as well as the product form of the power constraints. As pointed out in Chapter 1, this
thesis focuses on short-term hydro-scheduling. Short-term hydro-scheduling assumes that the
power demand, inflows, unit availability and electric cost are all known. The following
notations are used.
3.2 List of Notations

\( A^P_j \) = Efficiency coefficient for the jth pump
\( A^{S1} \) = Coefficient for the stage-storage relationship in the upper reservoir
\( A^{S2} \) = Coefficient for the stage-storage relationship in the lower reservoir
\( A^{TR2} \) = Coefficient for the stage-discharge relationship in the lower tailrace
\( A^T_j \) = Efficiency coefficient for the jth turbine in the upper reservoir
\( A^{T2} \) = Efficiency coefficient for the jth turbine in the lower reservoir
\( A^{HP}_j \) = Coefficient for the head-discharge relationship for the jth pump in the upper reservoir
\( A^{Spill1} \) = Coefficient for the spillway stage-discharge relationship in the upper reservoir
\( A^{1}_{j} \) = Efficiency coefficient for the jth pump in the upper reservoir
\( B^P_j \) = Efficiency coefficient for the jth pump
\( B^{S1} \) = Constant for the stage-storage relationship in the upper reservoir
\( B^{S2} \) = Constant for the stage-storage relationship in the lower reservoir
\( B^{TR2} \) = Coefficient for the stage-discharge relationship in the lower tailrace
\( B^T_j \) = Efficiency coefficient for the jth turbine in the upper reservoir
\( B^{T2} \) = Efficiency coefficient for the jth turbine in the lower reservoir
\( B^{HP}_j \) = Coefficient for the head-discharge relationship for the jth pump in the upper reservoir
\( B^{Spill1} \) = Coefficient for the spillway stage-discharge relationship in the upper reservoir
\( C^P_j \) = Efficiency coefficient for the jth pump
\( C^{Spill1} \) = Constant for the spillway stage-discharge relationship in the upper reservoir
\( C^{TR2} \) = Coefficient for the stage-discharge relationship in the lower tailrace
\( C^T_j \) = Efficiency coefficient for the jth turbine in the upper reservoir
\( C^{T2} \) = Efficiency coefficient for the jth turbine in the lower reservoir
\( Cd \) = Orifice Discharge Coefficient
\( Chan(t) \) = Discharge through the downstream channel (cfs)
\( Chan_{\text{min}}, Chan_{\text{max}} \) = Minimum and maximum capacity of the downstream channel (cfs)
\( D^P_j \) = Efficiency constant for the jth pump
\( D^{TR2} \) = Constant for the stage-discharge relationship in the lower tailrace
\( D^T_j \) = Efficiency constant for the jth turbine in the upper reservoir
\( D^{T2} \) = Efficiency constant for the jth turbine in the lower reservoir
\( C(t) \) = Cost Coefficient ($/MW$)
\( FB1(t) \) = Forebay elevation for the upper reservoir (ft)
\( FB2(t) \) = Forebay elevation for the lower reservoir (ft)
\( g \) = Acceleration due to gravity (ft/s²)
\( Gated(t) \) = Controlled discharge through the lower dam (cfs)
\( Gated \) = Maximum discharge through the lower dam (cfs)
\( H_1(t) \) = Head for the upper reservoir (ft)
\( H_2(t) \) = Head for the lower reservoir (ft)
\( H_{PON}^j(t) \) = Head value for the jth unit when pumping (ft)
\( H_{POFF}^j(t) \) = Head value for the jth unit when not pumping (ft)
\( I_1(t) \) = Inflow to upper reservoir (cfs)
\( I_2(t) \) = Inflow to lower reservoir (cfs)
\( J_{T1} \) = Total number of turbines for the upper reservoir
\( J_{T2} \) = Total number of turbines for the lower reservoir
\( J_P \) = Total number of pumps
\( PP(t) \) = Total power consumed by the pumps (MW)
\( PP_j(t) \) = Power consumed by the jth pump (MW)
\( PT(t) \) = Total power produced from all of the turbines (MW)
\( PT_{1j}(t) \) = Power produced by the jth turbine for the upper reservoir (MW)
\( PT_{2j}(t) \) = Power produced by the jth turbine for the lower reservoir (MW)
\( QT_{1j}(t) \) = Discharge for the jth turbine for the upper reservoir (cfs)
\( QT_{2j}(t) \) = Discharge for the jth turbine for the lower reservoir (cfs)
\( QT_{1j}, QT_{1j}^{\text{min}} \) = Minimum and maximum discharge for the jth turbine for the upper reservoir (cfs)
\( QT_{2j}, QT_{2j}^{\text{min}} \) = Minimum and maximum discharge for the jth turbine for the lower reservoir (cfs)
\( OP_j(t) \) = Discharge for the jth pump (cfs)
\( OP_j^{\text{min}}, OP_j^{\text{max}} \) = Minimum and maximum discharge for the jth pump (cfs)
\( S_1(t) \) = Upper reservoir storage (ft\(^3\))
\( S_1^{\text{max}} \) = Maximum upper reservoir storage (ft\(^3\))
\( S_2(t) \) = Lower reservoir storage (ft\(^3\))
\( S_2^{\text{max}} \) = Maximum lower reservoir storage (ft\(^3\))
\( Spill_{1YES}(t) \) = Water elevation with spillage in the upper reservoir (ft)
\( Spill_{1NO}(t) \) = Water elevation with no spillage in the upper reservoir (ft)
\( Spill_{1YES}, Spill_{1YES}^{\text{max}} \) = Elevation of the dam crest and maximum water elevation in the upper reservoir (ft)
\( Spill_{1NO}, Spill_{1NO}^{\text{max}} \) = Minimum and maximum water elevation in the upper reservoir with out spillage (ft)
\( Spill_{2NO}(t) \) = Water elevation with no spillage in the upper reservoir (ft)
\( Spill_{2YES}(t) \) = Water elevation with spillage in the upper reservoir (ft)
\( Spill_{2NO}, Spill_{2NO}^{\text{max}} \) = Minimum and maximum water elevation in the lower reservoir with out spillage (ft)
\( Spill_{2YES}, Spill_{2YES}^{\text{max}} \) = Elevation of the dam crest and maximum water elevation in the lower reservoir (ft)
\( TR_{2}(t) \) = Tailrace elevation for the lower reservoir (ft)
\( t \) = Time
\( UnContRel(t) \) = Discharge through the spillway in the upper dam (cfs)
\( UnContRel \) = Maximum discharge through the spillway in the upper dam (cfs)

\( z \) = Objective Function ($)

\( \beta_{NO}(t) \) = 1, no spillage in the upper reservoir

\( \beta_{YES}(t) \) = 1, spillage in the upper reservoir

\( \delta_1(t) \) = 0, turbines offline

\( \delta_2(t) \) = 0, pumps offline

\( \eta_{T2,j}(t) \) = Efficiency for the jth turbine for the lower reservoir

\( \eta_{T1,j}(t) \) = Efficiency for the jth turbine for the upper reservoir

\( \eta_P(j) \) = Efficiency for the jth pump

\( \nu_j(t) \) = 1, jth pump is producing

\( \gamma \) = Specific weight of water (pcf)

\( \mu_{1,j}(t) \) = 1, jth turbine is producing for upper reservoir

\( \mu_{2,j}(t) \) = 1, jth turbine is producing for lower reservoir

\( \theta_{NO}(t) \) = 1, no spillage in the upper reservoir

\( \theta_{YES}(t) \) = 1, spillage in the upper reservoir
Figure 3-1. Schematic of Pumped Storage System

\[ FB1 = \max(\text{Spill}^{\text{YES}}, \text{Spill}^{\text{NO}}) \]

\[ H1 = \max(HP^{\text{OFF}}, HP^{\text{ON}}) \]

\[ FB2 = \max(\text{Spill}^{\text{YES}}_2, \text{Spill}^{\text{NO}}_2) \]
3.3 Nonlinear Mathematical Formulation

The following formulation is a nonlinear mixed-integer programming model and is a subproblem of the electrical system. Figure 3-1 gives a schematic of the pumped storage system. The objective function given in equation (3.2.1) consists of the time varying cost of power produced from the turbines, and the power consumed by the pumps. The formulation includes the following constraints. For clarity the constraints are organized as follows: Total power produced (3.2.2); upper reservoir power production which includes the definition of head over the unit (3.2.3), power produced (3.2.4), efficiency of the turbine (3.2.5), and flow limits (3.2.6); identical constraints (3.2.7) through (3.2.10) apply for the lower reservoir. The next set of constraints applies to power consumed by the pumps for lifting water back to the upper reservoir. These constraints are: pump power required in (3.2.11), total pump power (3.2.12), efficiency of pumps (3.2.13), and flow limits (3.2.14). Constraints (3.2.15) through (3.2.19) together accomplish the following. When the binary variable \( \nu_j = 0 \), no pumping is possible as the pump flow is set to zero and there may or may not be spillage from the upper reservoir by (3.2.15); also, HP^{ON}(t) is set to zero. When HP^{ON}(t) is zero, the actual head H1(t) is set to HPOFF(t) by (3.2.18). When the binary variable \( \nu_j(t) = 1 \), the upper reservoir water level is set below the spill level. The flow is defined by (3.2.14) and the corresponding head is selected from (3.2.19) based on the pump characteristic curve. The constraints (3.2.20) through (3.2.23) control the spill behavior by the binary variables, \( \Theta^{YES}(t) \) and \( \Theta^{NO}(t) \). The constraints (3.2.24) through (3.2.29) control whether the unit works as a pump or turbine aided by the binary variables \( \delta_1(t) \) and \( \delta_2(t) \). These two variables in turn, dictate to the unit a specific binary variables, \( \nu_j(t) \) for pumps and \( \mu_j(t) \) for turbines as given by
the constraints (3.2.24) and (3.2.25). The uncontrolled release from the upper reservoir during a spill is given by the constraints (3.2.30) and (3.2.31). The wicket gate area is determined by (3.2.32). The lower reservoir spill pattern is modeled by the constraints (3.2.33) through (3.2.36). The gated release from the lower reservoir during spill is given by (3.2.37). The tailrace-channel flow relation is given in (3.2.38). The instream flow requirement is given by (3.2.39). The channel flow including the gated release and lower dam turbine flow is given in (3.2.40). The storage-elevation relationships are given in the constraints (3.2.42) through (3.2.45) for the upper and lower reservoirs respectively. The continuity constrains are given in (3.2.46) and (3.2.47) for the upper and lower reservoirs. The entire formulation is given below.

Maximize:  \[ Z = \sum_i C(t)(PT(t) - PP(t)) \]  

Subject to:

**Total power production**

\[ PT(t) = \sum_{j=1}^{JT1} PT1_j(t) + \sum_{j=1}^{JT2} PT2_j(t) \]  

**Upper Reservoir Power Production**

**head definition**

\[ H1(t) = FB1(t) - FB2(t) \]  

Assume that the tailrace elevation for Smith Mountain Lake (see Figure 3-2) is equal to the forebay elevation for Leesville Lake (see Equation (3.2.3)).
Figure 3-2. Tailrace of Smith Mountain Dam

Power

\[ P_{T1J}(t) = \eta T1_j \gamma H1(t) Q_T1_j(t) \]  \hspace{1cm} (3.2.4)

Efficiency of turbine unit

\[ \eta T1_j(t) = A_j^{T1} Q_T1^2_j(t) + B_j^{T1} Q_T1^3_j(t) + C_j^{T1} Q_T1_j(t) + D_j^{T1} \]  \hspace{1cm} (3.2.5)

Flow limits

\[ \underline{Q_T1_j \mu 1_j(t)} \leq Q_T1_j(t) \leq \overline{Q_T1_j \mu 1_j(t)} \]  \hspace{1cm} (3.2.6)

Figure 3-3. 26 ft Penstock at Smith Mountain Dam
• Lower reservoir power production

\[ H_2(t) = F_B(t) - T_R(t) \quad (3.2.7) \]

power

\[ P_{T2_j}(t) = \eta T_2(t) \gamma H_2(t) T_2(t) \quad (3.2.8) \]

efficiency

\[ \eta T_{21_j}(t) = A_{j}^{T2} Q_2(t) + B_{j}^{T2} T_2(t) + C_{j}^{T2} T_2(t) + D_{j}^{T2} \quad (3.2.9) \]

flow limits

\[ Q_{T2} \mu_2(t) \leq Q_{T2}(t) \leq Q_{T2} \mu_2(t) \quad (3.2.10) \]

• Pump Consumption

power consumed by jth pump

\[ P_{P_j}(t) = \frac{\gamma H_{1}(t) \cdot Q_{P_j}(t)}{\eta P_j(t)} \quad (3.2.11) \]

total pump power

\[ P_{P}(t) = \sum_{j=1}^{J_P} P_{P_j}(t) \quad (3.2.12) \]

efficiency

\[ \eta P_j(t) = A_j^p Q_{P_j}(t) + B_j^p Q_{P_j}(t) + C_j^p Q_{P_j}(t) + D_j^p \quad (3.2.13) \]

flow limits

\[ Q_{P_j}(t) \leq Q_{P_j}(t) \leq Q_{P_j}(t) \quad (3.2.14) \]
Pump Operation constraints

**spill head**

\[ HP_{j}^{OFF}(t) \leq Spill1^{YES}(1 - \nu_j(t)) \]  \hspace{1cm} (3.2.15)

**pump head**

\[ HP_{j}^{ON}(t) \leq Spill1^{NO} \nu_j(t) \]  \hspace{1cm} (3.2.16)

**flow limit for pump j**

\[ QP_{j}(t) \leq QP \nu_j(t) \]  \hspace{1cm} (3.2.17)

**head for pump or spill**

\[ H1(t) = HP_{j}^{ON}(t) + HP_{j}^{OFF}(t) \]  \hspace{1cm} (3.2.18)

**pump characteristic curve**

\[ HP_{j}^{ON}(t) = A_{j}^{HP} QP_{j}(t) + B_{j}^{HP} \nu_j(t) \]  \hspace{1cm} (3.2.19)

Once it is decided that the pump is operating, then \( HP^{ON} \) assumes the value of \( H1 \) and \( \nu(t) \) equals 1. If the pump is not operating then \( HP^{ON} \) and \( \nu(t) \) must equal 0. When pumping, no spilling should occur at the upper dam. If the forebay (FB1) elevation is less than the dam crest, then there is no spillage (see Equations (3.2.20) and (3.2.21)). The forebay elevation for the upper reservoir has a range of 787.00 to 811.00 feet. If water is passing through the spillways, \( Spill1^{NO}(t) = 0 \) and \( Spill1^{YES}(t) \) will have a value within a certain range (see Equation (3.2.22)). At any given time, only one of the variables \( Spill1^{NO}(t) \) or \( Spill1^{YES}(t) \) will have a value. This value falls within a certain range as dictated by the physical constraints of the system (see Equations (3.2.21), (3.2.22) and (3.2.23)).
Spill constraints
forebay head for upper reservoir

\[ \text{FB1}(t) = \text{Spill}^{\text{NO}}(t) + \text{Spill}^{\text{YES}}(t) \]  \hspace{1cm} (3.2.20)

spill/ no spill constraints

\[ \text{Spill}^{\text{NO}}\theta^{\text{NO}}(t) \leq \text{Spill}^{\text{NO}}(t) < \text{Spill}^{\text{NO}}\theta^{\text{NO}}(t) \]  \hspace{1cm} (3.2.21)

\[ \text{Spill}^{\text{YES}}\theta^{\text{YES}}(t) \leq \text{Spill}^{\text{YES}}(t) \leq \text{Spill}^{\text{YES}}\theta^{\text{YES}}(t) \]  \hspace{1cm} (3.2.22)

\[ \theta^{\text{NO}}(t) + \theta^{\text{YES}}(t) = 1 \]  \hspace{1cm} (3.2.23)

Figure 3-4. Left spillway at Smith Mountain Dam

The turbines may operate at any head range above minimum power pool elevation (787.00ft). There are three issues that surround the operation of the units: (1) pumps should not operate if water is spilling from the upper reservoir, (2) it is not physically possible for a unit to operate as a turbine and a pump simultaneously, and (3) it is not practical for a unit to operate as a turbine with the adjacent unit operating as a pump. In part, equations (3.2.24) and (3.2.25) serve to overcome these issues. The main purpose of
equations (3.2.24) through (3.2.28) is to insure that if one unit operates as a turbine then any other unit if on, must also operate as a turbine. The same applies if one unit operates as a pump.

- **Unit selection constraints**
  
  **Turbine selection**
  
  \[
  \sum_{j}^{JT} \mu_j(t) \leq JT \cdot \delta(t) \quad \text{(Turbines)} \quad (3.2.24)
  \]
  
  **Pump selection**
  
  \[
  \sum_{j}^{JP} \nu_j(t) \leq JP \cdot \delta(t) \quad \text{(Pumps)} \quad (3.2.25)
  \]
  
  \[
  \mu_j(t) \in 0,1 \forall j \quad (3.2.26)
  \]
  
  \[
  \nu_j(t) \in 0,1 \forall j \quad (3.2.27)
  \]
  
  **Turbine or pump**
  
  \[
  \delta(t) + \delta(t) \leq 1 \quad (3.2.28)
  \]
  
  **pump only if no spill**
  
  \[
  \delta(t) \leq \theta^{NO}(t) \quad (3.2.29)
  \]

If there is no spillage, \( \theta^{NO}(t) = 1 \), then \( \delta(t) = 0 \) or \( 1 \). This relationship between discharge through the spillway (see Figure 3-4) and the forebay elevation (see Equation (3.2.21)) ensures that pumping will not occur if the forebay elevation is above 795.00ft.

When the forebay elevation is above the crest of the dam, then \( \theta^{NO}(t) = 0 \) and \( \theta^{YES}(t) = 1 \) causing \( \nu(t) = 0 \) (see Equation (3.2.25) and Equation (3.2.29)). Hence, \( \text{HP}^{OFF}(t) \) is equal to \( \text{H}1(t) \) because the forebay elevation is above the crest of the dam. If there is no
spillage then \(H_1\) will equal either \(HP^{ON}(t)\) or \(HP^{OFF}(t)\). This depends on the need to pump. If there is no pumping then \(v(t) = 0\) forces \(H_1(t) = HP^{OFF}(t)\) (see Equation (3.2.15) and Equation (3.2.18)). When there is no pumping, there may or may not be spillage because \(v(t) = 0, \delta 2(t) = 0\) or \(1,\) and \(\theta^{NO}(t) = 0\) or \(1\). If \(\theta^{NO}(t) = 0\) then there is no spillage, but there is spillage when \(\theta^{NO}(t) = 1\).

**Uncontrolled release at the upper dam**

\[
0 \leq UnContRel(t) \leq \overline{UnContRel} \tag{3.2.30}
\]

**Must spill for uncontrolled release**

\[
UnContRel(t) = A^{Spill^{YES}}Spill^{YES}(t)^2 - B^{Spill^{YES}}Spill^{YES}(t) + C^{Spill^{YES}}\theta^{YES}(t) \tag{3.2.31}
\]

**wicket gate area**

\[
QT_{1j}(t) = A_1(t)Cd\sqrt{2gH_1(t)} \tag{3.2.32}
\]

- **Lower Reservoir Spill Constraints**

\[
FB_2(t) = Spill^{NO}(t) + Spill^{YES}(t) \tag{3.2.33}
\]

\[
\overline{Spill^{NO}}\beta^{NO}(t) \leq Spill^{NO}(t) < \overline{Spill^{NO}}\beta^{NO}(t) \tag{3.2.34}
\]

\[
\overline{Spill^{YES}}\beta^{YES}(t) \leq Spill^{YES}(t) \leq \overline{Spill^{YES}}\beta^{YES}(t) \tag{3.2.35}
\]

\[
\beta^{NO}(t) + \beta^{YES}(t) = 1 \tag{3.2.36}
\]

The forebay range for the lower reservoir is the minimum power pool elevation to the top of the dam. For most situations the spillway at Leesville can pass a large flood (see Figure 3-5). Under normal operating conditions there is no need to pass water through the spillway. The release of water through the control structure is a function of
two variables, water elevation above the crest, and gate opening. The gate opening is controlled by a plant operator. The release of water can range from 0 to 150,000 cfs. Typical power pool elevation is from 600.00 to 613.00 ft. For this reason, the only constraint placed on the gated release of water is that the water elevation must be above 613.00 ft. However, water does not have to pass through the gate at this elevation. This only provides an opportunity for the release of water through the gate. If the water level is at or below 613.00 ft then $\beta^{\text{TES}}(t) = 0$ forcing the Gated($t$) variable to equal 0.

**Gated release**

$$0 \leq Gated(t) \leq Gated\beta^{\text{TES}}(t) \quad (3.2.37)$$

**Tailrace-flow relationship**

$$TR2(t) = A^{TR2} Chan^3(t) + B^{TR2} Chan^2(t) + C^{TR2} Chan(t) + D^{TR2} \quad (3.2.38)$$

**Instream flow requirement**

$$\text{weekly average}\left(\sum_{j=1}^{2} QT_{2,j}(t) + Gated(t)\right) \geq Chan \quad (3.2.39)$$

**Channel flow**

$$Chan(t) = \sum_{j=1}^{JT2} QT_{2,j}(t) + Gated(t) \quad (3.2.40)$$

$$Chan(t) \leq Chan \quad (3.2.41)$$
Figure 3-5. Leesville Dam and Spillway

Storage-Elevation relationship for the upper reservoir

\[ S_1(t) = A^{S_1} F B_1(t) - B^{S_1} \]  \hspace{1cm} (3.2.42)

\[ S_1(t) \leq \bar{S}_1 \]  \hspace{1cm} (3.2.43)

Storage-Elevation relationship for the lower reservoir

\[ S_2(t) = A^{S_2} F B_2(t) - B^{S_2} \]  \hspace{1cm} (3.2.44)

\[ S_2(t) \leq \bar{S}_2 \]  \hspace{1cm} (3.2.45)

Permit requirements set upper and lower limits on the down stream channel flow.

The permit states that a minimum average weekly flow of 650 cfs (109,200 cfsh/week) must be released from the Leesville Reservoir. The maximum flow must be less than
20,000 cfs during any time period. The minimum flow requirement is for stream habitat and the maximum flow requirement is to prevent downstream flooding.

**Continuity for the upper reservoir**

\[
S1(t + \Delta t) = S1(t) - \sum_{j=1}^{JT1} QT1_j(t)\Delta t + \sum_{j=1}^{JP} QP_j(t)\Delta t + \sum_{j=1}^{JP} I1_j(t)\Delta t - UnContRel(t)\Delta t
\]

\[
(3.2.46)
\]

**Continuity for the lower reservoir**

\[
S2(t + \Delta t) = S2(t) + \sum_{j=1}^{JT1} QT1_j(t)\Delta t - \sum_{j=1}^{JP} QP_j(t)\Delta t - \sum_{j=1}^{JT2} QT2_j(t)\Delta t + \sum_{j=1}^{JP} I2_j(t)\Delta t + UnContRel(t)\Delta t - Gated(t)\Delta t
\]

\[
(3.2.47)
\]

### 3.4 Solution Methodology

The above formulation is a nonlinear mixed-integer program and its solution is complex. The problem has a vast array of variables and constraints when analyzed for one hour time steps over a period of a few weeks. A simplified problem has been created in order to provide actual solutions for the variables. The problem has the same constraints, but the number of generating and pumping units, and the time step was increased from one hour to one day. This smaller version is used so that the results can be checked for reasonableness. The nonlinear formulation is solved using LINGO (see APPENDIX B). The results of this program are presented in Chapter 5. For more information on NLP please see Ravindran et al. (1987) and Reklaitis et al. (1983). For more information on LINGO please see Schrage (1998) and LINDO Systems (1998).
Chapter 4  Mixed-integer Linear Formulation

