ENERGY AND COST MODELLING OF WATER RETICULATION SYSTEMS IN DEEP-LEVEL GOLD MINES

by

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SUMMARY

Gold mines in South Africa consume a great proportion of the country's total electricity production. A significant part of this consumption is the electricity used by their water reticulation systems. Low gold prices and other financial pressures are causing gold mines to examine various means of cost saving. Scientific management of the water reticulation systems promises to result in significant cost savings.

By developing mathematical energy conversion models of all major components found in typical water reticulation systems of deep-level gold mines, these systems can be simulated under different operating conditions, configurations and schedules in order to find most efficient combinations. Proper integration of these models ensures that any system simulated produces accurate energy usage data. This data can then be applied to various available electricity tariffs to find the most cost effective.

Modelling the water reticulation systems in deep-level gold mines furthermore provides a tool allowing developers of future installations to experiment with different proposed systems and so take more informed decisions about system configurations and specifically choice of energy recovery systems.

This dissertation includes all methodologies, and mathematical tools used to develop the models. It verifies models generated using actual data obtained from a number of Anglogold gold-producing shafts and demonstrates how the models can be used to reduce electricity costs with examples using actual data.

KEYWORDS

Energy Conversion Modelling, Mining, Pumping, Energy Recovery

OPSOMMING

Suid-Afrika se goudmyne verbruik `n groot gedeelte van die land se totale produksie van elektrisiteit. `n Beduidende gedeelte van hierdie verbruik bestaan uit die elektrisiteit wat deur hulle waterpompstelsels gebruik word. Lae goudpryse en ander finansiële druk noop goudmyne om verskeie metodes van kostebesparing te ondersoek. Beduidende kostebesparing van die waterpompstelsels kan deur wetenskaplike bestuur teweeg gebring word.

Deur wiskundige energie-omsettings modelle van alle hoof komponente wat in tipiese waterpompstelsels in diepvlak goudmyne gevind word te ontwikkel, kan hierdie stelsels onder verskillende werkstoestande, konfigurasies en skedules nageboots word om die mees doeltreffende kombinasies te vind. Behoorlike integrasie van hierdie modelle verseker dat enige nagebootste stelsels akkurate data van energieverbruik lewer. Hierdie data kan dan toegepas word op die verskillende beskikbare elektrisiteitstariewe om die mees koste effektiewe een te vind.

Modellering van die waterpompstelsels in diepvlak goudmyne sal ook ontwikkelaars van toekomstige installasies in staat stel om met verskillende voorgestelde stelsels te eksperimenteer en sodanig besluite wat op beter inligting berus, te neem oor stelsel konfigurasies en spesifiek die keuse van energie-herwiningstelsels.

Hierdie verhandeling sluit alle metodes en wiskundige apparatuur in wat gebruik is om die modelle te ontwikkel. Dit verifiëer ontwikkelde modelle en gebruik werklike data wat verkry is van 'n aantal Anglogold goudproduserende skagte en demonstreer hoe die modelle aangewend kan word om elektrisiteitskoste te verminder deur gebruik te maak van voorbeelde wat op werklike data berus.

SLEUTELWOORDE

Energie-omsettings Modellering, Mynbou, Pomp, Energie herwining

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1.   INTRODUCTION, BACKGROUND AND PROBLEM IDENTIFICATION

1.1   INTRODUCTION

The Oxford English Dictionary [1, pp. 281 & 529] has the following definitions:

Energy: "Ability of matter to do work" and "Fuel or other sources allowing work to be done"

Manage: "Handle, wield, control and regulate"

According to these definitions, energy management can essentially be seen as the controlling and regulating of sources allowing work to be done. This broad observation does however not make provision for an important element in the reasonably new energy management concept. What is important now, is the minimisation of the cost associated with this ability to do the work. Within this context, we are particularly concerned with the cost minimisation of electrical energy.

Calmeyer [2, p. 1] mentions that energy management should not merely be seen as having the purpose of minimising energy consumption and demand, but that the ultimate objective is cost optimisation. He continues that this does not necessarily involve the reduction of total electrical costs, but the reduction of cost per product. So if reducing electricity costs can increase productivity, total profit will increase. In essence, electrical energy costs can be reduced by using energy more efficiently and / or by the correct selection of time-differentiated tariffs.

According to Roos [3, p. 97], the end users of electrical energy want to amongst others:

- Reduce their costs
- Conserve energy
- Maintain profitability

He continues that by understanding customer acceptance criteria, one can persuade them to actively participate in a load management program. What should be realised is that customers, do not necessarily need to be external parties to an organisation, but may in fact be internal parties that need to increase energy efficiency.

Thumann and Mehta [4, pp. 377 – 389] regard energy management as "the judicious and effective use of energy to maximise profits (minimise costs) and to enhance competitive position". They also importantly focus on the fact that successful energy management does not only revolve around the conservation of energy but the comprehensive organisation of all matters which influence or may be influenced by energy usage within an energy-using establishment. A comprehensive energy management program is certainly not purely technical. It must be a total program that involves all areas of business and needs to concentrate on planning, communication and marketing. Often simply making people