4.1  Introduction

In this chapter a linearized version of the nonlinear formulation of chapter 3 is presented. The nonlinear problem is difficult to solve and lacks a global optimal solution due to non-convexity. The linear problem has a global optimum but is valid only for the linearized constraints and the objective. Therefore, the form of the linearization is crucial. In the following, the range of head over the turbine and the range for the flows are divided into discrete class intervals. The mid points of these class intervals are utilized to obtain estimates of power, head over the turbine, pump, and the released flow. As intervals become small, the solution will improve at an increased computational burden. However, no new theoretical difficulties arise as far as the formulation is concerned. In the following, the formulation is presented following the flow. That is, the sequence of the constraints follow the physical entities, namely, upper reservoir, its turbine/pump discharge, lower reservoir, its turbine, gated release at the lower reservoir, and the downstream channel. The storage relations are included at the end for the upper and the lower reservoirs.
### 4.2 List of Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{1j}$</td>
<td>Efficiency coefficient for the jth pump in the upper reservoir</td>
</tr>
<tr>
<td>$A_{S1}$</td>
<td>Coefficient for the stage-storage relationship in the upper reservoir</td>
</tr>
<tr>
<td>$A_{S2}$</td>
<td>Coefficient for the stage-storage relationship in the lower reservoir</td>
</tr>
<tr>
<td>$A_{Spill}$</td>
<td>Coefficient for the spillway stage-discharge</td>
</tr>
<tr>
<td>$A_{TR2}$</td>
<td>Coefficient for the downstream tailrace stage-discharge relationship</td>
</tr>
<tr>
<td>$B_{S1}$</td>
<td>Constant for the stage-storage relationship in the upper reservoir</td>
</tr>
<tr>
<td>$B_{S2}$</td>
<td>Constant for the stage-storage relationship in the lower reservoir</td>
</tr>
<tr>
<td>$B_{Spill}$</td>
<td>Coefficient for the spillway stage-discharge relationship</td>
</tr>
<tr>
<td>$B_{TR2}$</td>
<td>Coefficient for the downstream tailrace stage-discharge relationship</td>
</tr>
<tr>
<td>$C_{Spill}$</td>
<td>Constant for the stage-storage relationship in the upper reservoir</td>
</tr>
<tr>
<td>$C_{TR2}$</td>
<td>Coefficient for the downstream tailrace stage-discharge relationship</td>
</tr>
<tr>
<td>$C(t)$</td>
<td>Cost Coefficient ($/MW$)</td>
</tr>
<tr>
<td>$Cd$</td>
<td>Orifice Discharge Coefficient</td>
</tr>
<tr>
<td>$Chan(t)$</td>
<td>Discharge through the downstream channel (cfs)</td>
</tr>
<tr>
<td>$Chan_{m}^l$, $Chan_{m}^u$</td>
<td>Lower and Upper bound on the channel flow for the mth interval (cfs)</td>
</tr>
<tr>
<td>$D_{TR2}$</td>
<td>Constant for the downstream tailrace stage-discharge relationship</td>
</tr>
<tr>
<td>$FB1(t)$</td>
<td>Forebay elevation for the upper reservoir (ft)</td>
</tr>
<tr>
<td>$FB1_k^l$, $FB1_k^u$</td>
<td>Lower and Upper Bound Forebay elevation for the upper reservoir for the kth head interval (ft)</td>
</tr>
<tr>
<td>$FB2(t)$</td>
<td>Forebay elevation for the lower reservoir (ft)</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity (ft/s$^2$)</td>
</tr>
<tr>
<td>$Gated(t)$</td>
<td>Controlled discharge through the lower dam (cfs)</td>
</tr>
<tr>
<td>$Gated$</td>
<td>Maximum discharge through the lower dam (cfs)</td>
</tr>
<tr>
<td>$H1(t)$</td>
<td>Head for the upper reservoir (ft)</td>
</tr>
<tr>
<td>$H1_k^l$, $H1_k^u$</td>
<td>Lower and upper bound for the kth head interval (ft)</td>
</tr>
<tr>
<td>$H2(t)$</td>
<td>Head for the lower reservoir (ft)</td>
</tr>
<tr>
<td>$H2_k^l$, $H2_k^u$</td>
<td>Lower and upper bound on the head for the kth head interval (ft)</td>
</tr>
<tr>
<td>$i$</td>
<td>Index variable</td>
</tr>
<tr>
<td>$I2(t)$</td>
<td>Inflow to lower reservoir (cfs)</td>
</tr>
<tr>
<td>$j$</td>
<td>Index variable for units</td>
</tr>
<tr>
<td>$JI1$</td>
<td>Total number of inflows for the upper reservoir</td>
</tr>
<tr>
<td>$JI2$</td>
<td>Total number of inflows for the lower reservoir</td>
</tr>
<tr>
<td>$JP$</td>
<td>Total number of pumps</td>
</tr>
<tr>
<td>$JT1$</td>
<td>Total number of turbines for the upper reservoir</td>
</tr>
<tr>
<td>$JT2$</td>
<td>Total number of turbines for the lower reservoir</td>
</tr>
<tr>
<td>$k$</td>
<td>Index variable for head</td>
</tr>
<tr>
<td>$K1$</td>
<td>Total number of head intervals for the upper reservoir</td>
</tr>
<tr>
<td>$K2$</td>
<td>Total number of head intervals for the lower reservoir</td>
</tr>
<tr>
<td>$M1$</td>
<td>Total number of discharge intervals for the upper reservoir</td>
</tr>
<tr>
<td>$M2$</td>
<td>Total number of discharge intervals for the lower reservoir</td>
</tr>
</tbody>
</table>
\[ PP(t) = \text{Total power consumed by the pumps (MW)} \]

\[ PP_j(t) = \text{Power consumed by the jth pump (MW)} \]

\[ PP_{k,j} = \text{Power consumed by the jth pumps in the kth head interval (MW)} \]

\[ PT(t) = \text{Total power produced from all of the turbines (MW)} \]

\[ PT_1(t) = \text{Power produced by the turbine for the upper reservoir (MW)} \]

\[ PT_{1,j}(t) = \text{Power produced by the jth turbine for the upper reservoir (MW)} \]

\[ PT_{1,k,j,m} = \text{Power produced for the kth head and mth discharge interval by the jth turbine in the upper reservoir (MW)} \]

\[ PT_2(t) = \text{Power produced by the turbine for the lower reservoir (MW)} \]

\[ PT_{2,j}(t) = \text{Power produced by the jth turbine for the lower reservoir (MW)} \]

\[ PT_{2,k,j,m} = \text{Power produced for the kth head and mth discharge interval by the jth turbine in the lower reservoir (MW)} \]

\[ Produce(t) = 1, \text{no pumps can operate} \]

\[ Pump(t) = 1, \text{no turbines can operate} \]

\[ QP(t) = \text{Total discharge for the pumps (cfs)} \]

\[ QP_j(t) = \text{Discharge for the jth pump (cfs)} \]

\[ QP_{k,j} = \text{Lower and upper discharge bound for the jth unit at the kth head (cfs)} \]

\[ QT_1(t) = \text{Total discharge for the turbine for the upper reservoir (cfs)} \]

\[ QT_{1,j}(t) = \text{Discharge for the jth turbine for the upper reservoir (cfs)} \]

\[ QT_{1,k,j,m} = \text{Lower and upper bound on discharge for the kth head, jth unit, and mth discharge for the upper reservoir (cfs)} \]

\[ QT_2(t) = \text{Total discharge for the turbine for the lower reservoir (cfs)} \]

\[ QT_{2,j}(t) = \text{Discharge for the jth turbine for the lower reservoir (cfs)} \]

\[ QT_{2,k,j,m} = \text{Lower and upper bound on discharge for the kth head, jth unit, and mth discharge for the lower reservoir (cfs)} \]

\[ S1(t) = \text{Upper reservoir storage (ft}^3\text{)} \]

\[ S1 = \text{Maximum upper reservoir storage (ft}^3\text{)} \]

\[ S2(t) = \text{Lower reservoir storage (ft}^3\text{)} \]

\[ S2 = \text{Maximum lower reservoir storage (ft}^3\text{)} \]

\[ SpillNO_{i}(t) = \text{Water elevation with no spillage in the upper reservoir (ft)} \]

\[ SpillYES_{i}(t) = \text{Water elevation with spillage in the upper reservoir (ft)} \]

\[ SpillNO_{NO}, SpillNO_{YES} = \text{Minimum and maximum water elevation in the upper reservoir with out spillage (ft)} \]

\[ SpillYES_{NO}, SpillYES_{YES} = \text{Elevation of the dam crest and maximum water elevation in the upper reservoir (ft)} \]

\[ Spill_{NO}, Spill_{YES} = \text{Lower and Upper elevation bound of spillage for the i th head interval for the upper reservoir (ft)} \]

\[ SpillNO_{2}(t) = \text{Water elevation with no spillage in the upper reservoir (ft)} \]

\[ SpillYES_{2}(t) = \text{Water elevation with spillage in the upper reservoir (ft)} \]
\( \text{Spill}^2_{\text{NO}}, \text{Spill}^2_{\text{NO}} \) = Minimum and maximum water elevation in the lower reservoir with out spillage (ft)

\( \text{Spill}^2_{\text{YES}}, \text{Spill}^2_{\text{YES}} \) = Elevation of the dam crest and maximum water elevation in the lower reservoir (ft)

\( TR_2(t) \) = Tailrace elevation for the lower reservoir (ft)

\( TR_{2l}^1, TR_{2u}^u \) = Lower and Upper bound of tailrace elevation for the mth discharge interval for the downstream channel (ft)

\( \text{Turbine}(t) \) = Controls all units produce or not produce

\( \text{UnContRel}(t) \) = Discharge through the spillway in the upper dam (cfs)

\( \text{UnContRel}_i \) = Discharge through the spillway for the ith head interval in the upper dam (cfs)

\( x \) = mid-point of upper reservoir head

\( \alpha_j(t) \) = 1, pump operating

\( \beta_j(t) \) = 1, turbine operating

\( \delta_1^k(t) \) = Determines the kth head interval for the upper reservoir

\( \delta_2^k(t) \) = Determines the kth head interval for the lower reservoir

\( \gamma \) = Specific weight of water (pcf)

\( \theta_i(t) \) = 1, sets discharge for the ith interval through the spillway

\( \theta^\text{YES}(t) \) = 1, spillage only in one head interval for the upper reservoir

\( \theta^i_\text{YES}(t) \) = 1, spillage in the upper reservoir for the ith head interval

\( \theta^\text{NO}(t) \) = 1, no spillage in the upper reservoir

\( \eta_{k,j} \) = Efficiency for the jth pump at the kth head interval

\( \eta_{k,j,m} \) = Efficiency for the jth turbine for the mth discharge at the kth head interval

\( \phi_{1,k,j,m}(t) \) = 1, discharge from the jth unit for the mth discharge at the kth head interval for the upper reservoir

\( \phi_{2,k,j,m}(t) \) = 1, discharge from the jth unit for the mth discharge at the kth head interval for the lower reservoir

\( \nu_{k,j} \) = 1, jth pump is producing

\( \sigma^\text{YES}(t) \) = Controls gated discharge from the lower reservoir

\( \sigma^\text{NO}(t) \) = No spillage at the lower reservoir

\( \zeta_m(t) \) = Tailrace elevation at the mth discharge
4.3 Linear Mathematical Formulation

- **Discretization of upper reservoir head for the turbine**

  Consider the upper reservoir. The head is divided into several intervals (see Figure 4-1 and Table 4-3) $k=1,2\ldots K$. The interval one has an upper head value of $H1^U_1$ and a lower head value of $H1^L_1$; note that $H1^U_1 = H1^L_1$. The actual head $H1(t)$ for the upper reservoir can lie in only one of these intervals, as given by equation (4.2.1) and (4.2.2). The head value is bracketed by the appropriate bounds as given below:

  \[
  H1^L_k \delta H_k(t) \leq H1(t) \leq H1^U_k \delta H_k(t)
  \]  

  (4.2.1)

  and

  \[
  \sum_{k=1}^{K1} \delta H_k(t) = 1 \text{ and } \delta H_k(t) = 0 \text{ or } 1
  \]

  (4.2.2)

  There will be $K1T_t$ many variables with $K1 =$ total number of head intervals and $T_t =$ total number of time steps. The head was divided into intervals because power, which is a nonlinear equation, is mainly a function of head and discharge (see equations (3.2.2), (3.2.4), and (3.2.11)).

![Figure 4-1. Head Intervals for Upper Reservoir](image-url)
\[ H1(t) = FB1(t) - FB2(t) \] (4.2.3)

- **Turbine Power Production**

  Consider the \( j^{\text{th}} \) turbine operating under the upper reservoir head interval \( k \). The value of the \( k^{\text{th}} \) head interval is utilized as the head for turbine operation denoted by \( H1(t) \). Under the head \( H1(t) \), the turbine operates with an efficiency versus flow curve as shown in Figure 4-2. The midpoint of the upper and lower bound on head is used to calculate the power generated by the turbines in equation (4.2.4). In equation (4.2.11), the flow range is divided into \( m=1,2\ldots M \) intervals, with the upper boundary flow as \( QT^u_{j,k,m} \) and the lower boundary flow as \( QT^l_{j,k,m} \). \( QT^u_{j,k,m} \) represents flow through turbine \( j \) for the \( k^{\text{th}} \) head interval and for the \( m^{\text{th}} \) flow interval. Also, note that \( QT^l_{j,k,m} = QT^u_{j,k,m+1} \).

  Efficiency is a function of the midpoint discharge (see Figure 4-2). The power for the \( m^{\text{th}} \) flow interval for the \( j^{\text{th}} \) turbine unit operating under the \( k^{\text{th}} \) head interval can be written as

  \[
  PT_{1,k,j,m} = \gamma \frac{QT^l_{k,j,m} + QT^u_{k,j,m}}{2} \frac{H1^l_k + H1^u_k}{2} \eta_{k,j,m} \tag{4.2.4}
  \]

  ![Figure 4-2. Efficiency vs. Turbine Discharge](image-url)
In reality, the discharge $Q_{T1j}$ is also a function of the wicket gate opening area.

Operating the wicket gate allows the operator direct control of the discharge (reduction of discharge for any head) which in effect controls the power produced by that turbine.

$$Q_{T1j} = A_1jCd\sqrt{2gH1} \tag{4.2.5}$$

- **Head Interval Selection**
  
  The $j^{th}$ turbine flow curve corresponding to the head interval $k$ is selected along with the most appropriate flow interval by

  $$\sum_{m=1}^{M1} \phi 1_{k,j,m}(t) \leq \delta 1_k(t), \text{ for } \forall j \text{ and } \forall k \tag{4.2.6}$$

  and

  $$\phi 1_{k,j,m}(t) = 0 \text{ or } 1 \tag{4.2.7}$$

  Equation (4.2.6), ensures that only the flow interval corresponding to the selected $k^{th}$ head interval, $k^*$, can be utilized. All other choices are discarded due to $\delta 1_k = 0$ for $k = k^*$.

- **Total Power at the Upper Reservoir**
  
  The power produced by the $j^{th}$ unit for time $t$, is written as

  $$PT1_j(t) = \sum_{k=1}^{K1} \sum_{m=1}^{M1} PT1_{k,j,m} \phi 1_{k,j,m}(t) \tag{4.2.8}$$

  There are $K1J1T1MT1$ such $\phi 1_{k,j,m}(t)$ variables. Therefore, the total power produced by all upper reservoir units for time $t$, is

  $$PT1(t) = \sum_{j=1}^{J1} PT1_j(t) \tag{4.2.9}$$
The total power produced by the entire facility, upper and lower reservoir turbines is

\[ PT(t) = PT1(t) + PT2(t) \]  \hspace{1cm} (4.2.10)

- **Continuous Flow**
  
  A continuous flow variable, \( QT1_j(t) \) in the reservoir continuity equation is used, as opposed to the midpoint value used in the turbine power equation (4.2.4) (see Table 4-4). The continuous flow is restricted by the bounds

\[ QT1_{k,j,m}^l \phi_{k,j,m}(t) \leq QT1_j(t) \leq QT1_{k,j,m}^u \phi_{k,j,m}(t) \]  \hspace{1cm} (4.2.11)

and the total flow through the turbines for time \( t \), is given by

\[ QT1(t) = \sum_{j=1}^{JT1} QT1_j(t) \text{ for each } j \]  \hspace{1cm} (4.2.12)

- **Pump Power Consumption**
  
  Pumps operate under the same head as the turbines because the same unit acts either as turbine or pump. When pumps are operational, no turbines can function. The flows are put into intervals the same as for the turbines. The power consumed by pump unit \( j \), for the head interval \( k \), is given by

\[ PP_{k,j} = \gamma \frac{\left( \frac{QP_{k,j}^{l} + QP_{k,j}^{u}}{2} \right) \left( \frac{H1_{k}^{l} + H1_{k}^{u}}{2} \right)}{\eta_{k,j}} \]  \hspace{1cm} (4.2.13)

The efficiency is a function of the pump discharge. The pump efficiency is calculated based on the midpoint of the discharge interval (see Figure 4-3), and then used in the pump power equation.
Note that the pump head will uniquely select the appropriate flow from the pump characteristic curve (see Figure 4-4). The power consumed by pump j for period t is given by

\[
PP_j(t) = \sum_{k=1}^{K} PP_{k,j} v_{k,j}(t)
\]  \hspace{1cm} (4.2.14)

\[
PP(t) = \sum_{j=1}^{J} PP_j(t)
\]  \hspace{1cm} (4.2.15)
Figure 4-4. Head vs. Pump Discharge

- **Spill Related Head Constraints**
  
  The pump head interval corresponds to $\delta I$ head interval (see Equation (4.2.16)).

  However, if the forebay elevation exceeds the dam crest then $\theta^{NO}(t) = 0$, forcing
  
  $$v_{k,j}(t) = 0 \text{ for all } k \text{ and all } j.$$  
  
  Thus, there is no pumping when the forebay elevation exceeds the dam crest, but the turbines may produce energy because no restrictions have been placed on $\phi l(t)$ with regards to the dam crest elevation.

  $$v_{k,j}(t) \leq \delta I_k(t) \text{ and } v_{k,j}(t) = 0 \text{ or } 1, \forall k \text{ and } \forall j$$

  (4.2.16)

  The piecewise linearization creates a small problem for the pumping head interval because the head is relative, whereas, the dam crest (795 ft) is in terms of an absolute elevation. There is a finite range of the head intervals where the possibility occurs that a pump could run with spillage. This happens because of the dependence of head on the forebay elevation of both the upper and lower reservoir. This possibility of a pump operating and spillage occurring simultaneously is considered in Equation (4.2.17). Equation (4.2.17) prevents any pump from running when the water level is above the crest of the dam (see Equation (4.2.28)).
• **Pump Shut-off with Spill**

\[
v_{k,j}(t) \leq \theta^{NO}(t), \ \forall k \text{ and } \forall j
\]

(4.2.17)

The flow through \(j^\text{th}\) pump is selected from

\[
Q_{k,j}^p v_{k,j}(t) \leq Q_j(t) \leq Q_{k,j}^m v_{k,j}(t)
\]

(4.2.18)

and the total pumped flow,

\[
Q(t) = \sum_{j=1}^{JP} Q_j(t)
\]

(4.2.19)

• **Either Turbine or Pump, but NOT Both**

The turbine operation is controlled by the integer variable \(\beta_j(t)\) (see Equation (4.2.20)). If \(\beta_j(t) = 1\), then the turbine unit \(j\) operates at a specific head \(k\) (see Equation (4.2.1) and (4.2.2)) and discharge \(m\) (see Equation (4.2.11) and (4.2.12)).

\[
\beta_j(t) = \sum_{k=1}^{K_1} \sum_{m=1}^{M_1} \phi_{k,j,m}(t), \text{ for each } j
\]

(4.2.20)

The pump operation is controlled by the integer variable \(\alpha_j(t)\) (see Equation (4.2.21)). If \(\alpha_j(t) = 1\), then the pump unit \(j\) operates at a specific head \(k\) and discharge \(m\).

\[
\alpha_j(t) = \sum_{k=1}^{K_1} v_{k,j}(t), \text{ for each } j
\]

(4.2.21)

A unit cannot simultaneously operate as a pump and turbine, nor should a unit operate as a turbine and the adjacent unit operate as a pump. Therefore, the pumps and turbines are restricted from operating at the same time (see Equation (4.2.22)). The unit \(j\) will operate either as turbine or pump is given by

\[
\beta_j(t) + \alpha_j(t) \leq 1, \text{ for } \forall j
\]

(4.2.22)
To ensure no pump is operating when at least one turbine is operating the following constraints are imposed. The number of turbines and pumps that operate at time, t

\[ \text{Turbine}(t) = \sum_{j=1}^{JT} \beta_j(t) \]  

(4.2.23)

and

\[ \text{Pump}(t) = \sum_{j=1}^{JP} \alpha_j(t) \]  

(4.2.24)

The following equations (4.2.25) and (4.2.26) provide a switch between turbine, pump, and idle (no) operation. If at least one turbine is operating then the variable Produce(t)=1.

\[ \text{Turbine}(t) \leq JT \cdot \text{Produce}(t) \quad \text{and} \quad \text{Produce}(t) = 0 \text{ or } 1 \]  

(4.2.25)

If at least one turbine is operating, then the pumps cannot operate (see Equation (4.2.26)) because Produce(t)=1. If pumps are operational then Produce(t)=0, by equation (4.2.26), which shuts down all upper reservoir turbines.

\[ \text{Pump}(t) \leq JP \cdot (1 - \text{Produce}(t)) \]  

(4.2.26)

- **Spillage for Upper Reservoir**

\[ \text{FB1}(t) = \text{Spill}^{\text{NO}}(t) + \text{Spill}^{\text{YES}}(t) \]  

(4.2.27)

\[ \overline{\text{Spill}^{\text{NO}}} \theta^{\text{NO}}(t) \leq \text{Spill}^{\text{NO}}(t) \leq \overline{\text{Spill}^{\text{NO}}} \theta^{\text{NO}}(t) \]  

(4.2.28)

\[ \overline{\text{Spill}^{\text{YES}}} \theta^{\text{YES}}(t) \leq \text{Spill}^{\text{YES}}(t) \leq \overline{\text{Spill}^{\text{YES}}} \theta^{\text{YES}}(t) \]  

(4.2.29)

FB1(t) is controlled by the head interval, storage equation, and the continuity equation. Once the forebay elevation is greater than 795 ft then spillage will occur. This
spillage can be controlled by piecewise linearization of the forebay elevation (see Table 4-6).

\[ SpillV^I_i \theta_i^{YES} (t) \leq SpillV^H_i \theta_i^{YES} (t) \leq SpillV^U_i \theta_i^{YES} (t) \]  

(4.2.30)

- **Uncontrolled Spillway Flow from Upper Reservoir**

\[ \sum_{i=1}^{I} UnContRel_i \theta_i (t) = UnContRel(t) \]  

(4.2.31)

\[ \theta^{NO} (t) + \theta^{YES} (t) = 1 \]  

(4.2.32)

\[ \sum_{i=1}^{I} \theta_i (t) = \theta^{YES} \]  

(4.2.33)

- **Discretization for Uncontrolled Flow**

\[ UnContRel_i = A^{Spill} x^2 - B^{Spill} x + C^{Spill} \]  

(4.2.34)

\[ x = \frac{FB1^I_k + FB1^U_k}{2} \]  

(4.2.35)

- **Leesville Lower Reservoir Height**

The lower reservoir head is divided into intervals (see Equation (4.2.36) and (4.2.37)). Under the head \( H2(t) \) (see Equation (4.2.38)), the turbine will operate in a specific discharge range and efficiency. The head is the difference of the lower reservoir’s forebay elevation and the tailrace elevation (see Equation (4.2.52)). The midpoints of a given head interval and discharge interval are used to calculate the power generated by the turbines (see Equation (4.2.39)).

\[ H2^I_k \delta 2_k (t) \leq H2(t) \leq H2^U_k \delta 2_k (t) \]  

(4.2.36)

\[ \text{and } \sum_{k=1}^{K^2} \delta 2_k (t) = 1 \text{ and } \delta 2_k (t) = 0 \text{ or } 1 \]  

(4.2.37)
\[ H(t) = FB(t) - TR(t) \] (4.2.38)

- **Power Constraints**
  The lower reservoir head is discretized and provides an interval that is used in the lower turbine power production equation:

  \[
  PT_{k,j,m} = \gamma \frac{Q^I_{k,j,m} + Q^U_{k,j,m}}{2} \eta_{k,j,m} H^I_k + H^U_k
  \] (4.2.39)

  \[
  \sum_{m=1}^{M^2} \phi_{k,j,m}^2(t) \leq \delta x(t), \quad \forall j, \forall k
  \] (4.2.40)

  and \( \phi_{k,j,m}^2(t) = 0 \) or \( 1 \) (4.2.41)

- **Total Power from Lower Reservoir**
  The turbine power production equation for the lower reservoir is the same as equation (4.2.4) except for the variables. The turbine power production is given by:

  \[
  PT_{j}(t) = \sum_{k=1}^{K^2} \sum_{m=1}^{M^2} PT_{k,j,m} \phi_{k,j,m}^2(t)
  \] (4.2.42)

  \[
  PT_2(t) = \sum_{j=1}^{J^2} PT_{j}(t)
  \] (4.2.43)

  The power generated from equation (4.2.42) is used in equation (4.2.10) to provide a total power produced between the upper and lower reservoir.

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Figure 4-5. Height Intervals for the lower reservoir

- **Continuous Flow Selection for Lower Reservoir**

A continuous flow variable, \( QT^2_j(t) \), is used in the lower reservoir continuity equation. This continuous flow variable is restricted by the bounds (see Table 4-8)

\[
QT^2_{k,j,m} \phi_{2,k,j,m}(t) \leq QT^2_j(t) \leq QT^2_{k,j,m} \phi_{2,k,j,m}(t)
\]  \hspace{1cm} (4.2.44)

The total flow through the turbines for time, \( t \) is given by

\[
QT^2(t) = \sum_{j=1}^{JT^2} QT^2_j(t) \quad \text{for each } j
\]  \hspace{1cm} (4.2.45)

The lower reservoir has a gated spillway. Discharge through the spillway can occur with any head, which is also capable of producing power. The operation of the controlled discharge through this gated spillway adds some difficulty in achieving a solution. The elevation of the spillway is below the power pool level. The formulation allows the solution to release water through the spillway at any head level above the crest of the spillway. The program must decide if it is best to release water, which cannot
generate a profit, through the spillway, hold the water for another time period, or pump the water in to the upper reservoir (see Equations (4.2.46) through (4.2.50)).

- **Spill Related Constraints for Lower Reservoir**

  \[ FB2(t) = Spill_{NO}^2(t) + Spill_{YES}^2(t) \]  
  \[ Spill_{NO}^2 \sigma_{NO}(t) \leq Spill_{NO}^2(t) < Spill_{NO}^2 \sigma_{NO}(t) \]  
  \[ Spill_{YES}^2 \sigma_{YES}(t) \leq Spill_{YES}^2(t) \leq Spill_{YES}^2 \sigma_{YES}(t) \]  
  \[ \sigma_{NO}(t) + \sigma_{YES}(t) = 1 \]

- **Gated Release**

  \[ 0 \leq Gated(t) \leq Gated_{YES}(t) \]

- **Channel Flow**

  \[ Chan(t) = \sum_{j=1}^{JT} QT_j(t) + Gated(t) \]

- **Tailrace Discretization**

  \[ TR^L_m \xi_m(t) \leq TR^2(t) \leq TR^U_m \xi_m(t) \]  
  
  **Figure 4-6. Lower Reservoir Gate**
The tailrace elevation for the lower reservoir is divided into intervals that correspond to a given channel discharge (see Equation (4.2.52)). For a given \( m \) value, there is a specific range that contains the channel discharge, \( \text{Chan}(t) \). The tailrace elevation is then based on this specific range of channel discharge, such that there is a lower bound and an upper bound for the tailrace (see Equation (4.2.52) and Table 4-9).

\[ TR2(t) = A^{TR2} \text{Chan}^3(t) + B^{TR2} \text{Chan}^2(t) + C^{TR2} \text{Chan}(t) + D^{TR2} \]  

(4.2.53)

- **Channel flow Discretization**

\[ \text{Chan}_{m_l} \leq \text{Chan}(t) \leq \text{Chan}_{m_u} \]  

(4.2.54)

\[ \sum_{m=1}^{M_{\text{Chan}}} \varsigma_m(t) \leq 1 \]  

(4.2.55)

- **Storage-Elevation Relationship**

\[ S1(t) = A^{S1} F1(t) - B^{S1} \]  

(4.2.56)

\[ S2(t) = A^{S2} F2(t) - B^{S2} \]  

(4.2.57)
Table 4-1. Smith Mountain Lake Stage-Storage Relationship

Table 4-2. Leesville Stage-Storage Relationship
• **Storage Constraints**

\[ S1(t) \leq S1 \]  

\[ S2(t) \leq S2 \]

(4.2.58)

(4.2.59)

• **Upper Reservoir continuity**

\[ S1(t + \Delta t) = S1(t) - QT1(t)\Delta t + QP(t)\Delta t + \sum_{j=1}^{n1} I1_j(t)\Delta t - UnContRel(t)\Delta t \]

(4.2.60)

• **Lower reservoir continuity**

\[ S2(t + \Delta t) = S2(t) + QT1(t)\Delta t - QP(t)\Delta t - QT2(t)\Delta t \]

\[ + \sum_{j=1}^{n2} I2_j(t)\Delta t + UnContRel(t)\Delta t - Gated(t)\Delta t \]

(4.2.61)

**4.4 Implementation of the Linear Formulation**

The above formulation is applied to the Smith Mountain-Leesville data. The data tables are given below. Table 4-3, Table 4-4, and Table 4-5 list the head intervals for the Smith Mountain turbines, turbine flows, and pump flows. Table 4-7 and Table 4-8 list the intervals for the Leesville head, and turbine flows. Table 4-6 lists the spillage intervals for the upper reservoir. Table 4-9 provides the channel flow and tail race intervals. Short-term scheduling assumes that certain values are known. These known values (see Table 4-10) are the forebay elevations for the upper and lower reservoirs for the first time step and the inflows for both reservoirs for all the time steps. This data is used to solve the problem. The results are documented in the next chapter.
Table 4-3. Upper Reservoir Head Discretization

<table>
<thead>
<tr>
<th>Interval</th>
<th>Lower Bound (ft)</th>
<th>Upper Bound (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170.00</td>
<td>179.999</td>
</tr>
<tr>
<td>2</td>
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<tr>
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<td>187.999</td>
</tr>
<tr>
<td>10</td>
<td>188.00</td>
<td>195.000</td>
</tr>
</tbody>
</table>

Table 4-4. Upper Reservoir Discharge Discretization

<table>
<thead>
<tr>
<th>Interval, m</th>
<th>Lower Bound (ft)</th>
<th>Upper Bound (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.450</td>
<td>4.65</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>4.8501</td>
<td>5.05</td>
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<td>5.0501</td>
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<td>5.45</td>
</tr>
<tr>
<td>6</td>
<td>5.4501</td>
<td>5.65</td>
</tr>
</tbody>
</table>
Table 4-5. Upper Reservoir Pump Discharge Discretization

<table>
<thead>
<tr>
<th>Interval, k</th>
<th>Upper Bound (1000 cfs)</th>
<th>Lower Bound (1000 cfs)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4.6803</td>
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<td>4.6573</td>
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<td>4.6342</td>
</tr>
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<td>6</td>
<td>4.5881</td>
<td>4.6111</td>
</tr>
<tr>
<td>7</td>
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<td>4.519</td>
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</tr>
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<td>10</td>
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<td>4.5189</td>
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</table>

Table 4-6. Upper Reservoir Spillway Elevation Discretization

<table>
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<th>Interval i</th>
<th>Lower Bound (ft)</th>
<th>Upper Bound (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>795.001</td>
<td>798</td>
</tr>
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<td>2</td>
<td>798.001</td>
<td>805</td>
</tr>
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<td>3</td>
<td>805.001</td>
<td>811</td>
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### Table 4-7. Lower Reservoir Head Discretization

<table>
<thead>
<tr>
<th>Interval, k</th>
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<th>Upper Bound (ft)</th>
</tr>
</thead>
<tbody>
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<td>60.75</td>
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<td>3</td>
<td>62.50</td>
<td>64.24</td>
</tr>
<tr>
<td>4</td>
<td>64.25</td>
<td>65.99</td>
</tr>
<tr>
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<td>66.00</td>
<td>67.74</td>
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<td>67.75</td>
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</tr>
<tr>
<td>10</td>
<td>74.75</td>
<td>76.49</td>
</tr>
</tbody>
</table>

### Table 4-8. Lower Reservoir Discharge Discretization

<table>
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<tr>
<th>Interval, m</th>
<th>Lower Bound (1000 cfs)</th>
<th>Upper Bound (1000 cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>3.450</td>
</tr>
<tr>
<td>2</td>
<td>3.4501</td>
<td>3.6500</td>
</tr>
<tr>
<td>3</td>
<td>3.6501</td>
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<tr>
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<td>4.0500</td>
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<tr>
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<td>4.2500</td>
</tr>
<tr>
<td>6</td>
<td>4.2501</td>
<td>5.0000</td>
</tr>
</tbody>
</table>
Table 4-9. Channel Discharge and Tailrace Discretization

<table>
<thead>
<tr>
<th>Channel Discharge (1000 cfs)</th>
<th>Channel Elevation (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Bound</td>
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</tr>
<tr>
<td>8</td>
<td>17.5</td>
</tr>
<tr>
<td>9</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 4-10. Given Data for Upper and Lower Reservoirs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Given Value</th>
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</thead>
<tbody>
<tr>
<td>FB1(1)</td>
<td>792.00 ft</td>
</tr>
<tr>
<td>FB2(1)</td>
<td>605.00 ft</td>
</tr>
<tr>
<td>I1(1)</td>
<td>3 (1000 cfs)</td>
</tr>
<tr>
<td>I1(2)</td>
<td>1 (1000 cfs)</td>
</tr>
<tr>
<td>I1(3)</td>
<td>2 (1000 cfs)</td>
</tr>
<tr>
<td>I2(1)</td>
<td>3 (1000 cfs)</td>
</tr>
<tr>
<td>I2(2)</td>
<td>6 (1000 cfs)</td>
</tr>
<tr>
<td>I2(3)</td>
<td>3 (1000 cfs)</td>
</tr>
</tbody>
</table>
Chapter 5  Results and Discussion

5.1 Overview

Two formulations were developed and applied to a simplified scheme of the Smith Mountain - Leesville pumped storage and hydroelectric system. This scheme used a reduced number of generating and pumping units at the upper reservoir. This was done in order to reduce the number of variables and constraints. Both formulations were applied to the same scheme so that the results compared. The results are included in the proceeding sections.

5.2 Nonlinear Formulation Implementation

The nonlinear formulation does not guarantee a global optimal solution because the solution space is non-convex (Ravindran, et al., 1987 and Simmons, 1975). The solution space is non-convex because there are binary variables in the formulation and the power production/consumption functions are in product form. The computer software package LINGO was used to solve the nonlinear formulation. For ease of input to LINGO, the code was created within Excel using Visual Basic for Applications (VBA). The nonlinear programming code used in LINGO is included in APPENDIX B. There is computational difficulty with LINGO, which became apparent when making adjustments to the cost coefficients of the objective function. Consider the example objective function \( f(x) = CA \), where \( A \) is a variable and \( C \) is a cost coefficient. Assume that a feasible solution exists for \( C=10 \), then the objective function will return 10A. Given that a feasible solution exists for \( C=10 \), then \( C=100 \) should return 100A. However, when changing the cost coefficient of the objective function, LINGO has difficulty maintaining feasibility. There is no apparent reason for this instability. Because of this instability
finding a feasible solution was sporadic at best. To improve the chance of finding a feasible solution, if one does exist, initial conditions were given from the linear approximation of the nonlinear formulation. Using this starting point LINGO was able to find a near global optimal solution in less than 2 seconds with 53 iterations. The formulation consists of 145 variables of which 36 were binary variables, and 165 constraints of which 25 were nonlinear.

5.3 Linear Formulation Implementation

The mixed-integer linear formulation guarantees a global optimal solution, if a feasible solution exists, within the tolerance of its approximations (Ravindran, et al., 1987). It was solved using the computer program CPLEX, which uses a branch-and-bound algorithm and the simplex method. An interesting aspect of the formulation hidden in the linearization of the power constraint was realized. Because only midpoints are used in power computation, for any flow that lies between the lower and upper limits of the flow constraint, the same constant power value is reported for a selected head over the unit. The algorithm chooses the lower bound flow to conserve flow for later use. At the same time reports a slightly larger power value as done in the power constraint with the mid-interval flow value. For a specific discharge interval, the power output or consumption will be the same regardless of the actual discharge. The algorithm tends to conserve water for the next time step by releasing an amount that is representative of the lower bound for a given interval. This conservation of water will allow a slightly greater head and storage for the next time step. The solution from this formulation can be improved by increasing the discretized intervals of the nonlinear constraints. As the discretized intervals increase, the linear algorithm approaches the true global optimal
solution, as well as increasing the computational effort exponentially. This computational effort is becoming less of a disadvantage as improvements to computers and technology are made.

5.4 Results

Discussion of analyses 1 and 2

Four different solutions corresponding to four different runs named analysis 1, 2, 3, and 4 are reported in this section. Analyses 1 and 2 differ in the price of power for day 3. In analysis 1, the price of power on day 3 is $100 per unit and in analysis 2, the price of power is $1,000 per unit. The price of power for days 1 and 2 are kept the same for both the analyses at $10 and $0.0001 per unit of power respectively. The prices are suitably chosen to check the logic of the formulation as well as the performance of the software (Also, the real prices are not available!). Using the prices of $10, $0.0001, and $100 for days 1, 2, and 3 in analysis 1, should encourage near maximum power production on day 3. The whole schedule should be coordinated on how much power to produce in day 1 for tangible profit and how much flow to conserve in the reservoirs for maximum possible production on day 3. The same logic has been accentuated in analysis 2 by not only encouraging near maximum power production on day 3, but also inducing pumping on day 2 with an attractive price of $1,000 per unit of power for day 3. The objective function values are given in Table 5-1. Table 5-2 shows given data for the mixed integer linear and nonlinear formulations. Both formulations used the same given data for all the following variables and time steps, inflow and cost coefficient for all time steps, forebay and tailrace elevations for the 1st time step for the upper and lower reservoirs. See APPENDIX B for the initial conditions used in the LINGO implementation. CPLEX did not require input of initial conditions. Table 5-3 has the
results for forebay elevation, turbine head, and tailrace elevation values for the upper and lower reservoirs. The notation for forebay elevation FB12, indicates the elevation for reservoir 1 on day 2; H21 indicates head value at reservoir 2 on day 1; TR21 indicates tailrace elevation for reservoir 2 on day 1. Table 5-4 contains the turbine flows $Q Ti_{j,k}$ interpreted as the turbine flow on the $k^{th}$ day, through unit j, for reservoir i. Table 5-5 contains the pump flow values from unit j for $k^{th}$ day given as $QP_{j,k}$. The total power generated for days 1, 2, and 3 are given in Table 5-6. Table 5-7 and Table 5-8 as $PTi_{j,k}$, the power produced from the $i^{th}$ reservoir, using the $j^{th}$ turbine, on the $k^{th}$ day. Table 5-9 has pump power results. The lower reservoir turbine flows are listed in Table 5-10. Table 5-11 and Table 5-12 show the downstream channel release components made up of gated and uncontrolled releases and turbine releases. Table 5-13 and Table 5-14 contain the upper and lower reservoir storage values for days 1, 2, and 3.

For both analyses, the importance of head in the power equation has forced the solution to conserve water on day 2 (see Table 5-4). However, there is not enough of a cost benefit to increase the head in the first analysis through pumping (see Table 5-5). In analysis 2, there is enough of an increase in the cost coefficient to warrant the cost of pumping water back into the upper reservoir for use in the turbines during the 3rd time step. Not only does analysis 2 conserve water in the upper reservoir as in analysis 1, but it also conserves water in the lower reservoir (see Table 5-10).

**Discussion of analyses 3 and 4:**

To emphasize the main points of the nature of the formulation and maintain brevity, only the linear formulation results are reported for analyses 3 and 4. Table 5-15 has the objective function values. Table 5-16 contains the key input data. Table 5-17
contains the head values. Table 5-18 shows the turbine flow values by units and Table 5-19 shows the pump flow values. Tables 5-20 through Table 5-23 contain the total turbine power per day, power produced by each unit for the upper and lower reservoirs, and pump power consumed. Table 5-24 shows the turbine flow for the lower reservoir. Table 5-25 contains the downstream channel flows. Tables 5-26 and 5-27 present the storage values for the upper and lower reservoir respectively.

In analyses 3 and 4 all prices associated with power are zero except for day 3. Further, in analysis 4 all inflows are set to zero. It is anticipated that the pumps will work at no cost to lift water from the lower reservoir to the upper reservoir on days 1 and 2 in order to produce maximum power on day 3. This logic is borne out in Table 5-23 for analysis 3. Table 5-23 shows that the pumps run only on day 1. That is because in Table 5-17, FB22 is already at 601.5778 ft, which is a drop of almost 3.5 ft from the original FB21 of 605 ft. By constraint (4.2.18), once the head is fixed, all pumps run at the same rate, pumping the same amount of water. Therefore, if pumps 1 and 2 pump on day 2, FB22 will fall below 600 ft which is not permitted. In analysis 3, because of the inflow to the reservoir, the level FB22 recuperates to 603.8382 for the same rate of pumping. This level and further inflow support additional pumping on day 2, resulting in an improved profit value given in Table 5-15.

A most interesting point in analysis 4 is the wastage of water on day 2, by reservoir 1. Table 5-18 shows that through turbine 2, 2.45 units of flow are released to produce a power of 580.4 units on day 2, as given in Tables 5-20 and 5-21, without generating any revenue. This flow results in a drop of 0.253 ft in reservoir 1 which raises the reservoir 2 level to 603.4237 ft from 601.5778. Clearly, there is a larger head for the
turbine at reservoir 1 if no flow is released on day 2. This is explained by referring to Table 4-3 in which the 10th head interval (188.00 to 195.00 ft) contains both the head values H12 of 190.8913 and H13 of 188.7923 results in the same constant middle value of 191.5 used in the power calculation. Therefore, the release of 2.45 units through the turbine unit 2 on day 2 is an alternate optimum to the solution of not releasing any flow on day 2 and maintaining the lower reservoir elevation at 601.5778 ft. Therefore, the finer the discretization intervals, the more the software can sense small differences in the solutions. Also, note that because of the limited lower turbine capacity of 4.25 units, the maximum channel flow becomes 8.25 units in Table 5-25.

Table 5-1. Objective Function.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 1</th>
<th>Analysis 2</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Nonlinear Value</td>
<td>Linear Value</td>
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<tr>
<td>Z ($)</td>
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### Table 5-2. Constant Values for input to the Models.

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<td>Nonlinear</td>
<td>Linear</td>
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<td>CP1 ($)</td>
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<td>10.00</td>
<td>10.00</td>
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<td>0.0001</td>
<td>0.0001</td>
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<td>1000.00</td>
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<td>3.00</td>
<td>3.00</td>
</tr>
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<td>I12 (1000 cfs)</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>I13 (1000 cfs)</td>
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<td>2.00</td>
<td>2.00</td>
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<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>I22 (1000 cfs)</td>
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<td>6.00</td>
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### Table 5-3. Forebay Elevation and Head for Upper and Lower Reservoir.

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<td>Linear</td>
<td>Nonlinear</td>
<td>Linear</td>
</tr>
<tr>
<td></td>
<td>Value (ft)</td>
<td>Value (ft)</td>
<td>Value (ft)</td>
<td>Value (ft)</td>
</tr>
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<td>187.00</td>
<td>187.00</td>
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<td>187.74</td>
<td>184.56</td>
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<td>192.76</td>
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<td>603.98</td>
<td>606.98</td>
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<tr>
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<td>542.52</td>
<td>540.75</td>
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<td>542.52</td>
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<td>542.52</td>
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<td>62.48</td>
<td>64.25</td>
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<tr>
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<td>68.90</td>
<td>72.99</td>
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<td>57.48</td>
<td>64.25</td>
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Table 5-4. Turbine Discharge for Upper Reservoir.

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<th>Analysis 1</th>
<th>Analysis 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT111</td>
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<td>Linear Value (1000 cfs): 5.45</td>
</tr>
<tr>
<td>QT121</td>
<td>Nonlinear Value (1000 cfs): 5.65</td>
<td>Linear Value (1000 cfs): 5.45</td>
</tr>
<tr>
<td>QT112</td>
<td>Nonlinear Value (1000 cfs): 0.00</td>
<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QT122</td>
<td>Nonlinear Value (1000 cfs): 0.00</td>
<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QT113</td>
<td>Nonlinear Value (1000 cfs): 5.65</td>
<td>Linear Value (1000 cfs): 5.45</td>
</tr>
<tr>
<td>QT123</td>
<td>Nonlinear Value (1000 cfs): 5.65</td>
<td>Linear Value (1000 cfs): 5.45</td>
</tr>
</tbody>
</table>

Table 5-5. Pump Discharge for Upper Reservoir

<table>
<thead>
<tr>
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<th>Analysis 1</th>
<th>Analysis 2</th>
</tr>
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<tr>
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<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QP21</td>
<td>Nonlinear Value (1000 cfs): 0.00</td>
<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QP12</td>
<td>Nonlinear Value (1000 cfs): 0.00</td>
<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QP22</td>
<td>Nonlinear Value (1000 cfs): 0.00</td>
<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QP13</td>
<td>Nonlinear Value (1000 cfs): 0.00</td>
<td>Linear Value (1000 cfs): 0.00</td>
</tr>
<tr>
<td>QP23</td>
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<td>Linear Value (1000 cfs): 0.00</td>
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Table 5-6. Total Power Produced for Upper and Lower Dams.

<table>
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<tr>
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<th>Analysis 1</th>
<th>Analysis 2</th>
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<tbody>
<tr>
<td>PT1</td>
<td>Nonlinear Value: 2372.03</td>
<td>Linear Value: 2337.26</td>
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<tr>
<td>PT2</td>
<td>Nonlinear Value: 574.72</td>
<td>Linear Value: 534.82</td>
</tr>
<tr>
<td>PT3</td>
<td>Nonlinear Value: 2364.44</td>
<td>Linear Value: 2361.32</td>
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Table 5-7. Individual Unit Power Produced for Upper Reservoir

<table>
<thead>
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<th>Variable</th>
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<th>Analysis 2</th>
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</thead>
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<td></td>
<td>Nonlinear Value</td>
<td>Linear Value</td>
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<tr>
<td>PT111</td>
<td>912.82</td>
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<tr>
<td>PT121</td>
<td>912.82</td>
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</tr>
<tr>
<td>PT112</td>
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<td>0.00</td>
</tr>
<tr>
<td>PT122</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>PT113</td>
<td>908.04</td>
<td>920.44</td>
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<td>PT123</td>
<td>908.04</td>
<td>920.44</td>
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Table 5-8. Individual Unit Power Produced for Lower Reservoir

<table>
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<th>Variable</th>
<th>Analysis 1</th>
<th>Analysis 2</th>
</tr>
</thead>
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<td>Nonlinear Value</td>
<td>Linear Value</td>
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<td>PT211</td>
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<tr>
<td>PT221</td>
<td>273.20</td>
<td>267.41</td>
</tr>
<tr>
<td>PT212</td>
<td>287.36</td>
<td>267.41</td>
</tr>
<tr>
<td>PT222</td>
<td>287.36</td>
<td>267.41</td>
</tr>
<tr>
<td>PT213</td>
<td>274.18</td>
<td>260.22</td>
</tr>
<tr>
<td>PT223</td>
<td>274.18</td>
<td>260.22</td>
</tr>
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Table 5-9. Pump Power Consumed

<table>
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<th>Analysis 2</th>
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</thead>
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<td>Nonlinear Value</td>
<td>Linear Value</td>
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<td>PP11</td>
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<td>0.00</td>
</tr>
<tr>
<td>PP21</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>PP12</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>PP22</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>PP13</td>
<td>0.00</td>
<td>0.00</td>
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</table>
### Table 5-10. Turbine Discharge for Lower Reservoir

<table>
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<th>Analysis 2</th>
</tr>
</thead>
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<td>Nonlinear Value (1000 cfs)</td>
<td>Linear Value (1000 cfs)</td>
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</tr>
<tr>
<td>QT221</td>
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<td>4.50</td>
</tr>
<tr>
<td>QT212</td>
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<td>5.00</td>
</tr>
<tr>
<td>QT222</td>
<td>5.00</td>
<td>5.00</td>
</tr>
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<td>QT213</td>
<td>5.00</td>
<td>4.25</td>
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### Table 5-11. Spillway Discharge for Upper and Lower Dams

<table>
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<td>Nonlinear Value (1000 cfs)</td>
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<td>UNCONTREL2</td>
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<tr>
<td>UNCONTREL3</td>
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<td>0.00</td>
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<tr>
<td>GATED1</td>
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<td>0.00</td>
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<tr>
<td>GATED2</td>
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<tr>
<td>GATED3</td>
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### Table 5-12. Downstream Discharge

<table>
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<td>Nonlinear Value (1000 cfs)</td>
<td>Linear Value (1000 cfs)</td>
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<tr>
<td>CHAN2</td>
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<tr>
<td>CHAN3</td>
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### Table 5-13. Upper Reservoir Storage

<table>
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<th>Linear Value $(10^6 \text{ ft}^3)$</th>
<th>Nonlinear Value $(10^6 \text{ ft}^3)$</th>
<th>Linear Value $(10^6 \text{ ft}^3)$</th>
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</thead>
<tbody>
<tr>
<td>S11</td>
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<td>4.92526</td>
<td>4.92526</td>
<td>4.92526</td>
</tr>
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<td>4.85701</td>
<td>4.90237</td>
<td>4.88618</td>
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### Table 5-14. Lower Reservoir Storage

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<th>Linear Value $(10^6 \text{ ft}^3)$</th>
<th>Nonlinear Value $(10^6 \text{ ft}^3)$</th>
<th>Linear Value $(10^6 \text{ ft}^3)$</th>
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</thead>
<tbody>
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<td>0.31744</td>
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<tr>
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Output from the linear formulation for different cost coefficients and inflow values.

Table 5-15. Objective Function.

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Table 5-16. Constant Values for input to the Models.

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</tr>
<tr>
<td>CP2 ($)</td>
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<td>0.0000</td>
</tr>
<tr>
<td>CP3 ($)</td>
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<td>1000</td>
</tr>
<tr>
<td>I11 (1000 cfs)</td>
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<tr>
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</tr>
<tr>
<td>I21 (1000 cfs)</td>
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<td>0</td>
</tr>
<tr>
<td>I22 (1000 cfs)</td>
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<td>0</td>
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<tr>
<td>FB11 (ft)</td>
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<td>792</td>
</tr>
<tr>
<td>FB21 (ft)</td>
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<td>605</td>
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</table>
Table 5-17. Forebay Elevation and Head for Upper and Lower Reservoir.

<table>
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<th>Analysis 4 (ft)</th>
</tr>
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<tbody>
<tr>
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<td>FB13</td>
<td>793.3488</td>
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<tr>
<td>H11</td>
<td>187</td>
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<td>FB23</td>
<td>604.9541</td>
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<td>TR23</td>
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<td>H21</td>
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<td>72.427</td>
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<tr>
<td>H22</td>
<td>71.24</td>
<td>67.74</td>
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<tr>
<td>H23</td>
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<td>62.5</td>
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</table>
Table 5-18. Turbine Discharge for Upper Reservoir.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3 (1000 cfs)</th>
<th>Analysis 4 (1000 cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT111</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT121</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT112</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT122</td>
<td>0</td>
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<tr>
<td>QT113</td>
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<td>5.4501</td>
</tr>
<tr>
<td>QT123</td>
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<td>5.4501</td>
</tr>
</tbody>
</table>

Table 5-19. Pump Discharge for Upper Reservoir.

<table>
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<tr>
<th>Variable</th>
<th>Analysis 3 (1000 cfs)</th>
<th>Analysis 4 (1000 cfs)</th>
</tr>
</thead>
<tbody>
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<td>QP11</td>
<td>4.542</td>
<td>4.542</td>
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<td>QP21</td>
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<tr>
<td>QP12</td>
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<tr>
<td>QP22</td>
<td>0</td>
<td>0</td>
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<tr>
<td>QP13</td>
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<td>0</td>
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<tr>
<td>QP23</td>
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</tr>
</tbody>
</table>

Table 5-20. Individual Unit Power Produced for Upper Reservoir.

<table>
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<tr>
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<th>Analysis 3</th>
<th>Analysis 4</th>
</tr>
</thead>
<tbody>
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<td>PT111</td>
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<td>0</td>
</tr>
<tr>
<td>PT121</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PT112</td>
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<td>0</td>
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<tr>
<td>PT113</td>
<td>920.44</td>
<td>920.44</td>
</tr>
<tr>
<td>PT123</td>
<td>267.41</td>
<td>260.22</td>
</tr>
</tbody>
</table>
Table 5-21. Individual Unit Power Produced for Lower Reservoir.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3</th>
<th>Analysis 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT211</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PT221</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PT212</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PT222</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PT213</td>
<td>267.41</td>
<td>260.22</td>
</tr>
<tr>
<td>PT223</td>
<td>267.41</td>
<td>260.22</td>
</tr>
</tbody>
</table>

Table 5-22. Pump Power Consumed

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3</th>
<th>Analysis 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP11</td>
<td>945.699</td>
<td>945.699</td>
</tr>
<tr>
<td>PP21</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP12</td>
<td>942.211</td>
<td>0</td>
</tr>
<tr>
<td>PP22</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP23</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-23. Turbine Discharge for Lower Reservoir

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3 (1000 cfs)</th>
<th>Analysis 4 (1000 cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT211</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT221</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT212</td>
<td>4.2501</td>
<td>4.2501</td>
</tr>
<tr>
<td>QT222</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT213</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QT223</td>
<td>4.2501</td>
<td>4.2501</td>
</tr>
</tbody>
</table>
Table 5-24. Downstream Discharge.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3 (1000 cfs)</th>
<th>Analysis 4 (1000 cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAN1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CHAN2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CHAN3</td>
<td>8.5002</td>
<td>8.5002</td>
</tr>
</tbody>
</table>

Table 5-25. Upper Reservoir Storage.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3 (10^6 ft³)</th>
<th>Analysis 4 (10^6 ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>4.925264</td>
<td>4.925264</td>
</tr>
<tr>
<td>S12</td>
<td>4.990427</td>
<td>4.964507</td>
</tr>
<tr>
<td>S13</td>
<td>5.03811</td>
<td>4.943339</td>
</tr>
</tbody>
</table>

Table 5-26. Lower Reservoir Storage

<table>
<thead>
<tr>
<th>Variable</th>
<th>Analysis 3 (10^6 ft³)</th>
<th>Analysis 4 (10^6 ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S21</td>
<td>0.317435</td>
<td>0.317435</td>
</tr>
<tr>
<td>S22</td>
<td>0.304112</td>
<td>0.278192</td>
</tr>
<tr>
<td>S23</td>
<td>0.316909</td>
<td>0.29936</td>
</tr>
</tbody>
</table>
Chapter 6  Summary and Conclusions

Two methods of pumped storage optimization, mixed-integer nonlinear formulation, and mixed-integer linear formulation, have been presented. These two formulations are based on the Smith Mountain–Leesville system. The mixed-integer nonlinear formulation is a representation of the real system with no approximations. The solution space for the nonlinear formulation is non-convex; therefore, any optimal solution should be considered a local optimum and not a global optimum. To obtain a near global optimal solution, initial data has been supplied from the mixed-integer linear formulation.

The mixed-integer linear formulation provides the global optimal solution without any assistance. However, this solution is valid only for the linearized constraints. The formulation is quite general and overcomes computational difficulties associated with the nonlinear formulation. Because of these advantages it is recommended that a high quality solution be obtained first with the linear formulation and then tested for feasibility and near global optimum with the nonlinear formulation.

If computing power is a concern, the following method can be used to provide a more accurate solution. The formulation can be implemented in two phases. Phase one is the implementation of the formulation with a finite number of intervals over the entire range of each variable. This phase will develop a solution that is close to the global optimal solution. Phase two uses the solution computed in phase one to refine the range of each variable. The new range is composed of the same finite number of intervals, but is now denser around the phase 1 solution. This smaller interval will now provide a closer approximation of the global optimal solution.
If computing power is of no concern, then increase the number of intervals over the entire range of each variable. This will provide a denser interval, which will require more computational time than the previous method. The denser the intervals the better the approximation, such that an infinite number of intervals will provide an exact global optimal solution. These conclusions are borne out in the analysis 4 example of Chapter 5.

Either of the two formulations, linear and nonlinear, can be integrated as a subproblem into AEP’s electrical system. For more information on hydropower integration with thermal power, please see Gulliver and Arndt (1991). AEP has only one pumped storage and hydroelectric facility, numerous thermal facilities and run-of-the river hydroelectric facilities. The thermal facilities produce most of the power while the hydroelectric facilities provide support. However, with the deregulation of the electrical industry, companies will need to operate at maximum efficiency in order to be competitive. Existing hydropower facilities will play an important role in this new electrical industry because it is an inexpensive source of energy. In order to achieve the full benefit of hydropower, use of these facilities must be optimized. From an academic perspective, the difficult constraints are the power relationship, unit commitment, and pump operation as dictated by the pump curve. All these constraints have been well formulated and tested out with verifiable example runs illustrated in Chapter 5. Therefore, embedding the thermal units within the framework of the present formulation does not pose any theoretical difficulties.

The examples presented in this thesis entail all the main characteristics of hydropower optimization with a sufficiently detailed data set. Therefore, it may be considered
as a test problem to check the efficiency of other algorithms in generating improved local optimal solutions. An important concern is the growth in the number of constraints for real-time solutions. If the price of power changes every hour, and there are significant number of units, the number of constraints can increase several thousands. A dedicated, well tested formulation is essential. It is believed that the present formulation is sufficiently simple to track the performance of each unit separately, and it accommodates all aspects of hydro-power optimization.
Bibliography


Using the CPLEX Callable Library including Using the CPLEX Base System (1997). ILOG, Inc., Incline Village, NV.


APPENDIX A  Operations Research
Solution Methodologies and Solvers

A.1 Introduction
This thesis uses three types of solution methodologies to solve the two formulations: simplex method, branch-and-bound method, and gradient search method. The two formulations contain integer variables, which makes them both mixed integer formulations. The formulations have an objective function, decision variables, constraints, and parameters. The focus here is to maximize the objective function. The objective function is based on the power produced by the turbines, the power consumed by the pumps, and the cost of power as a function of time. The decision variables are related to the discharge quantities. The parameters are the coefficients and constants used in the constraints. The following contains a brief overview of some programming types and the solution methodologies to the optimization process. Two solvers for linear and nonlinear programming are CPLEX and LINGO, respectively.

A.2 Linear Programming
There are three basic steps to formulating a linear problem: (1) identify the unknown variables \(x_n\), (2) identify the activities (constraints), making sure that each is in a linear form, and (3) develop the objective function \(Z\) in terms of the unknown variables (Ravindran, et al., 1987). The standard form of the linear programming problem is
Maximize: \[ Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n \]

Subject to:
\[ \begin{align*}
a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1 \\
a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2 \\
& \vdots \\
a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n &= b_m \\
x_1, x_2, \ldots, x_n &\geq 0 \\
b_1, b_2, \ldots, b_m &\geq 0
\end{align*} \]

If \( m = n \) then the linear equations can be solved simultaneously through simple matrix manipulations. If \( m > n \), then the redundant equations can be removed and the remaining equations are solved using simple matrix manipulations. If \( n > m \), then it becomes more difficult to determine the best solution without complete enumeration of the solution space. This third case is one of the reasons for using linear programming. Two theorems of linear programming state that the basic feasible solutions represent the corner points of the solution space and the optimum is obtained at one of the corner points. The typical method used to solve the linear program is the simplex method. By the theorems, only the corner points of the feasible region need to be checked. The simplex method looks at an adjacent corner point such that the new corner point has a better objective function value when compared to the previous solution. The simplex method is an efficient process that works around the boundary of the feasible region until it selects the optimal solution. It saves time by ignoring the solution space inside of the boundary and only enumerates the corner points. Also, it checks each of the corner points in systematic fashion that ensures it will reach the optimal solution (Hillier, 2001; Ravindran, et al., 1987; and Wagner, 1969).

The simplex method can be solved by an algebraic from, a tabular form, or a matrix form. The matrix form is called the revised simplex method and is well suited for computer manipulations. The revised simplex method uses the same foundation as the simplex method, but it takes advantage of the computer’s ability to work with matrixes. Also, the revised simplex method is efficient in its optimality test because it does not do a complete enumeration of the
variables. Instead, the method calculates only the coefficients of the variables important for the
determination of optimality. (Ravindran, et al., 1987)

A.3 Nonlinear Programming

Nonlinear programming does not guarantee the return of an optimal solution, even if a
solution does exist. Unlike linear programming, nonlinear programming may find an optimal
solution at a corner point, a point inside the feasible region, or at a point of discontinuity. There
have been numerous algorithms developed to solve nonlinear programs, but few have had
success in solving applied problems (Ravindran, et al., 1987). A crucial consideration for
nonlinear programming is whether or not the solution space is convex. If the solution space is
convex then there is global maximum solution that exists for the problem. If the problem has
equality and inequality constraints and a convex solution space, then the problem can be solved
using the Kuhn-Tucker conditions. If a solution exists such that the Kuhn-Tucker conditions are
satisfied, then this solution is the global optimal solution. If the solution space is non-convex
then there is no guarantee that the solution will be the global optimal solution. An analytical
approach can be applied to the nonlinear formulation through the use of derivatives.

The gradient method determines a good direction in which to search for new solutions
and works well for unconstrained models. For constrained models, there are variations of the
gradient method. The reduced gradient method works with the linear differentials of the
objective function and constraints. It uses the differentiated equations to search along a linear
path for the best local solution. The generalized reduced gradient (GRG) algorithm is based on
the reduced gradient method. The GRG is modified so that it will work with nonlinear objective
function and nonlinear constraints. This method works to approximate the constraints through
linear representations. The gradient is then modified to utilize the approximate linear constraints
and search for a local optimal point (Himmelblau, 1972; Reklaitis, 1983; and Simmons, 1975)
However, the analytical approach does not work well with large problems because of its reliance upon mathematical relationships and rules. Numerical methods can be used to solve the nonlinear problems. One such method used to solve constrained nonlinear problems is successive linear programming. Through the use of Taylor’s expansion, the nonlinear equations are approximated with linear equations. An initial point is chosen as the starting point from which to solve the approximate linear program. This method will then use the previous solution to generate another solution. It works by an iterative process that tries to find the local optimal solution. This method does not guarantee a global optimal solution (Reklaitis, 1983).

A.4 Integer Programming

The branch-and-bound algorithm is typically used to solve the integer programming model. The branch-and-bound algorithm first works with the optimal solution from the linear program. This solution typically contains continuous values because it ignores the integer restrictions. The algorithm will then choose one of the fractional values and check the integer value above and below the fractional value, creating branches. The algorithm will then search for a valid lower bound by checking the numerous fractional values obtained. The algorithm compares the values from the same level and will terminate the branch with the lower objective value. It can terminate this branch with strong certainty because the addition of more integer restriction cannot improve the solution. The branch-and-bound algorithm will enumerate the remaining branches in search of terminating another branch. This process continues until all the branches have been terminated. This will provide the global optimum solution to the integer program. Also, it can be used in conjunction with linear and nonlinear solvers. The solution methodology is the same as above except the branch-and-bound algorithm will enumerate only the branches that require integer restriction.
A.5 Solvers: CPLEX and LINGO

CPLEX is a solver that works with linear and integer programs. The solver uses a revised simplex method to solve linear programming problems and a branch-and-bound algorithm to solve integer programming problems (CPLEX, 1997).

LINGO is a solver that works with linear, nonlinear, and integer programs. LINGO’s linear solver is based on the revised simplex method. Its nonlinear solver uses both a successive linear program and a generalized reduced gradient algorithm. The integer solver is based on the branch-and-bound method (LINGO, 1998).
APPENDIX B  Lingo Implementation

Input code to LINGO for Analysis 1

!Given Data
Data:
CP1=10;
CP2=0.0001;
CP3=100;

I10=0;
I11=3;
I12=1;
I13=2;

I20=0;
I21=3;
I22=6;
I23=3;
FB11=792;
FB21=605;

ENDDATA

!INITIAL STARTING POINTS;
INIT:

H12=182.88;
H13=188.33;
FB12=791.277;
FB13=792.34;
QT111=5;
QT112=0;
QT113=4.85;
QT121=5;
QT122=0;
QT123=4.85;
QP11=0;
QP12=4.66;
QP13=0;
QP21=0;
QP22=4.66;
QP23=0;
TR21=540.75;
TR22=536.685;
TR23=541.449;
QT211=4.25;
QT212=0;
QT213=4.25;
QT221=4.25;
QT222=2.5;
QT223=4.25;
ENDINIT

[OBJECTIVE] MAX =CP1*PT1-CP1*PP1+CP2*PT2-CP2*PP2+CP3*PT3-CP3*PP3;

[Eqn1_2] PT1=PT111+PT121+PT211+PT221;
[Eqn1_3] PT2=PT112+PT122+PT212+PT222;
[Eqn1_4] PT3=PT113+PT123+PT213+PT223;

[Eqn1_5] PP1=PP11+PP21;
[Eqn1_6] PP2=PP12+PP22;
[Eqn1_7] PP3=PP13+PP23;

[Eqn1_8] H11=FB11-FB21;
[Eqn1_9] H12=FB12-FB22;
[Eqn1_10] H13=FB13-FB23;

[Eqn1_11] PT111= (0.00663*QT111^4-0.11057*QT111^3+0.59393*QT111^2-
0.15787*QT111)*H11;
[Eqn1_12] PT112= (0.00663*QT112^4-0.11057*QT112^3+0.59393*QT112^2-
0.15787*QT112)*H12;
[Eqn1_13] PT113= (0.00663*QT113^4-0.11057*QT113^3+0.59393*QT113^2-
0.15787*QT113)*H13;

[Eqn1_14] PT121= (0.00663*QT121^3-0.11057*QT121^2+0.59393*QT121-
0.15787)*H11*PT11;
[Eqn1_15] PT122= (0.00663*QT122^3-0.11057*QT122^2+0.59393*QT122-
0.15787)*H12*PT12;
[Eqn1_16] PT123= (0.00663*QT123^3-0.11057*QT123^2+0.59393*QT123-
0.15787)*H13*PT13;

[Eqn1_17] 2.45*MU111<=QT111;
[Eqn1_18] 2.45*MU112<=QT112;
[Eqn1_19] 2.45*MU113<=QT113;

[Eqn1_20] QT111<=5.65*MU111;
[Eqn1_21] QT112<=5.65*MU112;
[Eqn1_22] QT113<=5.65*MU113;
\[\text{Eqn1_23}] \quad 2.45 \cdot \text{MU121} \leq \text{QT121};
\[\text{Eqn1_24}] \quad 2.45 \cdot \text{MU122} \leq \text{QT122};
\[\text{Eqn1_25}] \quad 2.45 \cdot \text{MU123} \leq \text{QT123};
\[\text{Eqn1_26}] \quad \text{QT121} \leq 5.65 \cdot \text{MU121};
\[\text{Eqn1_27}] \quad \text{QT122} \leq 5.65 \cdot \text{MU122};
\[\text{Eqn1_28}] \quad \text{QT123} \leq 5.65 \cdot \text{MU123};
\]
\[\text{Eqn1_29}] \quad \text{PT211} = (-0.0280 \cdot \text{QT211}^3 + 0.2555 \cdot \text{QT211}^2 - 0.5263 \cdot \text{QT211} + 0.6185) \cdot H21 \cdot \text{QT211};
\[\text{Eqn1_30}] \quad \text{PT212} = (-0.0280 \cdot \text{QT212}^3 + 0.2555 \cdot \text{QT212}^2 - 0.5263 \cdot \text{QT212} + 0.6185) \cdot H22 \cdot \text{QT212};
\[\text{Eqn1_31}] \quad \text{PT213} = (-0.0280 \cdot \text{QT213}^3 + 0.2555 \cdot \text{QT213}^2 - 0.5263 \cdot \text{QT213} + 0.6185) \cdot H23 \cdot \text{QT213};
\]
\[\text{Eqn1_32}] \quad \text{PT221} = (-0.0280 \cdot \text{QT221}^3 + 0.2555 \cdot \text{QT221}^2 - 0.5263 \cdot \text{QT221} + 0.6185) \cdot H21 \cdot \text{QT221};
\[\text{Eqn1_33}] \quad \text{PT222} = (-0.0280 \cdot \text{QT222}^3 + 0.2555 \cdot \text{QT222}^2 - 0.5263 \cdot \text{QT222} + 0.6185) \cdot H22 \cdot \text{QT222};
\[\text{Eqn1_34}] \quad \text{PT223} = (-0.0280 \cdot \text{QT223}^3 + 0.2555 \cdot \text{QT223}^2 - 0.5263 \cdot \text{QT223} + 0.6185) \cdot H23 \cdot \text{QT223};
\]
\[\text{Eqn1_35}] \quad 2.2 \cdot \text{MU211} \leq \text{QT211};
\[\text{Eqn1_36}] \quad 2.2 \cdot \text{MU212} \leq \text{QT212};
\[\text{Eqn1_37}] \quad 2.2 \cdot \text{MU213} \leq \text{QT213};
\]
\[\text{Eqn1_38}] \quad \text{QT211} \leq 5 \cdot \text{MU211};
\[\text{Eqn1_39}] \quad \text{QT212} \leq 5 \cdot \text{MU212};
\[\text{Eqn1_40}] \quad \text{QT213} \leq 5 \cdot \text{MU213};
\]
\[\text{Eqn1_41}] \quad 2.2 \cdot \text{MU221} \leq \text{QT221};
\[\text{Eqn1_42}] \quad 2.2 \cdot \text{MU222} \leq \text{QT222};
\[\text{Eqn1_43}] \quad 2.2 \cdot \text{MU223} \leq \text{QT223};
\]
\[\text{Eqn1_44}] \quad \text{QT221} \leq 5 \cdot \text{MU221};
\[\text{Eqn1_45}] \quad \text{QT222} \leq 5 \cdot \text{MU222};
\[\text{Eqn1_46}] \quad \text{QT223} \leq 5 \cdot \text{MU223};
\]
\[\text{Eqn1_47}] \quad \text{PP11} = H11 \cdot \text{QP11}/(0.1683 \cdot \text{QP11}^3 - 2.3937 \cdot \text{QP11}^2 + 11.291 \cdot \text{QP11} - 16.769);
\[\text{Eqn1_48}] \quad \text{PP12} = H12 \cdot \text{QP12}/(0.1683 \cdot \text{QP12}^3 - 2.3937 \cdot \text{QP12}^2 + 11.291 \cdot \text{QP12} - 16.769);
\[\text{Eqn1_49}] \quad \text{PP13} = H13 \cdot \text{QP13}/(0.1683 \cdot \text{QP13}^3 - 2.3937 \cdot \text{QP13}^2 + 11.291 \cdot \text{QP13} - 16.769);
\]
\[\text{Eqn1_50}] \quad \text{PP21} = H11 \cdot \text{QP21}/(0.1683 \cdot \text{QP21}^3 - 2.3937 \cdot \text{QP21}^2 + 11.291 \cdot \text{QP21} - 16.769);
\[\text{Eqn1_51}] \quad \text{PP22} = H12 \cdot \text{QP22}/(0.1683 \cdot \text{QP22}^3 - 2.3937 \cdot \text{QP22}^2 + 11.291 \cdot \text{QP22} - 16.769);
\[PP23 = \frac{H13 \cdot QP23}{(0.1683 \cdot QP23^3 - 2.3937 \cdot QP23^2 + 11.291 \cdot QP23 - 16.769)};\]

\[FB11 = SPILL1\_NO1 + SPILL1\_YES1;\]
\[FB12 = SPILL1\_NO2 + SPILL1\_YES2;\]
\[FB13 = SPILL1\_NO3 + SPILL1\_YES3;\]

\[787 \cdot THETA\_NO1 \leq SPILL1\_NO1;\]
\[787 \cdot THETA\_NO2 \leq SPILL1\_NO2;\]
\[787 \cdot THETA\_NO3 \leq SPILL1\_NO3;\]

\[SPILL1\_NO1 \leq 795 \cdot THETA\_NO1;\]
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\[SPILL1\_NO3 \leq 795 \cdot THETA\_NO3;\]

\[795.01 \cdot THETA\_YES1 \leq SPILL1\_YES1;\]
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\[SPILL1\_YES1 \leq 811 \cdot THETA\_YES1;\]
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\[SPILL1\_YES3 \leq 811 \cdot THETA\_YES3;\]

\[THETA\_NO1 + THETA\_YES1 = 1;\]
\[THETA\_NO2 + THETA\_YES2 = 1;\]
\[THETA\_NO3 + THETA\_YES3 = 1;\]

\[UNCONTREL1 = 0.127193 \cdot SPILL1\_YES1^2 - 201.334682 \cdot SPILL1\_YES1 + 79671.751374 \cdot THETA\_YES1;\]
\[UNCONTREL2 = 0.127193 \cdot SPILL1\_YES2^2 - 201.334682 \cdot SPILL1\_YES2 + 79671.751374 \cdot THETA\_YES2;\]
\[UNCONTREL3 = 0.127193 \cdot SPILL1\_YES3^2 - 201.334682 \cdot SPILL1\_YES3 + 79671.751374 \cdot THETA\_YES3;\]

\[MU111 + MU121 \leq 2 \cdot DELTA11;\]
\[MU112 + MU122 \leq 2 \cdot DELTA12;\]
\[MU113 + MU123 \leq 2 \cdot DELTA13;\]

\[NU111 + NU121 \leq 2 \cdot DELTA21;\]
\[NU112 + NU122 \leq 2 \cdot DELTA22;\]
\[NU113 + NU123 \leq 2 \cdot DELTA23;\]

\[DELTA21 + DELTA11 \leq 1;\]
\[DELTA22 + DELTA12 \leq 1;\]
\[DELTA23 + DELTA13 \leq 1;\]

\[DELTA21 \leq THETA\_NO1;\]
\[DELTA22 \leq THETA\_NO2;\]
\[DELTA23 \leq THETA\_NO3;\]
[Eqn1_86] \text{HPOFF11} \leq 211 \cdot (1 - \text{NU111});
[Eqn1_87] \text{HPOFF12} \leq 211 \cdot (1 - \text{NU112});
[Eqn1_88] \text{HPOFF13} \leq 211 \cdot (1 - \text{NU113});

[Eqn1_89] \text{HPOFF21} \leq 211 \cdot (1 - \text{NU121});
[Eqn1_90] \text{HPOFF22} \leq 211 \cdot (1 - \text{NU122});
[Eqn1_91] \text{HPOFF23} \leq 211 \cdot (1 - \text{NU123});

[Eqn1_92] \text{HPON11} \leq 195 \cdot \text{NU111};
[Eqn1_93] \text{HPON12} \leq 195 \cdot \text{NU112};
[Eqn1_94] \text{HPON13} \leq 195 \cdot \text{NU113};

[Eqn1_95] \text{HPON21} \leq 195 \cdot \text{NU121};
[Eqn1_96] \text{HPON22} \leq 195 \cdot \text{NU122};
[Eqn1_97] \text{HPON23} \leq 195 \cdot \text{NU123};

[Eqn1_98] \text{H11} = \text{HPON11} + \text{HPOFF11};
[Eqn1_99] \text{H12} = \text{HPON12} + \text{HPOFF12};
[Eqn1_100] \text{H13} = \text{HPON13} + \text{HPOFF13};

[Eqn1_101] \text{H11} = \text{HPON21} + \text{HPOFF21};
[Eqn1_102] \text{H12} = \text{HPON22} + \text{HPOFF22};
[Eqn1_103] \text{H13} = \text{HPON23} + \text{HPOFF23};

[Eqn1_104] \text{HPON11} = -43.282 \cdot \text{QP11} + 383.61 \cdot \text{NU111};
[Eqn1_105] \text{HPON12} = -43.282 \cdot \text{QP12} + 383.61 \cdot \text{NU112};
[Eqn1_106] \text{HPON13} = -43.282 \cdot \text{QP13} + 383.61 \cdot \text{NU113};

[Eqn1_107] \text{HPON21} = -43.282 \cdot \text{QP21} + 383.61 \cdot \text{NU121};
[Eqn1_108] \text{HPON22} = -43.282 \cdot \text{QP22} + 383.61 \cdot \text{NU122};
[Eqn1_109] \text{HPON23} = -43.282 \cdot \text{QP23} + 383.61 \cdot \text{NU123};

[Eqn1_110] \text{QP11} \leq 4.9 \cdot \text{NU111};
[Eqn1_111] \text{QP12} \leq 4.9 \cdot \text{NU112};
[Eqn1_112] \text{QP13} \leq 4.9 \cdot \text{NU113};

[Eqn1_113] \text{QP21} \leq 4.9 \cdot \text{NU121};
[Eqn1_114] \text{QP22} \leq 4.9 \cdot \text{NU122};
[Eqn1_115] \text{QP23} \leq 4.9 \cdot \text{NU123};

[Eqn1_116] \text{H21} = \text{FB21} - \text{TR21};
[Eqn1_117] \text{H22} = \text{FB22} - \text{TR22};
[Eqn1_118] \text{H23} = \text{FB23} - \text{TR23};

[Eqn1_119] \text{FB21} = \text{SPILL2} \_\text{NO1} + \text{SPILL2} \_\text{YES1};
[Eqn1_120] \text{FB22} = \text{SPILL2} \_\text{NO2} + \text{SPILL2} \_\text{YES2};
[Eqn1_121] \text{FB23} = \text{SPILL2} \_\text{NO3} + \text{SPILL2} \_\text{YES3};

[Eqn1_122] \text{GATED1} \leq 150 \cdot \text{BETA} \_\text{YES1};
[Eqn1_123] \( \text{GATED}_2 \leq 150 \times \text{BETA}_\text{YES}_2 \)
[Eqn1_124] \( \text{GATED}_3 \leq 150 \times \text{BETA}_\text{YES}_3 \)

[Eqn1_125] \( 600 \times \text{BETA}_\text{NO}_1 \leq \text{SPILL}_2 \text{NO}_1 \)
[Eqn1_126] \( 600 \times \text{BETA}_\text{NO}_2 \leq \text{SPILL}_2 \text{NO}_2 \)
[Eqn1_127] \( 600 \times \text{BETA}_\text{NO}_3 \leq \text{SPILL}_2 \text{NO}_3 \)

[Eqn1_128] \( \text{SPILL}_2 \text{NO}_1 \leq 615 \times \text{BETA}_\text{NO}_1 \)
[Eqn1_129] \( \text{SPILL}_2 \text{NO}_2 \leq 615 \times \text{BETA}_\text{NO}_2 \)
[Eqn1_130] \( \text{SPILL}_2 \text{NO}_3 \leq 615 \times \text{BETA}_\text{NO}_3 \)

[Eqn1_131] 613.005 \times \text{BETA}_\text{YES}_1 \leq \text{SPILL}_2 \text{NO}_1 \\
[Eqn1_132] 613.005 \times \text{BETA}_\text{YES}_2 \leq \text{SPILL}_2 \text{NO}_2 \\
[Eqn1_133] 613.005 \times \text{BETA}_\text{YES}_3 \leq \text{SPILL}_2 \text{NO}_3 \\

[Eqn1_134] \text{SPILL}_2 \text{YES}_1 \leq 615 \times \text{BETA}_\text{YES}_1 \\
[Eqn1_135] \text{SPILL}_2 \text{YES}_2 \leq 615 \times \text{BETA}_\text{YES}_2 \\
[Eqn1_136] \text{SPILL}_2 \text{YES}_3 \leq 615 \times \text{BETA}_\text{YES}_3 \\

[Eqn1_137] \text{BETA}_\text{NO}_1 + \text{BETA}_\text{YES}_1 = 1 \\
[Eqn1_138] \text{BETA}_\text{NO}_2 + \text{BETA}_\text{YES}_2 = 1 \\
[Eqn1_139] \text{BETA}_\text{NO}_3 + \text{BETA}_\text{YES}_3 = 1 \\

[Eqn1_140] \text{TR}_{20} = 0.000095 \times \text{CHAN}^0 \times 3 - 0.017586 \times \text{CHAN}^0 \times 2 + 1.161031 \times \text{CHAN}0 + 532.573 \\
[Eqn1_141] \text{TR}_{21} = 0.000095 \times \text{CHAN}^1 \times 3 - 0.017586 \times \text{CHAN}^1 \times 2 + 1.161031 \times \text{CHAN}1 + 532.573 \\
[Eqn1_142] \text{TR}_{22} = 0.000095 \times \text{CHAN}^2 \times 3 - 0.017586 \times \text{CHAN}^2 \times 2 + 1.161031 \times \text{CHAN}2 + 532.573 \\
[Eqn1_143] \text{TR}_{23} = 0.000095 \times \text{CHAN}^3 \times 3 - 0.017586 \times \text{CHAN}^3 \times 2 + 1.161031 \times \text{CHAN}3 + 532.573 \\

[Eqn1_144] \text{CHAN}0 = \text{QT}_{210} + \text{QT}_{220} + \text{GATED}_0 \\
[Eqn1_145] \text{CHAN}1 = \text{QT}_{211} + \text{QT}_{221} + \text{GATED}_1 \\
[Eqn1_146] \text{CHAN}2 = \text{QT}_{212} + \text{QT}_{222} + \text{GATED}_2 \\
[Eqn1_147] \text{CHAN}3 = \text{QT}_{213} + \text{QT}_{223} + \text{GATED}_3 \\

[Eqn1_148] \text{CHAN}1 \leq 20 \\
[Eqn1_149] \text{CHAN}2 \leq 20 \\
[Eqn1_150] \text{CHAN}3 \leq 20 \\

[Eqn1_151] \text{S10} = 0.083667 \times \text{FB}10 - 61.339 \\
[Eqn1_152] \text{S11} = 0.083667 \times \text{FB}11 - 61.339 \\
[Eqn1_153] \text{S12} = 0.083667 \times \text{FB}12 - 61.339 \\
[Eqn1_154] \text{S13} = 0.083667 \times \text{FB}13 - 61.339 \\
[Eqn1_155] \text{S14} = 0.083667 \times \text{FB}14 - 61.339 \\

[Eqn1_156] \text{S20} = 0.011467 \times \text{FB}20 - 6.6201 \\
[Eqn1_157] \text{S21} = 0.011467 \times \text{FB}21 - 6.6201 \\
[Eqn1_158] \text{S22} = 0.011467 \times \text{FB}22 - 6.6201
[Eqn1_159] S23 = 0.011467*FB23 - 6.6201;
[Eqn1_160] S24 = 0.011467*FB24 - 6.6201;

[Eqn1_161] S11 = S10 + (- (QT110 + QT120) + QP10 + QP20 + I10 - UNCONTREL0) * 3600 * 24 / 10000000;
[Eqn1_162] S12 = S11 + (- (QT111 + QT121) + QP11 + QP21 + I11 - UNCONTREL1) * 3600 * 24 / 10000000;
[Eqn1_163] S13 = S12 + (- (QT112 + QT122) + QP12 + QP22 + I12 - UNCONTREL2) * 3600 * 24 / 10000000;
[Eqn1_164] S14 = S13 + (- (QT113 + QT123) + QP13 + QP23 + I13 - UNCONTREL3) * 3600 * 24 / 10000000;

[Eqn1_165] S21 = S20 + (QT110 + QT120 - QP10 - QP20 + UNCONTREL0 + I20 - QT210 - QT220 - GATED0) * 3600 * 24 / 10000000;
[Eqn1_166] S22 = S21 + (QT111 + QT121 - QP11 - QP21 + UNCONTREL1 + I21 - QT211 - QT221 - GATED1) * 3600 * 24 / 10000000;
[Eqn1_167] S23 = S22 + (QT112 + QT122 - QP12 - QP22 + UNCONTREL2 + I22 - QT212 - QT222 - GATED2) * 3600 * 24 / 10000000;

[Eqn1_169] @BIN(MU111);
[Eqn1_170] @BIN(MU112);
[Eqn1_171] @BIN(MU113);

[Eqn1_172] @BIN(MU121);
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[Eqn1_175] @BIN(MU211);
[Eqn1_176] @BIN(MU212);
[Eqn1_177] @BIN(MU213);

[Eqn1_178] @BIN(MU221);
[Eqn1_179] @BIN(MU222);
[Eqn1_180] @BIN(MU223);

[Eqn1_181] @BIN(THETA_NO1);
[Eqn1_182] @BIN(THETA_NO2);
[Eqn1_183] @BIN(THETA_NO3);

[Eqn1_184] @BIN(THETA_YES1);
[Eqn1_185] @BIN(THETA_YES2);
[Eqn1_186] @BIN(THETA_YES3);

[Eqn1_187] @BIN(DELTA11);
[Eqn1_188] @BIN(DELTA12);
[Eqn1_189] @BIN(DELTA13);
[Eqn1_190]@BIN(NU111);
[Eqn1_191]@BIN(NU112);
[Eqn1_192]@BIN(NU113);

[Eqn1_193]@BIN(NU121);
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[Eqn1_195]@BIN(NU123);

[Eqn1_196]@BIN(DELTA21);
[Eqn1_197]@BIN(DELTA22);
[Eqn1_198]@BIN(DELTA23);

[Eqn1_199]@BIN(BETA_NO1);
[Eqn1_200]@BIN(BETA_NO2);
[Eqn1_201]@BIN(BETA_NO3);

[Eqn1_202]@BIN(BETA_YES1);
[Eqn1_203]@BIN(BETA_YES2);
[Eqn1_204]@BIN(BETA_YES3);
Output from LINGO for Analysis 1

Rows= 165 Vars= 145 No. integer vars= 36
Nonlinear rows= 25 Nonlinear vars= 30 Nonlinear constraints= 25
Nonzeros= 492 Constraint nonz= 434 Density=0.020
No. < : 84 No. =: 80 No. > : 0, Obj=MAX Single cols= 5

** WARNING ** Problem is poorly scaled. The units of the rows and variables should be changed so the coefficients cover a much smaller range.

Local optimal solution found at step: 242
Objective value: 260164.8
Branch count: 4

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Input to LINGO for Analysis 2

Data:
CP1=10;
CP2=0.0001;
CP3=1000;

All others remained the same.

Output from LINGO for Analysis 2

Local optimal solution found at step: 441
Objective value: 2399176.
Branch count: 6

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APPENDIX C  CPLEX Implementation

Input to CPLEX for Analysis 1

MAXIMIZE
10PT1_1+.0001PT1_2+100PT1_3-10PP_1-.0001PP_2-
100PP_3+10PT2_1+.0001PT2_2+100PT2_3

st

\ Equation 8.1

188delta1_101+187delta1_91+186delta1_81+185delta1_71+184delta1_61+183delta1_51+182de
ltal_41+181delta1_31+180delta1_21+
170delta1_11-H1_1<=0
188delta1_102+187delta1_92+186delta1_82+185delta1_72+184delta1_62+183delta1_52+182de
ltal_42+181delta1_32+180delta1_22+
170delta1_12-H1_2<=0
188delta1_103+187delta1_93+186delta1_83+185delta1_73+184delta1_63+183delta1_53+182de
ltal_43+181delta1_33+180delta1_23+
170delta1_13-H1_3<=0
195delta1_101+187.999delta1_91+186.999delta1_81+185.999delta1_71+184.999delta1_61+18
3.999delta1_51+182.999delta1_41+
181.999delta1_31+180.999delta1_21+179.999delta1_11-H1_1=>0
195delta1_102+187.999delta1_92+186.999delta1_82+185.999delta1_72+184.999delta1_62+18
3.999delta1_52+182.999delta1_42+
181.999delta1_32+180.999delta1_22+179.999delta1_12-H1_2=>0
195delta1_103+187.999delta1_93+186.999delta1_83+185.999delta1_73+184.999delta1_63+18
3.999delta1_53+182.999delta1_43+
181.999delta1_33+180.999delta1_23+179.999delta1_13-H1_3=>0

\ Equation 8.2

delta1_101+delta1_91+delta1_81+delta1_71+delta1_61+delta1_51+delta1_41+delta1_31+delta
1_21+delta1_11=1
delta1_102+delta1_92+delta1_82+delta1_72+delta1_62+delta1_52+delta1_42+delta1_32+delta
1_22+delta1_12=1
delta1_103+delta1_93+delta1_83+delta1_73+delta1_63+delta1_53+delta1_43+delta1_33+delta
1_23+delta1_13=1

\ Equation 8.3

108
\text{\texttt{FB1_1-FB2_1-H1_1=0}}
\text{\texttt{FB1_2-FB2_2-H1_2=0}}
\text{\texttt{FB1_3-FB2_3-H1_3=0}}

\text{\texttt{\\ Equation 8.6}}

\begin{align*}
\phi_{1161} + \phi_{1141} + \phi_{1131} + \phi_{1121} + \phi_{1111} - \delta_{111} & \leq 0 \\
\phi_{2161} + \phi_{2151} + \phi_{2141} + \phi_{2131} + \phi_{2121} + \phi_{2111} - \delta_{211} & \leq 0 \\
\phi_{3161} + \phi_{3151} + \phi_{3141} + \phi_{3131} + \phi_{3121} + \phi_{3111} - \delta_{311} & \leq 0 \\
\phi_{4161} + \phi_{4151} + \phi_{4141} + \phi_{4131} + \phi_{4121} + \phi_{4111} - \delta_{411} & \leq 0 \\
\phi_{5161} + \phi_{5151} + \phi_{5141} + \phi_{5131} + \phi_{5121} + \phi_{5111} - \delta_{511} & \leq 0 \\
\phi_{6161} + \phi_{6151} + \phi_{6141} + \phi_{6131} + \phi_{6121} + \phi_{6111} - \delta_{611} & \leq 0 \\
\phi_{7161} + \phi_{7151} + \phi_{7141} + \phi_{7131} + \phi_{7121} + \phi_{7111} - \delta_{711} & \leq 0 \\
\phi_{8161} + \phi_{8151} + \phi_{8141} + \phi_{8131} + \phi_{8121} + \phi_{8111} - \delta_{811} & \leq 0 \\
\phi_{9161} + \phi_{9151} + \phi_{9141} + \phi_{9131} + \phi_{9121} + \phi_{9111} - \delta_{911} & \leq 0 \\
\phi_{10161} + \phi_{10151} + \phi_{10141} + \phi_{10131} + \phi_{10121} + \phi_{10111} - \delta_{1011} & \leq 0 \\
\phi_{1261} + \phi_{1251} + \phi_{1241} + \phi_{1231} + \phi_{1221} + \phi_{1211} - \delta_{1211} & \leq 0 \\
\phi_{2261} + \phi_{2251} + \phi_{2241} + \phi_{2231} + \phi_{2221} + \phi_{2211} - \delta_{2211} & \leq 0 \\
\phi_{3261} + \phi_{3251} + \phi_{3241} + \phi_{3231} + \phi_{3221} + \phi_{3211} - \delta_{3211} & \leq 0 \\
\phi_{4261} + \phi_{4251} + \phi_{4241} + \phi_{4231} + \phi_{4221} + \phi_{4211} - \delta_{4211} & \leq 0 \\
\phi_{5261} + \phi_{5251} + \phi_{5241} + \phi_{5231} + \phi_{5221} + \phi_{5211} - \delta_{5211} & \leq 0 \\
\phi_{6261} + \phi_{6251} + \phi_{6241} + \phi_{6231} + \phi_{6221} + \phi_{6211} - \delta_{6211} & \leq 0 \\
\phi_{7261} + \phi_{7251} + \phi_{7241} + \phi_{7231} + \phi_{7221} + \phi_{7211} - \delta_{7211} & \leq 0 \\
\phi_{8261} + \phi_{8251} + \phi_{8241} + \phi_{8231} + \phi_{8221} + \phi_{8211} - \delta_{8211} & \leq 0 \\
\phi_{9261} + \phi_{9251} + \phi_{9241} + \phi_{9231} + \phi_{9221} + \phi_{9211} - \delta_{9211} & \leq 0 \\
\phi_{10261} + \phi_{10251} + \phi_{10241} + \phi_{10231} + \phi_{10221} + \phi_{10211} - \delta_{10211} & \leq 0 \\
\phi_{1162} + \phi_{1152} + \phi_{1142} + \phi_{1132} + \phi_{1122} + \phi_{1112} - \delta_{1112} & \leq 0 \\
\phi_{2162} + \phi_{2152} + \phi_{2142} + \phi_{2132} + \phi_{2122} + \phi_{2112} - \delta_{2112} & \leq 0 \\
\phi_{3162} + \phi_{3152} + \phi_{3142} + \phi_{3132} + \phi_{3122} + \phi_{3112} - \delta_{3112} & \leq 0 \\
\phi_{4162} + \phi_{4152} + \phi_{4142} + \phi_{4132} + \phi_{4122} + \phi_{4112} - \delta_{4112} & \leq 0 \\
\phi_{5162} + \phi_{5152} + \phi_{5142} + \phi_{5132} + \phi_{5122} + \phi_{5112} - \delta_{5112} & \leq 0 \\
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\phi_{7262} + \phi_{7252} + \phi_{7242} + \phi_{7232} + \phi_{7222} + \phi_{7212} - \delta_{7212} & \leq 0 \\
\phi_{8262} + \phi_{8252} + \phi_{8242} + \phi_{8232} + \phi_{8222} + \phi_{8212} - \delta_{8212} & \leq 0 \\
\phi_{9262} + \phi_{9252} + \phi_{9242} + \phi_{9232} + \phi_{9222} + \phi_{9212} - \delta_{9212} & \leq 0
\end{align*}
\begin{align*}
\phi_1_{10262} + \phi_1_{10252} + \phi_1_{10242} + \phi_1_{10232} + \phi_1_{10222} + \phi_1_{10212} - \delta_{1_{102}} &\leq 0 \\
\phi_1_{1163} + \phi_1_{1153} + \phi_1_{1143} + \phi_1_{1133} + \phi_1_{1123} + \phi_1_{1113} - \delta_{1_{113}} &\leq 0 \\
\phi_1_{2163} + \phi_1_{2153} + \phi_1_{2143} + \phi_1_{2133} + \phi_1_{2123} + \phi_1_{2113} - \delta_{1_{213}} &\leq 0 \\
\phi_1_{3163} + \phi_1_{3153} + \phi_1_{3143} + \phi_1_{3133} + \phi_1_{3123} + \phi_1_{3113} - \delta_{1_{313}} &\leq 0 \\
\phi_1_{4163} + \phi_1_{4153} + \phi_1_{4143} + \phi_1_{4133} + \phi_1_{4123} + \phi_1_{4113} - \delta_{1_{413}} &\leq 0 \\
\phi_1_{5163} + \phi_1_{5153} + \phi_1_{5143} + \phi_1_{5133} + \phi_1_{5123} + \phi_1_{5113} - \delta_{1_{513}} &\leq 0 \\
\phi_1_{6163} + \phi_1_{6153} + \phi_1_{6143} + \phi_1_{6133} + \phi_1_{6123} + \phi_1_{6113} - \delta_{1_{613}} &\leq 0 \\
\phi_1_{7163} + \phi_1_{7153} + \phi_1_{7143} + \phi_1_{7133} + \phi_1_{7123} + \phi_1_{7113} - \delta_{1_{713}} &\leq 0 \\
\phi_1_{8163} + \phi_1_{8153} + \phi_1_{8143} + \phi_1_{8133} + \phi_1_{8123} + \phi_1_{8113} - \delta_{1_{813}} &\leq 0 \\
\phi_1_{9163} + \phi_1_{9153} + \phi_1_{9143} + \phi_1_{9133} + \phi_1_{9123} + \phi_1_{9113} - \delta_{1_{913}} &\leq 0 \\
\phi_1_{10163} + \phi_1_{10153} + \phi_1_{10143} + \phi_1_{10133} + \phi_1_{10123} + \phi_1_{10113} - \delta_{1_{1013}} &\leq 0 \\
\phi_1_{1263} + \phi_1_{1253} + \phi_1_{1243} + \phi_1_{1233} + \phi_1_{1223} + \phi_1_{1213} - \delta_{1_{1213}} &\leq 0 \\
\phi_1_{2263} + \phi_1_{2253} + \phi_1_{2243} + \phi_1_{2233} + \phi_1_{2223} + \phi_1_{2213} - \delta_{1_{2213}} &\leq 0 \\
\phi_1_{3263} + \phi_1_{3253} + \phi_1_{3243} + \phi_1_{3233} + \phi_1_{3223} + \phi_1_{3213} - \delta_{1_{3213}} &\leq 0 \\
\phi_1_{4263} + \phi_1_{4253} + \phi_1_{4243} + \phi_1_{4233} + \phi_1_{4223} + \phi_1_{4213} - \delta_{1_{4213}} &\leq 0 \\
\phi_1_{5263} + \phi_1_{5253} + \phi_1_{5243} + \phi_1_{5233} + \phi_1_{5223} + \phi_1_{5213} - \delta_{1_{5213}} &\leq 0 \\
\phi_1_{6263} + \phi_1_{6253} + \phi_1_{6243} + \phi_1_{6233} + \phi_1_{6223} + \phi_1_{6213} - \delta_{1_{6213}} &\leq 0 \\
\phi_1_{7263} + \phi_1_{7253} + \phi_1_{7243} + \phi_1_{7233} + \phi_1_{7223} + \phi_1_{7213} - \delta_{1_{7213}} &\leq 0 \\
\phi_1_{8263} + \phi_1_{8253} + \phi_1_{8243} + \phi_1_{8233} + \phi_1_{8223} + \phi_1_{8213} - \delta_{1_{8213}} &\leq 0 \\
\phi_1_{9263} + \phi_1_{9253} + \phi_1_{9243} + \phi_1_{9233} + \phi_1_{9223} + \phi_1_{9213} - \delta_{1_{9213}} &\leq 0 \\
\phi_1_{10263} + \phi_1_{10253} + \phi_1_{10243} + \phi_1_{10233} + \phi_1_{10223} + \phi_1_{10213} - \delta_{1_{10213}} &\leq 0
\end{align*}
\[901.22\phi_1 \cdot 9162 + 872.84\phi_1 \cdot 9152 + 843.83\phi_1 \cdot 9142 + 813.94\phi_1 \cdot 9132 + 782.96\phi_1 \cdot 9122 + 568.27\phi_1 \cdot 9112 + 896.41\phi_1 \cdot 8162 + 868.18\phi_1 \cdot 8152 + 839.33\phi_1 \cdot 8142 + 809.6\phi_1 \cdot 8132 + 778.78\phi_1 \cdot 8122 + 565.24\phi_1 \cdot 8112 + 891.6\phi_1 \cdot 7162 + 863.53\phi_1 \cdot 7152 + 834.83\phi_1 \cdot 7142 + 805.26\phi_1 \cdot 7132 + 774.61\phi_1 \cdot 7122 + 562.21\phi_1 \cdot 7112 + 886.8\phi_1 \cdot 6162 + 858.87\phi_1 \cdot 6152 + 830.33\phi_1 \cdot 6142 + 800.92\phi_1 \cdot 6132 + 770.43\phi_1 \cdot 6122 + 591.18\phi_1 \cdot 6112 + 881.99\phi_1 \cdot 5162 + 854.22\phi_1 \cdot 5152 + 825.83\phi_1 \cdot 5142 + 796.58\phi_1 \cdot 5132 + 766.26\phi_1 \cdot 5122 + 556.15\phi_1 \cdot 5112 + 877.18\phi_1 \cdot 4162 + 849.56\phi_1 \cdot 4152 + 821.33\phi_1 \cdot 4142 + 792.24\phi_1 \cdot 4132 + 762.08\phi_1 \cdot 4122 + 553.12\phi_1 \cdot 4112 + 872.38\phi_1 \cdot 3162 + 844.91\phi_1 \cdot 3152 + 816.83\phi_1 \cdot 3142 + 787.9\phi_1 \cdot 3132 + 757.9\phi_1 \cdot 3122 + 550.09\phi_1 \cdot 3112 + 867.57\phi_1 \cdot 2162 + 840.25\phi_1 \cdot 2152 + 812.33\phi_1 \cdot 2142 + 783.56\phi_1 \cdot 2132 + 753.73\phi_1 \cdot 2122 + 547.06\phi_1 \cdot 2112 + 841.13\phi_1 \cdot 1162 + 814.65\phi_1 \cdot 1152 + 787.58\phi_1 \cdot 1142 + 759.68\phi_1 \cdot 1132 + 730.76\phi_1 \cdot 1122 + 530.39\phi_1 \cdot 1112 - PT1_{12} = 0\]

\[920.44\phi_1 \cdot 10163 + 891.46\phi_1 \cdot 10153 + 861.84\phi_1 \cdot 10143 + 831.31\phi_1 \cdot 10133 + 799.66\phi_1 \cdot 10123 + 580.4\phi_1 \cdot 10113 + 901.22\phi_1 \cdot 9163 + 872.84\phi_1 \cdot 9153 + 843.83\phi_1 \cdot 9143 + 813.94\phi_1 \cdot 9133 + 782.96\phi_1 \cdot 9123 + 568.27\phi_1 \cdot 9113 + 896.41\phi_1 \cdot 8163 + 868.18\phi_1 \cdot 8153 + 839.33\phi_1 \cdot 8143 + 809.6\phi_1 \cdot 8133 + 778.78\phi_1 \cdot 8123 + 565.24\phi_1 \cdot 8113 + 891.6\phi_1 \cdot 7163 + 863.53\phi_1 \cdot 7153 + 834.83\phi_1 \cdot 7143 + 805.26\phi_1 \cdot 7133 + 774.61\phi_1 \cdot 7123 + 562.21\phi_1 \cdot 7113 + 886.8\phi_1 \cdot 6163 + 858.87\phi_1 \cdot 6153 + 830.33\phi_1 \cdot 6143 + 800.92\phi_1 \cdot 6133 + 770.43\phi_1 \cdot 6123 + 591.18\phi_1 \cdot 6113 + 881.99\phi_1 \cdot 5163 + 854.22\phi_1 \cdot 5153 + 825.83\phi_1 \cdot 5143 + 796.58\phi_1 \cdot 5133 + 766.26\phi_1 \cdot 5123 + 556.15\phi_1 \cdot 5113 + 877.18\phi_1 \cdot 4163 + 849.56\phi_1 \cdot 4153 + 821.33\phi_1 \cdot 4143 + 792.24\phi_1 \cdot 4133 + 762.08\phi_1 \cdot 4123 + 553.12\phi_1 \cdot 4113 + 872.38\phi_1 \cdot 3163 + 844.91\phi_1 \cdot 3153 + 816.83\phi_1 \cdot 3143 + 787.9\phi_1 \cdot 3133 + 757.9\phi_1 \cdot 3123 + 550.09\phi_1 \cdot 3113 + 867.57\phi_1 \cdot 2163 + 840.25\phi_1 \cdot 2153 + 812.33\phi_1 \cdot 2143 + 783.56\phi_1 \cdot 2133 + 753.73\phi_1 \cdot 2123 + 547.06\phi_1 \cdot 2113 + 841.13\phi_1 \cdot 1163 + 814.65\phi_1 \cdot 1153 + 787.58\phi_1 \cdot 1143 + 759.68\phi_1 \cdot 1133 + 730.76\phi_1 \cdot 1123 + 530.39\phi_1 \cdot 1113 - PT1_{13} = 0\]

\[920.44\phi_1 \cdot 10261 + 891.46\phi_1 \cdot 10251 + 861.84\phi_1 \cdot 10241 + 831.31\phi_1 \cdot 10231 + 799.66\phi_1 \cdot 10221 + 580.4\phi_1 \cdot 10211 + 901.22\phi_1 \cdot 9261 + 872.84\phi_1 \cdot 9251 + 843.83\phi_1 \cdot 9241 + 813.94\phi_1 \cdot 9231 + 782.96\phi_1 \cdot 9221 + 568.27\phi_1 \cdot 9211 + 896.41\phi_1 \cdot 8261 + 868.18\phi_1 \cdot 8251 + 839.33\phi_1 \cdot 8241 + 809.6\phi_1 \cdot 8231 + 778.78\phi_1 \cdot 8221 + 565.24\phi_1 \cdot 8211 + 891.6\phi_1 \cdot 7261 + 863.53\phi_1 \cdot 7251 + 834.83\phi_1 \cdot 7241 + 805.26\phi_1 \cdot 7231 + 774.61\phi_1 \cdot 7221 + 562.21\phi_1 \cdot 7211 + 886.8\phi_1 \cdot 6261 + 858.87\phi_1 \cdot 6251 + 830.33\phi_1 \cdot 6241 + 800.92\phi_1 \cdot 6231 + 770.43\phi_1 \cdot 6221 +\]
\[ 867.57\phi_1_{2263}+840.25\phi_1_{2253}+812.33\phi_1_{2243}+783.56\phi_1_{2233}+753.73\phi_1_{2223}+54.706\phi_1_{2213} \\
+841.13\phi_1_{1263}+814.65\phi_1_{1253}+787.58\phi_1_{1243}+759.68\phi_1_{1233}+730.76\phi_1_{1223}+530.39\phi_1_{1213}-PT_1_{23}=0 \]
\ Equation 8.9

\[ PT_1_{21}+PT_1_{11}-PT_1_{1}=0 \\
PT_1_{22}+PT_1_{12}-PT_1_{2}=0 \\
PT_1_{23}+PT_1_{13}-PT_1_{3}=0 \]
\ Equation 8.10

\[ PT_1-PT_1_1-PT_2_1=0 \\
PT_2-PT_1_2-PT_2_2=0 \\
PT_3-PT_1_3-PT_2_3=0 \]
\ Equation 8.11

\[ 5.4501\phi_1_{10161}+5.2501\phi_1_{10115}+5.0501\phi_1_{10141}+4.8501\phi_1_{10131}+4.6501\phi_1_{10121}+2.4501\phi_1_{10111}+5.4501\phi_1_{9161}+5.2501\phi_1_{9115}+ \\
5.0501\phi_1_{9141}+4.8501\phi_1_{9131}+4.6501\phi_1_{9121}+2.4501\phi_1_{9111}+5.4501\phi_1_{8161}+5.2501\phi_1_{8115}+ \\
5.0501\phi_1_{8141}+4.8501\phi_1_{8131}+4.6501\phi_1_{8121}+2.4501\phi_1_{8111}+5.4501\phi_1_{7161}+5.2501\phi_1_{7115}+ \\
5.0501\phi_1_{7141}+4.8501\phi_1_{7131}+4.6501\phi_1_{7121}+2.4501\phi_1_{7111}+ \\
5.4501\phi_1_{6161}+5.2501\phi_1_{6115}+5.0501\phi_1_{6141}+4.8501\phi_1_{6131}+4.6501\phi_1_{6121}+2.4501\phi_1_{6111}+ \\
5.4501\phi_1_{5161}+5.2501\phi_1_{5115}+5.0501\phi_1_{5141}+4.8501\phi_1_{5131}+4.6501\phi_1_{5121}+2.4501\phi_1_{5111}+ \\
5.4501\phi_1_{4161}+5.2501\phi_1_{4115}+5.0501\phi_1_{4141}+4.8501\phi_1_{4131}+4.6501\phi_1_{4121}+2.4501\phi_1_{4111}+ \\
5.4501\phi_1_{3161}+5.2501\phi_1_{3115}+5.0501\phi_1_{3141}+4.8501\phi_1_{3131}+4.6501\phi_1_{3121}+2.4501\phi_1_{3111}+ \\
5.4501\phi_1_{2161}+5.2501\phi_1_{2115}+5.0501\phi_1_{2141}+4.8501\phi_1_{2131}+4.6501\phi_1_{2121}+2.4501\phi_1_{2111}+ \\
5.4501\phi_1_{1161}+5.2501\phi_1_{1115}+5.0501\phi_1_{1141}+4.8501\phi_1_{1131}+4.6501\phi_1_{1121}+2.4501\phi_1_{1111}-QT_1_{11}=0 \]

\[ 5.6501\phi_1_{10161}+5.4501\phi_1_{10115}+5.2501\phi_1_{10141}+5.0501\phi_1_{10131}+4.8501\phi_1_{10121}+4.6501\phi_1_{10111}+5.6501\phi_1_{9161}+5.4501\phi_1_{9115}+ \\
5.2501\phi_1_{9141}+5.0501\phi_1_{9131}+4.8501\phi_1_{9121}+4.6501\phi_1_{9111}+5.6501\phi_1_{8161}+5.4501\phi_1_{8115}+ \\
5.2501\phi_1_{8141}+5.0501\phi_1_{8131}+4.8501\phi_1_{8121}+4.6501\phi_1_{8111}+5.6501\phi_1_{7161}+5.4501\phi_1_{7115}+ \\
5.2501\phi_1_{7141}+5.0501\phi_1_{7131}+4.8501\phi_1_{7121}+4.6501\phi_1_{7111}+5.6501\phi_1_{6161}+5.4501\phi_1_{6115}+ \\
5.2501\phi_1_{6141}+5.0501\phi_1_{6131}+4.8501\phi_1_{6121}+4.6501\phi_1_{6111}+5.6501\phi_1_{5161}+5.4501\phi_1_{5115}+ \\
5.2501\phi_1_{5141}+5.0501\phi_1_{5131}+4.8501\phi_1_{5121}+4.6501\phi_1_{5111}+5.6501\phi_1_{4161}+5.4501\phi_1_{4115}+ \\
5.2501\phi_1_{4141}+5.0501\phi_1_{4131}+4.8501\phi_1_{4121}+4.6501\phi_1_{4111}+5.6501\phi_1_{3161}+5.4501\phi_1_{3115}+ \\
5.2501\phi_1_{3141}+5.0501\phi_1_{3131}+4.8501\phi_1_{3121}+4.6501\phi_1_{3111}+5.6501\phi_1_{2161}+ \\
5.4501\phi_1_{2115}+5.2501\phi_1_{2141}+4.8501\phi_1_{2131}+4.6501\phi_1_{2121}+5.4501\phi_1_{2111}+5.2501\phi_1_{2141}+ \\
5.0501\phi_1_{2131}+4.8501\phi_1_{2121}+4.6501\phi_1_{2111}+5.4501\phi_1_{1161}+5.2501\phi_1_{1115}+ \\
5.0501\phi_1_{1141}+4.8501\phi_1_{1131}+4.6501\phi_1_{1121}+5.4501\phi_1_{1111}+5.2501\phi_1_{1141}+ \\
5.0501\phi_1_{1131}+4.8501\phi_1_{1121}+4.6501\phi_1_{1111}+5.4501\phi_1_{1111}=0 \]
\[ 5.05\phi_{1_3131}+4.85\phi_{1_3121}+4.65\phi_{1_3111}+5.65\phi_{1_2161}+5.45\phi_{1_2151}+5.25\phi_{1_2141}+5.05\phi_{1_2131}+4.85\phi_{1_2121}+4.65\phi_{1_2111}+5.65\phi_{1_1161}+5.45\phi_{1_1151}+5.25\phi_{1_1141}+5.05\phi_{1_1131}+4.85\phi_{1_1121}+4.65\phi_{1_1111}+\text{QT1}_{11}\geqslant 0 \]

\[ 5.4501\phi_{1_10162}+5.2501\phi_{1_10152}+5.0501\phi_{1_10142}+4.8501\phi_{1_10132}+4.6501\phi_{1_10122}+2.4501\phi_{1_10112}+5.4501\phi_{1_9162}+5.2501\phi_{1_9152}+5.0501\phi_{1_9142}+4.8501\phi_{1_9132}+4.6501\phi_{1_9122}+2.4501\phi_{1_9112}+5.4501\phi_{1_8162}+5.2501\phi_{1_8152}+5.0501\phi_{1_8142}+4.8501\phi_{1_8132}+4.6501\phi_{1_8122}+2.4501\phi_{1_8112}+5.4501\phi_{1_7162}+5.2501\phi_{1_7152}+5.0501\phi_{1_7142}+4.8501\phi_{1_7132}+4.6501\phi_{1_7122}+2.4501\phi_{1_7112}+5.4501\phi_{1_6162}+5.2501\phi_{1_6152}+5.0501\phi_{1_6142}+4.8501\phi_{1_6132}+4.6501\phi_{1_6122}+2.4501\phi_{1_6112}+5.4501\phi_{1_5162}+5.2501\phi_{1_5152}+5.0501\phi_{1_5142}+4.8501\phi_{1_5132}+4.6501\phi_{1_5122}+2.4501\phi_{1_5112}+5.4501\phi_{1_4162}+5.2501\phi_{1_4152}+5.0501\phi_{1_4142}+4.8501\phi_{1_4132}+4.6501\phi_{1_4122}+2.4501\phi_{1_4112}+5.4501\phi_{1_3162}+5.2501\phi_{1_3152}+5.0501\phi_{1_3142}+4.8501\phi_{1_3132}+4.6501\phi_{1_3122}+2.4501\phi_{1_3112}+5.4501\phi_{1_2162}+5.2501\phi_{1_2152}+5.0501\phi_{1_2142}+4.8501\phi_{1_2132}+4.6501\phi_{1_2122}+2.4501\phi_{1_2112}+5.4501\phi_{1_1162}+5.2501\phi_{1_1152}+5.0501\phi_{1_1142}+4.8501\phi_{1_1132}+4.6501\phi_{1_1122}+2.4501\phi_{1_1112}\leqslant \text{QT1}_{12} \]

\[ 5.65\phi_{1_10162}+5.45\phi_{1_10152}+5.25\phi_{1_10142}+5.05\phi_{1_10132}+4.85\phi_{1_10122}+4.65\phi_{1_10112}+5.65\phi_{1_9162}+5.45\phi_{1_9152}+5.25\phi_{1_9142}+5.05\phi_{1_9132}+4.85\phi_{1_9122}+4.65\phi_{1_9112}+5.65\phi_{1_8162}+5.45\phi_{1_8152}+5.25\phi_{1_8142}+5.05\phi_{1_8132}+4.85\phi_{1_8122}+4.65\phi_{1_8112}+5.65\phi_{1_7162}+5.45\phi_{1_7152}+5.25\phi_{1_7142}+5.05\phi_{1_7132}+4.85\phi_{1_7122}+4.65\phi_{1_7112}+5.65\phi_{1_6162}+5.45\phi_{1_6152}+5.25\phi_{1_6142}+5.05\phi_{1_6132}+4.85\phi_{1_6122}+4.65\phi_{1_6112}+5.65\phi_{1_5162}+5.45\phi_{1_5152}+5.25\phi_{1_5142}+5.05\phi_{1_5132}+4.85\phi_{1_5122}+4.65\phi_{1_5112}+5.65\phi_{1_4162}+5.45\phi_{1_4152}+5.25\phi_{1_4142}+5.05\phi_{1_4132}+4.85\phi_{1_4122}+4.65\phi_{1_4112}+5.65\phi_{1_3162}+5.45\phi_{1_3152}+5.25\phi_{1_3142}+5.05\phi_{1_3132}+4.85\phi_{1_3122}+4.65\phi_{1_3112}+5.65\phi_{1_2162}+5.45\phi_{1_2152}+5.25\phi_{1_2142}+5.05\phi_{1_2132}+4.85\phi_{1_2122}+4.65\phi_{1_2112}+5.65\phi_{1_1162}+5.45\phi_{1_1152}+5.25\phi_{1_1142}+5.05\phi_{1_1132}+4.85\phi_{1_1122}+4.65\phi_{1_1112}-\text{QT1}_{12}\geqslant 0 \]
\begin{align*}
5.0501\phi_{1, 1143} + 4.8501\phi_{1, 1133} + 4.6501\phi_{1, 1123} + 2.4501\phi_{1, 1113} - QT_1_{13} & \leq 0 \\
5.65\phi_{1, 10163} + 5.45\phi_{1, 10153} + 5.25\phi_{1, 10143} + 5.05\phi_{1, 10133} + 4.85\phi_{1, 10123} + 4.65\phi_{1, 10113} & + 5.65\phi_{1, 9163} + 5.45\phi_{1, 9153} + 5.25\phi_{1, 9143} + 5.05\phi_{1, 9133} + 4.85\phi_{1, 9123} + 4.65\phi_{1, 8113} & + 5.65\phi_{1, 1013} + 5.45\phi_{1, 913} + 5.25\phi_{1, 813} + 5.05\phi_{1, 8113} + 4.85\phi_{1, 7113} & + 5.65\phi_{1, 6113} + 5.45\phi_{1, 5113} + 5.25\phi_{1, 4113} & + 5.05\phi_{1, 3113} + 4.85\phi_{1, 2113} & + 5.65\phi_{1, 1163} + 5.45\phi_{1, 1153} + 5.25\phi_{1, 1143} + 5.05\phi_{1, 1133} + 4.85\phi_{1, 1123} + 4.65\phi_{1, 1113} & - QT_1_{13} & \leq 0 \\
& + 5.65\phi_{1, 10261} + 5.45\phi_{1, 10251} + 5.25\phi_{1, 10241} + 5.05\phi_{1, 10231} + 4.85\phi_{1, 10221} + 4.65\phi_{1, 10211} & + 5.65\phi_{1, 9261} + 5.45\phi_{1, 9251} + 5.25\phi_{1, 9241} + 5.05\phi_{1, 9231} + 4.85\phi_{1, 9221} + 4.65\phi_{1, 9211} & + 5.65\phi_{1, 8261} + 5.45\phi_{1, 8251} + 5.25\phi_{1, 8241} + 5.05\phi_{1, 8231} + 4.85\phi_{1, 8221} + 4.65\phi_{1, 8211} & + 5.65\phi_{1, 7261} + 5.45\phi_{1, 7251} + 5.25\phi_{1, 7241} + 5.05\phi_{1, 7231} + 4.85\phi_{1, 7221} & + 4.65\phi_{1, 7211} & + 5.65\phi_{1, 6261} & + 5.45\phi_{1, 6251} & + 5.25\phi_{1, 6241} & + 5.05\phi_{1, 6231} & + 4.85\phi_{1, 6221} & + 4.65\phi_{1, 6211} & + 5.65\phi_{1, 5261} & + 5.45\phi_{1, 5251} & + 5.25\phi_{1, 5241} & + 5.05\phi_{1, 5231} & + 4.85\phi_{1, 5221} & + 4.65\phi_{1, 5211} & + 5.65\phi_{1, 4261} & + 5.45\phi_{1, 4251} & + 5.25\phi_{1, 4241} & + 5.05\phi_{1, 4231} & + 4.85\phi_{1, 4221} & + 4.65\phi_{1, 4211} & + 5.65\phi_{1, 3261} & + 5.45\phi_{1, 3251} & + 5.25\phi_{1, 3241} & + 5.05\phi_{1, 3231} & + 4.85\phi_{1, 3221} & + 4.65\phi_{1, 3211} & + 5.65\phi_{1, 2261} & + 5.45\phi_{1, 2251} & + 5.25\phi_{1, 2241} & + 5.05\phi_{1, 2231} & + 4.85\phi_{1, 2221} & + 4.65\phi_{1, 2211} & + 5.65\phi_{1, 1261} & + 5.45\phi_{1, 1251} & + 5.25\phi_{1, 1241} & + 5.05\phi_{1, 1231} & + 4.85\phi_{1, 1221} & + 4.65\phi_{1, 1211} & - QT_1_{21} & \leq 0 \\
& + 5.65\phi_{1, 10262} + 5.45\phi_{1, 10252} + 5.25\phi_{1, 10242} + 5.05\phi_{1, 10232} + 4.85\phi_{1, 10222} + 4.65\phi_{1, 10212} & + 5.65\phi_{1, 9262} & + 5.45\phi_{1, 9252} & + 5.25\phi_{1, 9242} & + 5.05\phi_{1, 9232} & + 4.85\phi_{1, 9222} & + 4.65\phi_{1, 9212} & + 5.65\phi_{1, 8262} & + 5.45\phi_{1, 8252} & + 5.25\phi_{1, 8242} & + 5.05\phi_{1, 8232} & + 4.85\phi_{1, 8222} & + 4.65\phi_{1, 8212} & + 5.65\phi_{1, 7262} & + 5.45\phi_{1, 7252} & + 5.25\phi_{1, 7242} & + 5.05\phi_{1, 7232} & + 4.85\phi_{1, 7222} & + 4.65\phi_{1, 7212} & + 5.65\phi_{1, 6262} & + 5.45\phi_{1, 6252} & + 5.25\phi_{1, 6242} & + 5.05\phi_{1, 6232} & + 4.85\phi_{1, 6222} & + 4.65\phi_{1, 6212} & + 5.65\phi_{1, 5262} & + 5.45\phi_{1, 5252} & + 5.25\phi_{1, 5242} & + 5.05\phi_{1, 5232} & + 4.85\phi_{1, 5222} & + 4.65\phi_{1, 5212} & + 5.65\phi_{1, 4262} & + 5.45\phi_{1, 4252} & + 5.25\phi_{1, 4242} & + 5.05\phi_{1, 4232} & + 4.85\phi_{1, 4222} & + 4.65\phi_{1, 4212} & + 5.65\phi_{1, 3262} & + 5.45\phi_{1, 3252} & + 5.25\phi_{1, 3242} & + 5.05\phi_{1, 3232} & + 4.85\phi_{1, 3222} & + 4.65\phi_{1, 3212} & + 5.65\phi_{1, 2262} & + 5.45\phi_{1, 2252} & + 5.25\phi_{1, 2242} & + 5.05\phi_{1, 2232} & + 4.85\phi_{1, 2222} & + 4.65\phi_{1, 2212} & + 5.65\phi_{1, 1262} & + 5.45\phi_{1, 1252} & + 5.25\phi_{1, 1242} & + 5.05\phi_{1, 1232} & + 4.85\phi_{1, 1222} & + 4.65\phi_{1, 1212} & - QT_1_{21} & \leq 0 
\end{align*}
5.0501phi_9242+4.8501phi_9232+4.6501phi_9222+2.45phi_9212+5.4501phi_8262+5.25
0phi_8252+5.0501phi_8242+4.8501phi_8232+4.6501phi_8222+2.45phi_8212+5.4501phi_7262+5.25
0phi_7252+5.0501phi_7242+4.8501phi_7232+4.6501phi_7222+2.45phi_7212+5.4501phi_6262+5.25
0phi_6252+5.0501phi_6242+4.8501phi_6232+4.6501phi_6222+2.45phi_6212+5.4501phi_5262+5.25
0phi_5252+5.0501phi_5242+4.8501phi_5232+4.6501phi_5222+2.45phi_5212+5.4501phi_4262+5.25
0phi_4252+5.0501phi_4242+4.8501phi_4232+4.6501phi_4222+2.45phi_4212+5.4501phi_3262+5.25
0phi_3252+5.0501phi_3242+4.8501phi_3232+4.6501phi_3222+2.45phi_3212+5.4501phi_2262+5.25
0phi_2252+5.0501phi_2242+4.8501phi_2232+4.6501phi_2222+2.45phi_2212+5.4501phi_1262+5.25
0phi_1252+5.0501phi_1242+4.8501phi_1232+4.6501phi_1222+2.45phi_1212-QT1_22<=0

5.65phi_10262+5.45phi_10252+5.25phi_10242+5.05phi_10232+4.85phi_10222+4.65phi
_10212+5.65phi_9262+5.45phi_9252+5.25phi_9242+5.05phi_9232+4.85phi_9222+4.65phi_9212
+5.05phi_8262+5.45phi_8252+5.25phi_8242+5.05phi_8232+4.85phi_8222+4.65phi_8212
+5.05phi_7262+5.45phi_7252+5.25phi_7242+5.05phi_7232+4.85phi_7222+4.65phi_7212
+5.05phi_6262+5.45phi_6252+5.25phi_6242+5.05phi_6232+4.85phi_6222+4.65phi_6212
+5.05phi_5262+5.45phi_5252+5.25phi_5242+5.05phi_5232+4.85phi_5222+4.65phi_5212
+5.05phi_4262+5.45phi_4252+5.25phi_4242+5.05phi_4232+4.85phi_4222+4.65phi_4212
+5.05phi_3262+5.45phi_3252+5.25phi_3242+5.05phi_3232+4.85phi_3222+4.65phi_3212
+5.05phi_2262+5.45phi_2252+5.25phi_2242+5.05phi_2232+4.85phi_2222+4.65phi_2212
+5.05phi_1262+5.45phi_1252+5.25phi_1242+5.05phi_1232+4.85phi_1222+4.65phi_1212

5.4501phi_10263+5.2501phi_10253+5.0501phi_10243+4.8501phi_10233+4.6501phi_10223+5.25
0phi_10213+5.4501phi_9263+5.2501phi_9253+5.0501phi_9243+4.8501phi_9233+4.6501phi_9223
+2.45phi_9213+5.4501phi_8263+5.2501phi_8253+5.0501phi_8243+4.8501phi_8233+4.6501phi_8223

5.65phi_10263+5.45phi_10253+5.25phi_10243+5.05phi_10233+4.85phi_10223+4.65phi
_10213+5.65phi_9263+5.45phi_9253+5.25phi_9243+5.05phi_9233+4.85phi_9223+4.65phi_9213
+5.05phi_8263+5.45phi_8253+5.25phi_8243+5.05phi_8233+4.85phi_8223+4.65phi_8213
+5.05phi_8233+4.85phi_8223+4.65phi_8213

5.65phi_10263+5.45phi_10253+5.25phi_10243+5.05phi_10233+4.85phi_10223+4.65phi
_10213+5.65phi_9263+5.45phi_9253+5.25phi_9243+5.05phi_9233+4.85phi_9223+4.65phi_9213
+5.05phi_8263+5.45phi_8253+5.25phi_8243+5.05phi_8233+4.85phi_8223+4.65phi_8213
-5.05phi_8233+4.85phi_8223+4.65phi_8213
\[ +5.65\phi_1_7263 + 5.45\phi_1_7253 + 5.25\phi_1_7243 + 5.05\phi_1_7233 + 4.85\phi_1_7223 + 4.65\phi_1_7213 + 5.65\phi_1_6263 + 5.45\phi_1_6253 + 5.25\phi_1_6243 + 5.05\phi_1_6233 + 4.85\phi_1_6223 + 4.65\phi_1_6213 + 5.65\phi_1_5263 + 5.45\phi_1_5253 + 5.25\phi_1_5243 + 5.05\phi_1_5233 + 4.85\phi_1_5223 + 4.65\phi_1_5213 + 5.65\phi_1_4263 + 5.45\phi_1_4253 + 5.25\phi_1_4243 + 5.05\phi_1_4233 + 4.85\phi_1_4223 + 4.65\phi_1_4213 + 5.65\phi_1_3263 + 5.45\phi_1_3253 + 5.25\phi_1_3243 + 5.05\phi_1_3233 + 4.85\phi_1_3223 + 4.65\phi_1_3213 + 5.65\phi_1_2263 + 5.45\phi_1_2253 + 5.25\phi_1_2243 + 5.05\phi_1_2233 + 4.85\phi_1_2223 + 4.65\phi_1_2213 + 5.65\phi_1_1263 + 5.45\phi_1_1253 + 5.25\phi_1_1243 + 5.05\phi_1_1233 + 4.85\phi_1_1223 + 4.65\phi_1_1213 - QT_1_{23} = 0 \]

\textit{Equation 8.12}

\begin{align*}
QT_1_{21} + QT_1_{11} - QT_1_{1} &= 0 \\
QT_1_{22} + QT_1_{12} - QT_1_{2} &= 0 \\
QT_1_{23} + QT_1_{13} - QT_1_{3} &= 0
\end{align*}

\textit{Equation 8.14}

\begin{align*}
942.211\nu_{1011} + 945.699\nu_{911} + 946.447\nu_{811} + 947.145\nu_{711} + 947.793\nu_{611} + 948.391\nu_{511} + 948.939\nu_{411} + 949.436\nu_{311} + 949.883\nu_{211} + 951.427\nu_{111} - PP_{11} &= 0 \\
942.211\nu_{1012} + 945.699\nu_{912} + 946.447\nu_{812} + 947.145\nu_{712} + 947.793\nu_{612} + 948.391\nu_{512} + 948.939\nu_{412} + 949.436\nu_{312} + 949.883\nu_{212} + 951.427\nu_{112} - PP_{12} &= 0 \\
942.211\nu_{1013} + 945.699\nu_{913} + 946.447\nu_{813} + 947.145\nu_{713} + 947.793\nu_{613} + 948.391\nu_{513} + 948.939\nu_{413} + 949.436\nu_{313} + 949.883\nu_{213} + 951.427\nu_{113} - PP_{13} &= 0 \\
942.211\nu_{1021} + 945.699\nu_{921} + 946.447\nu_{821} + 947.145\nu_{721} + 947.793\nu_{621} + 948.391\nu_{521} + 948.939\nu_{421} + 949.436\nu_{321} + 949.883\nu_{221} + 951.427\nu_{121} - PP_{21} &= 0 \\
942.211\nu_{1022} + 945.699\nu_{922} + 946.447\nu_{822} + 947.145\nu_{722} + 947.793\nu_{622} + 948.391\nu_{522} + 948.939\nu_{422} + 949.436\nu_{322} + 949.883\nu_{222} + 951.427\nu_{122} - PP_{22} &= 0 \\
942.211\nu_{1023} + 945.699\nu_{923} + 946.447\nu_{823} + 947.145\nu_{723} + 947.793\nu_{623} + 948.391\nu_{523} + 948.939\nu_{423} + 949.436\nu_{323} + 949.883\nu_{223} + 951.427\nu_{123} - PP_{23} &= 0
\end{align*}

\textit{Equation 8.15}

\begin{align*}
PP_{21} + PP_{11} - PP_{1} &= 0 \\
PP_{22} + PP_{12} - PP_{2} &= 0 \\
PP_{23} + PP_{13} - PP_{3} &= 0
\end{align*}
\ Equation 8.16

\[\begin{align*}
\text{nu}_{111}-\text{delta}_{11} & \leq 0 \\
\text{nu}_{121}-\text{delta}_{11} & \leq 0 \\
\text{nu}_{211}-\text{delta}_{21} & \leq 0 \\
\text{nu}_{221}-\text{delta}_{21} & \leq 0 \\
\text{nu}_{311}-\text{delta}_{31} & \leq 0 \\
\text{nu}_{321}-\text{delta}_{31} & \leq 0 \\
\text{nu}_{411}-\text{delta}_{41} & \leq 0 \\
\text{nu}_{421}-\text{delta}_{41} & \leq 0 \\
\text{nu}_{511}-\text{delta}_{51} & \leq 0 \\
\text{nu}_{521}-\text{delta}_{51} & \leq 0 \\
\text{nu}_{611}-\text{delta}_{61} & \leq 0 \\
\text{nu}_{621}-\text{delta}_{61} & \leq 0 \\
\text{nu}_{711}-\text{delta}_{71} & \leq 0 \\
\text{nu}_{721}-\text{delta}_{71} & \leq 0 \\
\text{nu}_{811}-\text{delta}_{81} & \leq 0 \\
\text{nu}_{821}-\text{delta}_{81} & \leq 0 \\
\text{nu}_{911}-\text{delta}_{91} & \leq 0 \\
\text{nu}_{921}-\text{delta}_{91} & \leq 0 \\
\text{nu}_{1011}-\text{delta}_{101} & \leq 0 \\
\text{nu}_{1021}-\text{delta}_{101} & \leq 0 \\
\text{nu}_{112}-\text{delta}_{12} & \leq 0 \\
\text{nu}_{122}-\text{delta}_{12} & \leq 0 \\
\text{nu}_{212}-\text{delta}_{22} & \leq 0 \\
\text{nu}_{222}-\text{delta}_{22} & \leq 0 \\
\text{nu}_{312}-\text{delta}_{32} & \leq 0 \\
\text{nu}_{322}-\text{delta}_{32} & \leq 0 \\
\text{nu}_{412}-\text{delta}_{42} & \leq 0 \\
\text{nu}_{422}-\text{delta}_{42} & \leq 0 \\
\text{nu}_{512}-\text{delta}_{52} & \leq 0 \\
\text{nu}_{522}-\text{delta}_{52} & \leq 0 \\
\text{nu}_{612}-\text{delta}_{62} & \leq 0 \\
\text{nu}_{622}-\text{delta}_{62} & \leq 0 \\
\text{nu}_{712}-\text{delta}_{72} & \leq 0 \\
\text{nu}_{722}-\text{delta}_{72} & \leq 0 \\
\text{nu}_{812}-\text{delta}_{82} & \leq 0 \\
\text{nu}_{822}-\text{delta}_{82} & \leq 0 \\
\text{nu}_{912}-\text{delta}_{92} & \leq 0 \\
\text{nu}_{922}-\text{delta}_{92} & \leq 0 \\
\text{nu}_{1012}-\text{delta}_{102} & \leq 0 \\
\text{nu}_{1022}-\text{delta}_{102} & \leq 0 \\
\text{nu}_{113}-\text{delta}_{13} & \leq 0 \\
\text{nu}_{123}-\text{delta}_{13} & \leq 0 \\
\text{nu}_{213}-\text{delta}_{23} & \leq 0 \\
\text{nu}_{223}-\text{delta}_{23} & \leq 0 \\
\text{nu}_{313}-\text{delta}_{33} & \leq 0 \\
\text{nu}_{323}-\text{delta}_{33} & \leq 0 \\
\text{nu}_{413}-\text{delta}_{43} & \leq 0 \\
\text{nu}_{423}-\text{delta}_{43} & \leq 0 
\end{align*}\]
\text{EQUATION 8.17}

\begin{align*}
u_{513} - \delta_{153} &\leq 0 \\
u_{523} - \delta_{153} &\leq 0 \\
u_{613} - \delta_{163} &\leq 0 \\
u_{623} - \delta_{163} &\leq 0 \\
u_{713} - \delta_{173} &\leq 0 \\
u_{723} - \delta_{173} &\leq 0 \\
u_{813} - \delta_{183} &\leq 0 \\
u_{823} - \delta_{183} &\leq 0 \\
u_{913} - \delta_{193} &\leq 0 \\
u_{923} - \delta_{193} &\leq 0 \\
u_{1013} - \delta_{1103} &\leq 0 \\
u_{1023} - \delta_{1103} &\leq 0 \\

\begin{align*}
u_{111} - \theta_{NO1} &\leq 0 \\
u_{121} - \theta_{NO1} &\leq 0 \\
u_{211} - \theta_{NO1} &\leq 0 \\
u_{221} - \theta_{NO1} &\leq 0 \\
u_{311} - \theta_{NO1} &\leq 0 \\
u_{321} - \theta_{NO1} &\leq 0 \\
u_{411} - \theta_{NO1} &\leq 0 \\
u_{421} - \theta_{NO1} &\leq 0 \\
u_{511} - \theta_{NO1} &\leq 0 \\
u_{521} - \theta_{NO1} &\leq 0 \\
u_{611} - \theta_{NO1} &\leq 0 \\
u_{621} - \theta_{NO1} &\leq 0 \\
u_{711} - \theta_{NO1} &\leq 0 \\
u_{721} - \theta_{NO1} &\leq 0 \\
u_{811} - \theta_{NO1} &\leq 0 \\
u_{821} - \theta_{NO1} &\leq 0 \\
u_{911} - \theta_{NO1} &\leq 0 \\
u_{921} - \theta_{NO1} &\leq 0 \\
u_{1011} - \theta_{NO1} &\leq 0 \\
u_{1021} - \theta_{NO1} &\leq 0 \\
u_{112} - \theta_{NO2} &\leq 0 \\
u_{122} - \theta_{NO2} &\leq 0 \\
u_{212} - \theta_{NO2} &\leq 0 \\
u_{222} - \theta_{NO2} &\leq 0 \\
u_{312} - \theta_{NO2} &\leq 0 \\
u_{322} - \theta_{NO2} &\leq 0 \\
u_{412} - \theta_{NO2} &\leq 0 \\
u_{422} - \theta_{NO2} &\leq 0 \\
u_{512} - \theta_{NO2} &\leq 0 \\
u_{522} - \theta_{NO2} &\leq 0 \\
u_{612} - \theta_{NO2} &\leq 0 \\
u_{622} - \theta_{NO2} &\leq 0
\end{align*}
\textbf{EQUATION 8.18} \\
\begin{align*}
\nu_{712}-\theta_{NO_2} & \leq 0 \\
\nu_{722}-\theta_{NO_2} & \leq 0 \\
\nu_{812}-\theta_{NO_2} & \leq 0 \\
\nu_{822}-\theta_{NO_2} & \leq 0 \\
\nu_{912}-\theta_{NO_2} & \leq 0 \\
\nu_{922}-\theta_{NO_2} & \leq 0 \\
\nu_{1012}-\theta_{NO_2} & \leq 0 \\
\nu_{1022}-\theta_{NO_2} & \leq 0 \\
\nu_{113}-\theta_{NO_3} & \leq 0 \\
\nu_{123}-\theta_{NO_3} & \leq 0 \\
\nu_{213}-\theta_{NO_3} & \leq 0 \\
\nu_{223}-\theta_{NO_3} & \leq 0 \\
\nu_{313}-\theta_{NO_3} & \leq 0 \\
\nu_{323}-\theta_{NO_3} & \leq 0 \\
\nu_{413}-\theta_{NO_3} & \leq 0 \\
\nu_{423}-\theta_{NO_3} & \leq 0 \\
\nu_{513}-\theta_{NO_3} & \leq 0 \\
\nu_{523}-\theta_{NO_3} & \leq 0 \\
\nu_{613}-\theta_{NO_3} & \leq 0 \\
\nu_{623}-\theta_{NO_3} & \leq 0 \\
\nu_{713}-\theta_{NO_3} & \leq 0 \\
\nu_{723}-\theta_{NO_3} & \leq 0 \\
\nu_{813}-\theta_{NO_3} & \leq 0 \\
\nu_{823}-\theta_{NO_3} & \leq 0 \\
\nu_{913}-\theta_{NO_3} & \leq 0 \\
\nu_{923}-\theta_{NO_3} & \leq 0 \\
\nu_{1013}-\theta_{NO_3} & \leq 0 \\
\nu_{1023}-\theta_{NO_3} & \leq 0 \\
4.5189\nu_{1011} + 4.542\nu_{911} + 4.565\nu_{811} + 4.5881\nu_{711} + 4.6111\nu_{611} + 4.6342\nu_{511} + 4.6572\nu_{411} + 4.6803\nu_{311} + 4.7033\nu_{211} + 4.9338\nu_{111} & \geq 0 \\
4.3576\nu_{1011} + 4.519\nu_{911} + 4.542\nu_{811} + 4.5651\nu_{711} + 4.5881\nu_{611} + 4.6112\nu_{511} + 4.6342\nu_{411} + 4.6573\nu_{311} + 4.6803\nu_{211} + 4.7034\nu_{111} & \leq 0 \\
4.5189\nu_{1012} + 4.542\nu_{912} + 4.565\nu_{812} + 4.5881\nu_{712} + 4.6111\nu_{612} + 4.6342\nu_{512} + 4.6572\nu_{412} + 4.6803\nu_{312} + 4.7033\nu_{212} + 4.9338\nu_{112} & \geq 0 \\
4.3576\nu_{1012} + 4.519\nu_{912} + 4.542\nu_{812} + 4.5651\nu_{712} + 4.5881\nu_{612} + 4.6112\nu_{512} + 4.6342\nu_{412} + 4.6573\nu_{312} + 4.6803\nu_{212} + 4.7034\nu_{112} & \leq 0 \\
4.5189\nu_{1013} + 4.542\nu_{913} + 4.565\nu_{813} + 4.5881\nu_{713} + 4.6111\nu_{613} + 4.6342\nu_{513} + 4.6572\nu_{413} + 4.6803\nu_{313} + 4.7033\nu_{213} + 4.9338\nu_{113} & \geq 0 \\
4.3576\nu_{1013} + 4.519\nu_{913} + 4.542\nu_{813} + 4.5651\nu_{713} + 4.5881\nu_{613} + 4.6112\nu_{513} + 4.6342\nu_{413} + 4.6573\nu_{313} + 4.6803\nu_{213} + 4.7034\nu_{113} & \leq 0
\end{align*}
\textbf{Equation 8.19}

\begin{align*}
\text{QP}_{21} + \text{QP}_{11} - \text{QP}_1 &= 0 \\
\text{QP}_{22} + \text{QP}_{12} - \text{QP}_2 &= 0 \\
\text{QP}_{23} + \text{QP}_{13} - \text{QP}_3 &= 0
\end{align*}

\textbf{Equation 8.20}

\begin{align*}
\phi_{110161} + \phi_{110151} + \phi_{110141} + \phi_{110131} + \phi_{110121} + \phi_{110111} + \phi_{11011} + \phi_{11011} + \\
\phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \\
\phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \phi_{1111} + \\
\phi_{1111} + \phi_{1111} - \text{Beta}_{11} &= 0
\end{align*}
\( \phi_1_{12} + \phi_1_{21} - \beta_{12} = 0 \)
\( \phi_1_{13} + \phi_1_{23} - \beta_{13} = 0 \)
\( \phi_1_{21} + \phi_1_{22} - \beta_{21} = 0 \)
\( \phi_1_{23} + \phi_1_{24} - \beta_{23} = 0 \)

Equation 8.21
\nu_{1011} + \nu_{911} + \nu_{811} + \nu_{711} + \nu_{611} + \nu_{511} + \nu_{411} + \nu_{311} + \nu_{211} + \nu_{111} - \Alpha_{11} = 0
\nu_{1012} + \nu_{912} + \nu_{812} + \nu_{712} + \nu_{612} + \nu_{512} + \nu_{412} + \nu_{312} + \nu_{212} + \nu_{112} - \Alpha_{12} = 0
\nu_{1013} + \nu_{913} + \nu_{813} + \nu_{713} + \nu_{613} + \nu_{513} + \nu_{413} + \nu_{313} + \nu_{213} + \nu_{113} - \Alpha_{13} = 0
\nu_{1021} + \nu_{921} + \nu_{821} + \nu_{721} + \nu_{621} + \nu_{521} + \nu_{421} + \nu_{321} + \nu_{221} + \nu_{121} - \Alpha_{21} = 0
\nu_{1022} + \nu_{922} + \nu_{822} + \nu_{722} + \nu_{622} + \nu_{522} + \nu_{422} + \nu_{322} + \nu_{222} + \nu_{122} - \Alpha_{22} = 0
\nu_{1023} + \nu_{923} + \nu_{823} + \nu_{723} + \nu_{623} + \nu_{523} + \nu_{423} + \nu_{323} + \nu_{223} + \nu_{123} - \Alpha_{23} = 0

\text{Equation 8.22}
\Alpha_{11} + \Beta_{11} \leq 1
\Alpha_{12} + \Beta_{12} \leq 1
\Alpha_{13} + \Beta_{13} \leq 1
\Alpha_{21} + \Beta_{21} \leq 1
\Alpha_{22} + \Beta_{22} \leq 1
\Alpha_{23} + \Beta_{23} \leq 1

\text{Equation 8.23}
\Beta_{21} + \Beta_{11} - \text{Turbine}_1 = 0
\Beta_{22} + \Beta_{12} - \text{Turbine}_2 = 0
\Beta_{23} + \Beta_{13} - \text{Turbine}_3 = 0

\text{Equation 8.24}
\Alpha_{21} + \Alpha_{11} - \text{Pump}_1 = 0
\Alpha_{22} + \Alpha_{12} - \text{Pump}_2 = 0
\Alpha_{23} + \Alpha_{13} - \text{Pump}_3 = 0

\text{Equation 8.25}
\text{Turbine}_1 - 2\text{Produce}_1 \leq 0
\text{Turbine}_2 - 2\text{Produce}_2 \leq 0
\text{Turbine}_3 - 2\text{Produce}_3 \leq 0

\text{Equation 8.26}
\text{Pump}_1 + 2\text{Produce}_1 \leq 2
\text{Pump}_2 + 2\text{Produce}_2 \leq 2
\text{Pump}_3 + 2\text{Produce}_3 \leq 2
\textbf{\textit{Equation 8.27}}

\begin{align*}
\text{FB1}_1\text{-Spill1}_\text{NO}_1\text{-Spill1}_\text{YES}_1 &= 0 \\
\text{FB1}_2\text{-Spill1}_\text{NO}_2\text{-Spill1}_\text{YES}_2 &= 0 \\
\text{FB1}_3\text{-Spill1}_\text{NO}_3\text{-Spill1}_\text{YES}_3 &= 0
\end{align*}

\textbf{\textit{Equation 8.28}}

\begin{align*}
787\theta_{\text{NO}_1}\text{-Spill1}_\text{NO}_1 &\leq 0 \\
787\theta_{\text{NO}_2}\text{-Spill1}_\text{NO}_2 &\leq 0 \\
787\theta_{\text{NO}_3}\text{-Spill1}_\text{NO}_3 &\leq 0 \\
\text{Spill1}_\text{NO}_1\text{-}795\theta_{\text{NO}_1} &\leq 0 \\
\text{Spill1}_\text{NO}_2\text{-}795\theta_{\text{NO}_2} &\leq 0 \\
\text{Spill1}_\text{NO}_3\text{-}795\theta_{\text{NO}_3} &\leq 0
\end{align*}

\textbf{\textit{Equation 8.29}}

\begin{align*}
795.0001\theta_{\text{YES}_1}\text{-Spill1}_\text{YES}_1 &\leq 0 \\
795.0001\theta_{\text{YES}_2}\text{-Spill1}_\text{YES}_2 &\leq 0 \\
795.0001\theta_{\text{YES}_3}\text{-Spill1}_\text{YES}_3 &\leq 0 \\
\text{Spill1}_\text{YES}_1\text{-}811\theta_{\text{YES}_1} &\leq 0 \\
\text{Spill1}_\text{YES}_2\text{-}811\theta_{\text{YES}_2} &\leq 0 \\
\text{Spill1}_\text{YES}_3\text{-}811\theta_{\text{YES}_3} &\leq 0
\end{align*}

\textbf{\textit{Equation 8.31}}

\begin{align*}
811\theta_{31}\text{}+805\theta_{21}\text{}+798\theta_{11}\text{}-\text{SPILL1}_\text{YES}_1 &\leq 0 \\
811\theta_{32}\text{}+805\theta_{22}\text{}+798\theta_{12}\text{}-\text{SPILL1}_\text{YES}_2 &\leq 0 \\
811\theta_{33}\text{}+805\theta_{23}\text{}+798\theta_{13}\text{}-\text{SPILL1}_\text{YES}_3 &\leq 0
\end{align*}

\begin{align*}
808\theta_{31}\text{}+801.5\theta_{21}\text{}+796.5\theta_{11}\text{}-\text{SPILL1}_\text{YES}_1 &\geq 0 \\
808\theta_{32}\text{}+801.5\theta_{22}\text{}+796.5\theta_{12}\text{}-\text{SPILL1}_\text{YES}_2 &\geq 0 \\
808\theta_{33}\text{}+801.5\theta_{23}\text{}+796.5\theta_{13}\text{}-\text{SPILL1}_\text{YES}_3 &\geq 0
\end{align*}

\textbf{\textit{Equation 8.32}}

\begin{align*}
33.059\theta_{31}\text{}+11.073\theta_{21}\text{}+1.474\theta_{11}\text{}-\text{UnContRel}_1 &= 0 \\
33.059\theta_{32}\text{}+11.073\theta_{22}\text{}+1.474\theta_{12}\text{}-\text{UnContRel}_2 &= 0 \\
33.059\theta_{33}\text{}+11.073\theta_{23}\text{}+1.474\theta_{13}\text{}-\text{UnContRel}_3 &= 0
\end{align*}

\textbf{\textit{Equation 8.33}}

\begin{align*}
\theta_{\text{NO}_1}\text{}+\theta_{\text{YES}_1} &= 1
\end{align*}
theta_NO_2+theta_YES_2=1
theta_NO_3+theta_YES_3=1

\ Equation 8.34

theta_N1+theta_21+theta_11-theta_YES_1=0
theta_N2+theta_22+theta_12-theta_YES_2=0
theta_N3+theta_23+theta_13-theta_YES_3=0

\ Equation 8.36

74.75\delta^2_{101}+73\delta^2_{91}+71.25\delta^2_{81}+69.5\delta^2_{71}+67.75\delta^2_{61}+66\delta^2_{51}+64.25\delta^2_{41}+62.5\delta^2_{31}+60.75\delta^2_{21}+59\delta^2_{11} - H_2_1 <= 0
74.75\delta^2_{102}+73\delta^2_{92}+71.25\delta^2_{82}+69.5\delta^2_{72}+67.75\delta^2_{62}+66\delta^2_{52}+64.25\delta^2_{42}+62.5\delta^2_{32}+60.75\delta^2_{22}+59\delta^2_{12} - H_2_2 <= 0
74.75\delta^2_{103}+73\delta^2_{93}+71.25\delta^2_{83}+69.5\delta^2_{73}+67.75\delta^2_{63}+66\delta^2_{53}+64.25\delta^2_{43}+62.5\delta^2_{33}+60.75\delta^2_{23}+59\delta^2_{13} - H_2_3 <= 0

\ Equation 8.37

\delta^2_{101}+\delta^2_{91}+\delta^2_{81}+\delta^2_{71}+\delta^2_{61}+\delta^2_{51}+\delta^2_{41}+\delta^2_{31}+\delta^2_{21}+\delta^2_{11}=1
\delta^2_{102}+\delta^2_{92}+\delta^2_{82}+\delta^2_{72}+\delta^2_{62}+\delta^2_{52}+\delta^2_{42}+\delta^2_{32}+\delta^2_{22}+\delta^2_{12}=1
\delta^2_{103}+\delta^2_{93}+\delta^2_{83}+\delta^2_{73}+\delta^2_{63}+\delta^2_{53}+\delta^2_{43}+\delta^2_{33}+\delta^2_{23}+\delta^2_{13}=1

\ Equation 8.38

FB_1-TR_1-H_1=0
FB_2-TR_2-H_2=0
FB_3-TR_3-H_3=0

\ Equation 8.40

\phi_{1161}+\phi_{1151}+\phi_{1141}+\phi_{1131}+\phi_{1121}+\phi_{1111}-\delta^2_{11} <= 0
\[\begin{align*}
\phi_{2,161} + \phi_{2,151} + \phi_{2,141} + \phi_{2,131} + \phi_{2,121} + \phi_{2,111} - \delta_{2,21} & \leq 0 \\
\phi_{2,316} + \phi_{2,311} + \phi_{2,312} + \phi_{2,313} + \phi_{2,314} + \phi_{2,315} - \delta_{2,31} & \leq 0 \\
\phi_{2,416} + \phi_{2,411} + \phi_{2,412} + \phi_{2,413} + \phi_{2,414} + \phi_{2,415} - \delta_{2,41} & \leq 0 \\
\phi_{2,516} + \phi_{2,511} + \phi_{2,512} + \phi_{2,513} + \phi_{2,514} + \phi_{2,515} - \delta_{2,51} & \leq 0 \\
\phi_{2,616} + \phi_{2,611} + \phi_{2,612} + \phi_{2,613} + \phi_{2,614} + \phi_{2,615} - \delta_{2,61} & \leq 0 \\
\phi_{2,716} + \phi_{2,711} + \phi_{2,712} + \phi_{2,713} + \phi_{2,714} + \phi_{2,715} - \delta_{2,71} & \leq 0 \\
\phi_{2,816} + \phi_{2,811} + \phi_{2,812} + \phi_{2,813} + \phi_{2,814} + \phi_{2,815} - \delta_{2,81} & \leq 0 \\
\phi_{2,916} + \phi_{2,911} + \phi_{2,912} + \phi_{2,913} + \phi_{2,914} + \phi_{2,915} - \delta_{2,91} & \leq 0 \\
\phi_{2,1016} + \phi_{2,1011} + \phi_{2,1012} + \phi_{2,1013} + \phi_{2,1014} + \phi_{2,1015} - \delta_{2,101} & \leq 0 \\
\phi_{2,126} + \phi_{2,121} + \phi_{2,122} + \phi_{2,123} + \phi_{2,124} + \phi_{2,125} - \delta_{2,12} & \leq 0 \\
\phi_{2,226} + \phi_{2,221} + \phi_{2,222} + \phi_{2,223} + \phi_{2,224} + \phi_{2,225} - \delta_{2,22} & \leq 0 \\
\phi_{2,326} + \phi_{2,321} + \phi_{2,322} + \phi_{2,323} + \phi_{2,324} + \phi_{2,325} - \delta_{2,32} & \leq 0 \\
\phi_{2,426} + \phi_{2,421} + \phi_{2,422} + \phi_{2,423} + \phi_{2,424} + \phi_{2,425} - \delta_{2,42} & \leq 0 \\
\phi_{2,526} + \phi_{2,521} + \phi_{2,522} + \phi_{2,523} + \phi_{2,524} + \phi_{2,525} - \delta_{2,52} & \leq 0 \\
\phi_{2,626} + \phi_{2,621} + \phi_{2,622} + \phi_{2,623} + \phi_{2,624} + \phi_{2,625} - \delta_{2,62} & \leq 0 \\
\phi_{2,726} + \phi_{2,721} + \phi_{2,722} + \phi_{2,723} + \phi_{2,724} + \phi_{2,725} - \delta_{2,72} & \leq 0 \\
\phi_{2,826} + \phi_{2,821} + \phi_{2,822} + \phi_{2,823} + \phi_{2,824} + \phi_{2,825} - \delta_{2,82} & \leq 0 \\
\phi_{2,926} + \phi_{2,921} + \phi_{2,922} + \phi_{2,923} + \phi_{2,924} + \phi_{2,925} - \delta_{2,92} & \leq 0 \\
\phi_{2,1026} + \phi_{2,1021} + \phi_{2,1022} + \phi_{2,1023} + \phi_{2,1024} + \phi_{2,1025} - \delta_{2,102} & \leq 0 \\
\phi_{2,116} + \phi_{2,111} + \phi_{2,112} + \phi_{2,113} + \phi_{2,114} + \phi_{2,115} - \delta_{2,11} & \leq 0 \\
\phi_{2,216} + \phi_{2,211} + \phi_{2,212} + \phi_{2,213} + \phi_{2,214} + \phi_{2,215} - \delta_{2,21} & \leq 0 \\
\phi_{2,316} + \phi_{2,311} + \phi_{2,312} + \phi_{2,313} + \phi_{2,314} + \phi_{2,315} - \delta_{2,31} & \leq 0 \\
\phi_{2,416} + \phi_{2,411} + \phi_{2,412} + \phi_{2,413} + \phi_{2,414} + \phi_{2,415} - \delta_{2,41} & \leq 0 \\
\phi_{2,516} + \phi_{2,511} + \phi_{2,512} + \phi_{2,513} + \phi_{2,514} + \phi_{2,515} - \delta_{2,51} & \leq 0 \\
\phi_{2,616} + \phi_{2,611} + \phi_{2,612} + \phi_{2,613} + \phi_{2,614} + \phi_{2,615} - \delta_{2,61} & \leq 0 \\
\phi_{2,716} + \phi_{2,711} + \phi_{2,712} + \phi_{2,713} + \phi_{2,714} + \phi_{2,715} - \delta_{2,71} & \leq 0 \\
\phi_{2,816} + \phi_{2,811} + \phi_{2,812} + \phi_{2,813} + \phi_{2,814} + \phi_{2,815} - \delta_{2,81} & \leq 0 \\
\phi_{2,916} + \phi_{2,911} + \phi_{2,912} + \phi_{2,913} + \phi_{2,914} + \phi_{2,915} - \delta_{2,91} & \leq 0 \\
\phi_{2,1016} + \phi_{2,1011} + \phi_{2,1012} + \phi_{2,1013} + \phi_{2,1014} + \phi_{2,1015} - \delta_{2,101} & \leq 0
\end{align*}\]
\phi_2_{2263} + \phi_2_{2253} + \phi_2_{2243} + \phi_2_{2233} + \phi_2_{2223} + \phi_2_{2213} - \delta_2_{23} \leq 0 \\
\phi_2_{3263} + \phi_2_{3253} + \phi_2_{3243} + \phi_2_{3233} + \phi_2_{3223} + \phi_2_{3213} - \delta_2_{33} \leq 0 \\
\phi_2_{4263} + \phi_2_{4253} + \phi_2_{4243} + \phi_2_{4233} + \phi_2_{4223} + \phi_2_{4213} - \delta_2_{43} \leq 0 \\
\phi_2_{5263} + \phi_2_{5253} + \phi_2_{5243} + \phi_2_{5233} + \phi_2_{5223} + \phi_2_{5213} - \delta_2_{53} \leq 0 \\
\phi_2_{6263} + \phi_2_{6253} + \phi_2_{6243} + \phi_2_{6233} + \phi_2_{6223} + \phi_2_{6213} - \delta_2_{63} \leq 0 \\
\phi_2_{7263} + \phi_2_{7253} + \phi_2_{7243} + \phi_2_{7233} + \phi_2_{7223} + \phi_2_{7213} - \delta_2_{73} \leq 0 \\
\phi_2_{8263} + \phi_2_{8253} + \phi_2_{8243} + \phi_2_{8233} + \phi_2_{8223} + \phi_2_{8213} - \delta_2_{83} \leq 0 \\
\phi_2_{9263} + \phi_2_{9253} + \phi_2_{9243} + \phi_2_{9233} + \phi_2_{9223} + \phi_2_{9213} - \delta_2_{93} \leq 0 \\
\phi_2_{10263} + \phi_2_{10253} + \phi_2_{10243} + \phi_2_{10233} + \phi_2_{10223} + \phi_2_{10213} - \delta_2_{103} \leq 0 \\

\text{Equation 8.42}
\[\text{Equation 8.43}\]

\[\begin{align*}
\text{PT2}_{21} + & \text{PT2}_{11} - \text{PT2}_1 = 0 \\
\text{PT2}_{22} + & \text{PT2}_{12} - \text{PT2}_2 = 0 \\
\text{PT2}_{23} + & \text{PT2}_{13} - \text{PT2}_3 = 0
\end{align*}\]

\[\text{Equation 8.44}\]

\[\begin{align*}
4.2501\phi_{10161} + & 4.0501\phi_{10151} + 3.8501\phi_{10141} + 3.6501\phi_{10131} + 3.4501\phi_{10121} + 2.45\phi_{10111} + 4.2501\phi_{9161} + 4.0501\phi_{9151} + 3.8501\phi_{9141} + 3.6501\phi_{9131} + 3.4501\phi_{9121} + 2.45\phi_{9111} + 4.2501\phi_{8161} + 4.0501\phi_{8151} + 3.8501\phi_{8141} + 3.6501\phi_{8131} + 3.4501\phi_{8121} + 2.45\phi_{8111} + 4.2501\phi_{7161} + 4.0501\phi_{7151} + 3.8501\phi_{7141} + 3.6501\phi_{7131} + 3.4501\phi_{7121} + 2.45\phi_{7111} + 4.2501\phi_{6161} + 4.0501\phi_{6151} + 3.8501\phi_{6141} + 3.6501\phi_{6131} + 3.4501\phi_{6121} + 2.45\phi_{6111} + 4.2501\phi_{5161} + 4.0501\phi_{5151} + 3.8501\phi_{5141} + 3.6501\phi_{5131} + 3.4501\phi_{5121} + 2.45\phi_{5111} + 4.2501\phi_{4161} + 4.0501\phi_{4151} + 3.8501\phi_{4141} + 3.6501\phi_{4131} + 3.4501\phi_{4121} + 2.45\phi_{4111} + 4.2501\phi_{3161} + 4.0501\phi_{3151} + 3.8501\phi_{3141} + 3.6501\phi_{3131} + 3.4501\phi_{3121} + 2.45\phi_{3111} + 4.2501\phi_{2161} + 4.0501\phi_{2151} + 3.8501\phi_{2141} + 3.6501\phi_{2131} + 3.4501\phi_{2121} + 2.45\phi_{2111} + 4.2501\phi_{1161} + 4.0501\phi_{1151} + 3.8501\phi_{1141} + 3.6501\phi_{1131} + 3.4501\phi_{1121} + 2.45\phi_{1111} - & QT_{11} \leq 0
\end{align*}\]
\[ +5\phi_i^2_{2163} + 4.25\phi_i^2_{2153} + 4.05\phi_i^2_{2143} + 3.85\phi_i^2_{2133} + 3.65\phi_i^2_{2123} + 3.45\phi_i^2_{2113} + \\
5\phi_i^2_{1163} + 4.25\phi_i^2_{1153} + 4.05\phi_i^2_{1143} + 3.85\phi_i^2_{1133} + \\
3.65\phi_i^2_{1123} + 3.45\phi_i^2_{1113} - QT_2 \_13 = 0 \]

\[ 4.2501\phi_i^2_{10261} + 4.0501\phi_i^2_{10251} + 3.8501\phi_i^2_{10241} + 3.6501\phi_i^2_{10231} + 3.4501\phi_i^2_{10221} + 2.4501\phi_i^2_{10211} + \\
3.8501\phi_i^2_{9261} + 3.6501\phi_i^2_{9251} + 3.4501\phi_i^2_{9241} + 3.2501\phi_i^2_{9231} + 2.4501\phi_i^2_{9221} + \\
3.8501\phi_i^2_{8261} + 3.6501\phi_i^2_{8251} + 3.4501\phi_i^2_{8241} + 3.2501\phi_i^2_{8231} + 2.4501\phi_i^2_{8221} + \\
3.8501\phi_i^2_{7261} + 3.6501\phi_i^2_{7251} + 3.4501\phi_i^2_{7241} + 3.2501\phi_i^2_{7231} + 2.4501\phi_i^2_{7221} + \\
3.8501\phi_i^2_{6261} + 3.6501\phi_i^2_{6251} + 3.4501\phi_i^2_{6241} + 3.2501\phi_i^2_{6231} + 2.4501\phi_i^2_{6221} + \\
3.8501\phi_i^2_{5261} + 3.6501\phi_i^2_{5251} + 3.4501\phi_i^2_{5241} + 3.2501\phi_i^2_{5231} + 2.4501\phi_i^2_{5221} + \\
3.8501\phi_i^2_{4261} + 3.6501\phi_i^2_{4251} + 3.4501\phi_i^2_{4241} + 3.2501\phi_i^2_{4231} + 2.4501\phi_i^2_{4221} + \\
3.8501\phi_i^2_{3261} + 3.6501\phi_i^2_{3251} + 3.4501\phi_i^2_{3241} + 3.2501\phi_i^2_{3231} + 2.4501\phi_i^2_{3221} + \\
3.8501\phi_i^2_{2261} + 3.6501\phi_i^2_{2251} + 3.4501\phi_i^2_{2241} + 3.2501\phi_i^2_{2231} + 2.4501\phi_i^2_{2221} + \\
3.8501\phi_i^2_{1261} + 3.6501\phi_i^2_{1251} + 3.4501\phi_i^2_{1241} + 3.2501\phi_i^2_{1231} + 2.4501\phi_i^2_{1221} + \\
3.8501\phi_i^2_{1211} - QT_2 \_21 = 0 \]

\[ 4.2501\phi_i^2_{10262} + 4.0501\phi_i^2_{10252} + 3.8501\phi_i^2_{10242} + 3.6501\phi_i^2_{10232} + 3.4501\phi_i^2_{10222} + 2.4501\phi_i^2_{10212} + \\
3.8501\phi_i^2_{9262} + 3.6501\phi_i^2_{9252} + 3.4501\phi_i^2_{9242} + 3.2501\phi_i^2_{9232} + 2.4501\phi_i^2_{9222} + \\
3.8501\phi_i^2_{8262} + 3.6501\phi_i^2_{8252} + 3.4501\phi_i^2_{8242} + 3.2501\phi_i^2_{8232} + 2.4501\phi_i^2_{8222} + \\
3.8501\phi_i^2_{7262} + 3.6501\phi_i^2_{7252} + 3.4501\phi_i^2_{7242} + 3.2501\phi_i^2_{7232} + 2.4501\phi_i^2_{7222} + \\
3.8501\phi_i^2_{6262} + 3.6501\phi_i^2_{6252} + 3.4501\phi_i^2_{6242} + 3.2501\phi_i^2_{6232} + 2.4501\phi_i^2_{6222} + \\
3.8501\phi_i^2_{5262} + 3.6501\phi_i^2_{5252} + 3.4501\phi_i^2_{5242} + 3.2501\phi_i^2_{5232} + 2.4501\phi_i^2_{5222} + \\
3.8501\phi_i^2_{4262} + 3.6501\phi_i^2_{4252} + 3.4501\phi_i^2_{4242} + 3.2501\phi_i^2_{4232} + 2.4501\phi_i^2_{4222} + \\
3.8501\phi_i^2_{3262} + 3.6501\phi_i^2_{3252} + 3.4501\phi_i^2_{3242} + 3.2501\phi_i^2_{3232} + 2.4501\phi_i^2_{3222} + \\
3.8501\phi_i^2_{2262} + 3.6501\phi_i^2_{2252} + 3.4501\phi_i^2_{2242} + 3.2501\phi_i^2_{2232} + 2.4501\phi_i^2_{2222} + \\
3.8501\phi_i^2_{1262} + 3.6501\phi_i^2_{1252} + 3.4501\phi_i^2_{1242} + 3.2501\phi_i^2_{1232} + 2.4501\phi_i^2_{1222} + \\
3.8501\phi_i^2_{1212} - QT_2 \_22 = 0 \]
\[ 5 \phi_2_{10262} + 4.25 \phi_2_{10252} + 4.05 \phi_2_{10242} + 3.85 \phi_2_{10232} + 3.65 \phi_2_{10222} + 3.45 \phi_2_{10212} + 5 \phi_2_{9262} + 4.25 \phi_2_{9252} + 4.05 \phi_2_{9242} + 3.85 \phi_2_{9232} + 3.65 \phi_2_{9222} + 3.45 \phi_2_{9212} + 5 \phi_2_{8262} + 4.25 \phi_2_{8252} + 4.05 \phi_2_{8242} + 3.85 \phi_2_{8232} + 3.65 \phi_2_{8222} + 3.45 \phi_2_{8212} + 5 \phi_2_{7262} + 4.25 \phi_2_{7252} + 4.05 \phi_2_{7242} + 3.85 \phi_2_{7232} + 3.65 \phi_2_{7222} + 3.45 \phi_2_{7212} + 5 \phi_2_{6262} + 4.25 \phi_2_{6252} + 4.05 \phi_2_{6242} + 3.85 \phi_2_{6232} + 3.65 \phi_2_{6222} + 3.45 \phi_2_{6212} + 5 \phi_2_{5262} + 4.25 \phi_2_{5252} + 4.05 \phi_2_{5242} + 3.85 \phi_2_{5232} + 3.65 \phi_2_{5222} + 3.45 \phi_2_{5212} + 5 \phi_2_{4262} + 4.25 \phi_2_{4252} + 4.05 \phi_2_{4242} + 3.85 \phi_2_{4232} + 3.65 \phi_2_{4222} + 3.45 \phi_2_{4212} + 5 \phi_2_{3262} + 4.25 \phi_2_{3252} + 4.05 \phi_2_{3242} + 3.85 \phi_2_{3232} + 3.65 \phi_2_{3222} + 3.45 \phi_2_{3212} + 5 \phi_2_{2262} + 4.25 \phi_2_{2252} + 4.05 \phi_2_{2242} + 3.85 \phi_2_{2232} + 3.65 \phi_2_{2222} + 3.45 \phi_2_{2212} + 5 \phi_2_{1262} + 4.25 \phi_2_{1252} + 4.05 \phi_2_{1242} + 3.85 \phi_2_{1232} + 3.65 \phi_2_{1222} + 3.45 \phi_2_{1212} - QT_2_{22} = 0 \\
4.2501 \phi_2_{10263} + 4.0501 \phi_2_{10253} + 3.8501 \phi_2_{10243} + 3.6501 \phi_2_{10233} + 3.4501 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} + 2.45 \phi_2_{10223} + 2.45 \phi_2_{10213} - QT_2_{23} = 0 \\
5 \phi_2_{10263} + 4.25 \phi_2_{10253} + 4.05 \phi_2_{10243} + 3.85 \phi_2_{10233} + 3.65 \phi_2_{10223} + 3.45 \phi_2_{10213} + 5 \phi_2_{9263} + 4.25 \phi_2_{9253} + 4.05 \phi_2_{9243} + 3.85 \phi_2_{9233} + 3.65 \phi_2_{9223} + 3.45 \phi_2_{9213} + 5 \phi_2_{8263} + 4.25 \phi_2_{8253} + 4.05 \phi_2_{8243} + 3.85 \phi_2_{8233} + 3.65 \phi_2_{8223} + 3.45 \phi_2_{8213} + 5 \phi_2_{7263} + 4.25 \phi_2_{7253} + 4.05 \phi_2_{7243} + 3.85 \phi_2_{7233} + 3.65 \phi_2_{7223} + 3.45 \phi_2_{7213} + 5 \phi_2_{6263} + 4.25 \phi_2_{6253} + 4.05 \phi_2_{6243} + 3.85 \phi_2_{6233} + 3.65 \phi_2_{6223} + 3.45 \phi_2_{6213} + 5 \phi_2_{5263} + 4.25 \phi_2_{5253} + 4.05 \phi_2_{5243} + 3.85 \phi_2_{5233} + 3.65 \phi_2_{5223} + 3.45 \phi_2_{5213} + 5 \phi_2_{4263} + 4.25 \phi_2_{4253} + 4.05 \phi_2_{4243} + 3.85 \phi_2_{4233} + 3.65 \phi_2_{4223} + 3.45 \phi_2_{4213} + 5 \phi_2_{3263} + 4.25 \phi_2_{3253} + 4.05 \phi_2_{3243} + 3.85 \phi_2_{3233} + 3.65 \phi_2_{3223} + 3.45 \phi_2_{3213} + 5 \phi_2_{2263} + 4.25 \phi_2_{2253} + 4.05 \phi_2_{2243} + 3.85 \phi_2_{2233} + 3.65 \phi_2_{2223} + 3.45 \phi_2_{2213} + 5 \phi_2_{1263} + 4.25 \phi_2_{1253} + 4.05 \phi_2_{1243} + 3.85 \phi_2_{1233} + 3.65 \phi_2_{1223} + 3.45 \phi_2_{1213} - QT_2_{23} <= 0 \\
\text{\textbf{\textbackslash Equation 8.45}} \\
QT_2_{21} + QT_2_{11} - QT_2_{1} = 0 \\
QT_2_{22} + QT_2_{12} - QT_2_{2} = 0
\ Equation 8.46

FB2\_1-Spill2\_NO\_1-Spill2\_YES\_1=0
FB2\_2-Spill2\_NO\_2-Spill2\_YES\_2=0
FB2\_3-Spill2\_NO\_3-Spill2\_YES\_3=0

\ Equation 8.47

600\sigma\_NO\_1-Spill2\_NO\_1<=0
600\sigma\_NO\_2-Spill2\_NO\_2<=0
600\sigma\_NO\_3-Spill2\_NO\_3<=0
Spill2\_NO\_1-613\sigma\_NO\_1<=0
Spill2\_NO\_2-613\sigma\_NO\_2<=0
Spill2\_NO\_3-613\sigma\_NO\_3<=0

\ Equation 8.48

600.00001\sigma\_YES\_1-Spill2\_YES\_1<=0
600.00001\sigma\_YES\_2-Spill2\_YES\_2<=0
600.00001\sigma\_YES\_3-Spill2\_YES\_3<=0
Spill2\_YES\_1-615\sigma\_YES\_1<=0
Spill2\_YES\_2-615\sigma\_YES\_2<=0
Spill2\_YES\_3-615\sigma\_YES\_3<=0

\ Equation 8.49

\sigma\_NO\_1+\sigma\_YES\_1=1
\sigma\_NO\_2+\sigma\_YES\_2=1
\sigma\_NO\_3+\sigma\_YES\_3=1

\ Equation 8.50

Gated\_1>=0
Gated\_2>=0
Gated\_3>=0
Gated\_1-150\sigma\_YES\_1<=0
Gated\_2-150\sigma\_YES\_2<=0
Gated\_3-150\sigma\_YES\_3<=0

\ Equation 8.51

QT2\_21+QT2\_11+Gated\_1-Chan\_1=0
QT2\_22+QT2\_12+Gated\_2-Chan\_2=0
QT2\_23+QT2\_13+Gated\_3-Chan\_3=0

\ Equation 8.52
Equation 8.53

\[549.519\zeta_{91} + 548.014\zeta_{81} + 546.352\zeta_{71} + 544.524\zeta_{61} + 542.52\zeta_{51} + 540.332\zeta_{41} + 537.95\zeta_{31} + 535.367\zeta_{21} + 532.573\zeta_{11} - TR_2_1 \leq 0\]

\[549.519\zeta_{92} + 548.014\zeta_{82} + 546.352\zeta_{72} + 544.524\zeta_{62} + 542.52\zeta_{52} + 540.332\zeta_{42} + 537.95\zeta_{32} + 535.367\zeta_{22} + 532.573\zeta_{12} - TR_2_2 \leq 0\]

\[549.519\zeta_{93} + 548.014\zeta_{83} + 546.352\zeta_{73} + 544.524\zeta_{63} + 542.52\zeta_{53} + 540.332\zeta_{43} + 537.95\zeta_{33} + 535.367\zeta_{23} + 532.573\zeta_{13} - TR_2_3 \leq 0\]

Equation 8.54

\[550.215\zeta_{91} + 548.786\zeta_{81} + 547.204\zeta_{71} + 545.459\zeta_{61} + 543.544\zeta_{51} + 541.449\zeta_{41} + 539.166\zeta_{31} + 536.685\zeta_{21} + 533.997\zeta_{11} - TR_2_1 \geq 0\]

\[550.215\zeta_{92} + 548.786\zeta_{82} + 547.204\zeta_{72} + 545.459\zeta_{62} + 543.544\zeta_{52} + 541.449\zeta_{42} + 539.166\zeta_{32} + 536.685\zeta_{22} + 533.997\zeta_{12} - TR_2_2 \geq 0\]

\[550.215\zeta_{93} + 548.786\zeta_{83} + 547.204\zeta_{73} + 545.459\zeta_{63} + 543.544\zeta_{53} + 541.449\zeta_{43} + 539.166\zeta_{33} + 536.685\zeta_{23} + 533.997\zeta_{13} - TR_2_3 \geq 0\]

\[20\zeta_{91} + 17.5\zeta_{81} + 15\zeta_{71} + 12.5\zeta_{61} + 10\zeta_{51} + 7.5\zeta_{41} + 5\zeta_{31} + 2.5\zeta_{21} + 0\zeta_{11} - Chan_1 \leq 0\]

\[20\zeta_{92} + 17.5\zeta_{82} + 15\zeta_{72} + 12.5\zeta_{62} + 10\zeta_{52} + 7.5\zeta_{42} + 5\zeta_{32} + 2.5\zeta_{22} + 0\zeta_{12} - Chan_2 \leq 0\]

\[20\zeta_{93} + 17.5\zeta_{83} + 15\zeta_{73} + 12.5\zeta_{63} + 10\zeta_{53} + 7.5\zeta_{43} + 5\zeta_{33} + 2.5\zeta_{23} + 0\zeta_{13} - Chan_3 \leq 0\]

Equation 8.55

\[21.25\zeta_{91} + 18.75\zeta_{81} + 16.25\zeta_{71} + 13.75\zeta_{61} + 11.25\zeta_{51} + 8.75\zeta_{41} + 6.25\zeta_{31} + 3.75\zeta_{21} + 1.25\zeta_{11} - Chan_1 \geq 0\]

\[21.25\zeta_{92} + 18.75\zeta_{82} + 16.25\zeta_{72} + 13.75\zeta_{62} + 11.25\zeta_{52} + 8.75\zeta_{42} + 6.25\zeta_{32} + 3.75\zeta_{22} + 1.25\zeta_{12} - Chan_2 \geq 0\]

\[21.25\zeta_{93} + 18.75\zeta_{83} + 16.25\zeta_{73} + 13.75\zeta_{63} + 11.25\zeta_{53} + 8.75\zeta_{43} + 6.25\zeta_{33} + 3.75\zeta_{23} + 1.25\zeta_{13} - Chan_3 \geq 0\]

Equation 8.56

\[zeta_{91} + zeta_{81} + zeta_{71} + zeta_{61} + zeta_{51} + zeta_{41} + zeta_{31} + zeta_{21} + zeta_{11} = 1\]

\[zeta_{92} + zeta_{82} + zeta_{72} + zeta_{62} + zeta_{52} + zeta_{42} + zeta_{32} + zeta_{22} + zeta_{12} = 1\]

\[zeta_{93} + zeta_{83} + zeta_{73} + zeta_{63} + zeta_{53} + zeta_{43} + zeta_{33} + zeta_{23} + zeta_{13} = 1\]

\[S_1_1 - 0.083667 FB_1_1 = -61.339\]

\[S_1_2 - 0.083667 FB_1_2 = -61.339\]

\[S_1_3 - 0.083667 FB_1_3 = -61.339\]
\textbf{Equation 8.56}

\begin{align*}
S_{2\_1} - 0.01147FB_{2\_1} &= -6.6201 \\
S_{2\_2} - 0.01147FB_{2\_2} &= -6.6201 \\
S_{2\_3} - 0.01147FB_{2\_3} &= -6.6201
\end{align*}

\textbf{Equation 8.59}

\begin{align*}
S_{1\_2} - S_{1\_1} + 0.00864QT_{1\_1} - 0.00864QP_{1\_1} - 0.00864I_{1\_1} + 0.00864UnContRel_{1\_1} &= 0 \\
S_{1\_3} - S_{1\_2} + 0.00864QT_{1\_2} - 0.00864QP_{1\_2} - 0.00864I_{1\_2} + 0.00864UnContRel_{1\_2} &= 0 \\
S_{1\_4} - S_{1\_3} + 0.00864QT_{1\_3} - 0.00864QP_{1\_3} - 0.00864I_{1\_3} + 0.00864UnContRel_{1\_3} &= 0
\end{align*}

\textbf{Equation 8.60}

\begin{align*}
S_{2\_2} - S_{2\_1} + 0.00864QT_{1\_1} + 0.00864QT_{2\_1} - 0.00864QP_{1\_1} - 0.00864I_{2\_1} + 0.00864Gated_{1\_1} - 0.00864UnContRel_{1\_1} &= 0 \\
S_{2\_3} - S_{2\_2} + 0.00864QT_{1\_2} + 0.00864QT_{2\_2} - 0.00864QP_{2\_2} - 0.00864I_{2\_2} + 0.00864Gated_{2\_2} - 0.00864UnContRel_{2\_2} &= 0 \\
S_{2\_4} - S_{2\_3} + 0.00864QT_{1\_3} + 0.00864QT_{2\_3} - 0.00864QP_{3\_3} - 0.00864I_{2\_3} + 0.00864Gated_{3\_3} - 0.00864UnContRel_{3\_3} &= 0
\end{align*}

\textbf{Fixed Values}

\begin{align*}
I_{1\_1} &= 3 \\
I_{1\_2} &= 1 \\
I_{1\_3} &= 2 \\
I_{2\_1} &= 3 \\
I_{2\_2} &= 6 \\
I_{2\_3} &= 3
\end{align*}

\begin{align*}
FB_{1\_1} &= 792 \\
FB_{2\_1} &= 605
\end{align*}

\textbf{Bounds}

\begin{align*}
3 < S_{1\_4} < 7 \\
0 < S_{2\_4} < 10
\end{align*}

\textbf{Equation 8.1}

\begin{align*}
0 < H_{1\_1} < 212
\end{align*}
Equation 8.3

\[
\begin{align*}
0 &< H_1,2 < 212 \\
0 &< H_1,3 < 212 \\
600 &< F B_2,1 < 615 \\
600 &< F B_2,2 < 615 \\
600 &< F B_2,3 < 615
\end{align*}
\]

Bounds on the upper turbine flow

\[
\begin{align*}
0 &< Q T_1,21 < 5.5 \\
0 &< Q T_1,11 < 5.5 \\
0 &< Q T_1,22 < 5.5 \\
0 &< Q T_1,12 < 5.5 \\
0 &< Q T_1,23 < 5.5 \\
0 &< Q T_1,13 < 5.5 \\
0 &< Q T_2,21 < 5.5 \\
0 &< Q T_2,11 < 5.5 \\
0 &< Q T_2,22 < 5.5 \\
0 &< Q T_2,12 < 5.5 \\
0 &< Q T_2,23 < 5.5 \\
0 &< Q T_2,13 < 5.5 \\
532 &\leq T R_2,1 \leq 551 \\
532 &\leq T R_2,2 \leq 551 \\
532 &\leq T R_2,3 \leq 551
\end{align*}
\]

binaries

delta_1,11 \delta_1,21 \delta_1,31 \delta_1,41 \delta_1,51 \delta_1,61 \delta_1,71 \delta_1,81 \delta_1,91 \\
delta_1,101 \\
delta_1,12 \delta_1,22 \delta_1,32 \delta_1,42 \delta_1,52 \delta_1,62 \delta_1,72 \delta_1,82 \delta_1,92 \\
delta_1,102 \\
delta_1,13 \delta_1,23 \delta_1,33 \delta_1,43 \delta_1,53 \delta_1,63 \delta_1,73 \delta_1,83 \delta_1,93 \\
delta_1,103
delta2_12 delta2_22 delta2_32 delta2_42 delta2_52 delta2_62 delta2_72 delta2_82 delta2_92 delta2_102
delta2_13 delta2_23 delta2_33 delta2_43 delta2_53 delta2_63 delta2_73 delta2_83 delta2_93 delta2_103

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Output from CPLEX for Analysis 1

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2 - COLUMN

.....CO LUMN..... AT ...ACTIVITY....INPUT COST...LOWER LIMIT..UPPER LIMIT..REDUCED COST.

PT1_1 BS   1802.44 10  0   NONE  0
PT1_2 BS   0       0.0001 0   NONE  0
PT1_3 BS   1840.88 100 0   NONE  0
PP_1 BS    0       -10   0   NONE  0
PP_2 BS    0       -0.0001 0   NONE  0
PP_3 BS    0       -100   0   NONE  0
PT2_1 BS   534.82 10  0   NONE  0
PT2_2 BS   534.82 0.0001 0   NONE  0
PT2_3 BS   520.44 100 0   NONE  0
delta1_  101 EQ  0       0       0     -9012.2
delta1_  91 BS  1       0       1     1   0
delta1_  81 BS  0       0       0     0   0
delta1_  71 EQ  0       0       0     -96.2
delta1_  61 EQ  0       0       0     -144.2
delta1_  51 EQ  0       0       0     -192.3
delta1_  41 EQ  0       0       0     -240.4
delta1_  31 EQ  0       0       0     -288.4

150
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| delta1_ | 11 | EQ | 0 | 0 | 0 | 0 | -600.9 |
| H1_1   | BS | 187| 0 | 0 | 212| 0 |
| delta1_| 102| EQ | 0 | 0 | 0 | 0 | 0.009612 |
| delta1_| 92 | EQ | 0 | 0 | 0 | 0 | 0.005768 |
| delta1_| 82 | EQ | 0 | 0 | 0 | 0 | 0.004806 |
| delta1_| 72 | EQ | 0 | 0 | 0 | 0 | 0.003844 |
| delta1_| 62 | EQ | 0 | 0 | 0 | 0 | 0.002884 |
| delta1_| 52 | EQ | 0 | 0 | 0 | 0 | 0.001922 |
| delta1_| 42 | EQ | 1 | 0 | 1 | 1 | -0.17448 |
| delta1_| 32 | BS | 0 | 0 | 0 | 0 | 0 |
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| delta1_| 12 | EQ | 0 | 0 | 0 | 0 | -0.00096 |
| H1_2   | BS | 182.3037| 0 | 0 | 212| 0 |
| delta1_| 103| EQ | 1 | 0 | 1 | 1 | 3844 |
| delta1_| 93 | BS | 0 | 0 | 0 | 0 | 0 |
| delta1_| 83 | EQ | 0 | 0 | 0 | 0 | -962 |
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| delta1_| 23 | EQ | 0 | 0 | 0 | 0 | -6730 |
| delta1_| 13 | EQ | 0 | 0 | 0 | 0 | -12018 |
| H1_3   | BS | 188.2463| 0 | 0 | 212| 0 |
| FB1_1  | BS | 792| 0 | 770| 812| 0 |
| FB1_2  | BS | 605| 0 | 587| 620| 0 |
| FB1_3  | BS | 791.1842| 0 | 770| 812| 0 |
| FB2_2  | BS | 608.8805| 0 | 587| 620| 0 |
| FB2_3  | BS | 603.0411| 0 | 587| 620| 0 |
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| phi1_11| 41 | EQ | 0 | 0 | 0 | 0 | -535.5 |
| phi1_11| 31 | EQ | 0 | 0 | 0 | 0 | -814.5 |
| phi1_11| 21 | EQ | 0 | 0 | 0 | 0 | -1103.7 |
| phi1_11| 11 | EQ | 0 | 0 | 0 | 0 | -3107.4 |
| phi1_21| 61 | BS | 0 | 0 | 0 | 0 | 0 |
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| phi1_21| 41 | EQ | 0 | 0 | 0 | 0 | -552.4 |
| phi1_21| 31 | EQ | 0 | 0 | 0 | 0 | -840.1 |
| phi1_21| 21 | EQ | 0 | 0 | 0 | 0 | -1138.4 |
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| PT_3 BS  | 2361.32 | BS | 0 | 0 | NONE | 0 |
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| QT_21 BS | 5.4501 | BS | 0 | 0 | 5.5 | 0 |
| QT_22 BS | 0     | BS | 0 | 0 | 5.5 | 0 |
| QT_23 BS | 5.4501 | BS | 0 | 0 | 5.5 | 0 |
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Input to CPLEX for Analysis 2

MAXIMIZE
10PT1_1+.0001PT1_2+1000PT1_3-10PP_1-.0001PP_2-
1000PP_3+10PT2_1+.0001PT2_2+1000PT2_3

st
all remained the same

Output from CPLEX for Analysis 2

Integer optimal solution (0.0001/0): Objective = 2.3943653104e+06
Current MIP best bound = 2.3946032854e+06 (gap = 237.975)
Solution time = 325.63 sec.  Iterations = 669466  Nodes = 45538 (584)

Iteration log . . .
Iteration:  1  Scaled infeas = 10.070089

Primal - Optimal: Objective = 2.3943653104e+06
Solution time = 0.02 sec.  Iterations = 5 (5)

PROBLEM NAME     cplex100.txt
DATA    NAME
OBJECTIVE VALUE  2394365
STATUS           OPTIMAL SOLN
ITERATION        5

OBJECTIVE                             (MAX)
RHS
RANGES
_BOUNDS

Row    AT    Activity    Slack Activity    Lower Limit    Upper Limit    Dual Activity
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MAXIMIZE
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all other remained the same

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nu_313  EQ  0  0  0  0  0  -949436
nu_213  EQ  0  0  0  0  0  -949883
nu_113  EQ  0  0  0  0  0  -951427
PP_13  BS  0  0  0  0  0  NONE  0
nu_1021 EQ  0  0  0  0  0  0
nu_921  EQ  0  0  0  0  0  0
nu_821  BS  0  0  0  0  0  0
nu_721  BS  0  0  0  0  0  0
nu_621  BS  0  0  0  0  0  0
nu_521  BS  0  0  0  0  0  0
nu_421  BS  0  0  0  0  0  0
nu_321  BS  0  0  0  0  0  0
nu_221  BS  0  0  0  0  0  0
nu_121  EQ  0  0  0  0  0  0
PP_21  BS  0  0  0  0  0  NONE  0
nu_1022 EQ  0  0  0  0  0  0
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nu_822  BS  0  0  0  0  0  0
nu_722  BS  0  0  0  0  0  0
nu_622  BS  0  0  0  0  0  0
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theta_NO_3 BS  1  0  0  0  1  1  0
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QP_12  BS  4.5189 0  0  0  0  NONE  0
QP_13  LL  0  0  0  0  0  NONE  0
QP_21  LL  0  0  0  0  0  NONE  0
QP_22  BS  0  0  0  0  0  NONE  0

220
QP_23   LL  0  0  0 NONE  0
QP_1     BS  4.542  0  0 NONE  0
QP_2     BS  4.5189  0  0 NONE  0
QP_3     BS  0  0  0 NONE  0
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Beta_21  BS  0  0  0  0  0
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Alpha_12 EQ  1  0  1  1  0
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Turbine_1 BS  0  0  0 NONE  0
Turbine_2 BS  0  0  0 NONE  0
Turbine_3 BS  2  0  0 NONE  0
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Pump_3    BS  0  0  0  0  0
Produce_1 EQ  0  0  0  0  0
Produce_2 EQ  0  0  0  0  0
Produce_3 BS  1  0  1  1  0
Spill1_NO_1 BS  792  0  0 NONE  0
Spill1_YES_1 LL  0  0  0 NONE  0
Spill1_NO_2 BS  792.7788  0  0 NONE  0
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theta_11   EQ  0  0  0  0  0
SPILL1_YES_1 LL  0  0  0 NONE  0
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theta_22   EQ  0  0  0  0  0
theta_12   BS  0  0  0  0  0
SPILL1_YES_2 LL  0  0  0 NONE  0
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theta_23   EQ  0  0  0  0  0
theta_13   BS  0  0  0  0  0
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UnContRel_2 BS  0  0  0 NONE  0
UnContRel_3 BS  0  0  0 NONE  0
delta2_101 EQ  0  0  0  0  0

221
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delta2_23  EQ  0  0  0  0  0 -28740
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TR2_3    BS  540.7041 0  532 551 0
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| phi2_1132  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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| phi2_2162  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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| phi2_2122  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_2112  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_3162  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_3152  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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| phi2_6122  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_6112  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_7162  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_7152  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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| phi2_7112  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_8162  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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MAXIMIZE
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delta2_42  EQ  0  0  0  0  0  0
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delta2_22  EQ  0  0  0  0  0  0
delta2_12  BS  0  0  0  0  0  0
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delta2_83  EQ  0  0  0  0  0  0  71860
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phi2_1141 EQ  0  0  0  0  0  0
phi2_1131 EQ  0  0  0  0  0  0
phi2_1121 EQ  0  0  0  0  0  0
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phi2_2161 EQ  0  0  0  0  0  0
phi2_2151 EQ  0  0  0  0  0  0
phi2_2141 EQ  0  0  0  0  0  0
phi2_2131 EQ  0  0  0  0  0  0
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| phi2_2241  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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| phi2_2221  | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
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| phi2_4251 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
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| phi2_4231 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
| phi2_4221 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
| phi2_4211 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
| phi2_5261 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
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| phi2_1152 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
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| phi2_2162 | EQ | 0   | 0   | 0   | 0   | 0   | 0   |
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|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
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| phi2_4232  | EQ | 0 | 0 | 0 | 0 | 0 |
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| phi2_10212 | EQ | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_1163 | BS | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_1153 | EQ | 0 | 0 | 0 | 0 | 0 | -37950 |
| phi2_1143 | EQ | 0 | 0 | 0 | 0 | 0 | -55720 |
| phi2_1133 | EQ | 0 | 0 | 0 | 0 | 0 | -73890 |
| phi2_1123 | EQ | 0 | 0 | 0 | 0 | 0 | -92090 |
| phi2_1113 | EQ | 0 | 0 | 0 | 0 | 0 | -143590 |
| phi2_2163 | BS | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_2153 | EQ | 0 | 0 | 0 | 0 | 0 | -39060 |
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| phi2_3113 | EQ | 0 | 0 | 0 | 0 | 0 | -151980 |
| phi2_4163 | BS | 0 | 0 | 0 | 0 | 0 | 0 |
| phi2_4153 | EQ | 0 | 0 | 0 | 0 | 0 | -41280 |
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Vita

Craig S. Moore

Craig S. Moore was born on January 24, 1972 in Lexington, Virginia. He graduated third in his class from Natural Bridge High School in 1990. Upon graduation from high school, Craig entered Va. Tech and completed one semester of study. Due to health problems, Craig was compelled to withdraw from Va. Tech and work with his father's construction business. During this time, Craig also attended Virginia Western Community College and earned two degrees, an Associate in Applied Science degree in Civil Engineering Technology and an Associate in Science degree in Engineering. In 1994, Craig was able to return to Va. Tech and complete his undergraduate education. He received a Bachelor of Science degree in Civil Engineering in May of 1996. After graduation, Craig worked for The Lane Construction Corporation in Buena Vista, Virginia for seven months. In January of 1997, Craig returned to Va. Tech under the Geodetics/Hydrosystems division to study for a Masters of Science degree. During his time in graduate school, Craig worked as a project engineer for a local engineering firm for one year. He developed hands-on labs that integrated engineering and math for freshman calculus students in the SUCCEED program. Within the department, Craig served as a hydraulics teaching assistant and surveying lab instructor. He helped develop the new course CEE Measurements and served as lab instructor for two semesters and an instructor for three semesters. He has worked as a surveying consultant to the Transportation Research Group locating sensors on the Smart Road. Craig has also
donated many hours to other graduate students assisting with such topics as GPS, GIS, surveying, and creating terrain models in AutoCAD for use in hydraulic analysis.

Craig is a member of the American Society of Civil Engineers, American Congress on Surveying and Mapping, American Society of Photogrammetry and Remote Sensing, and Chi Epsilon.

Craig will receive his Master of Science degree in Civil Engineering in December of 2000.

Craig is married to the former Paula Jeanette Kiefer of Norfolk, Virginia, who is also a graduate of the Civil Engineering Department at Va. Tech.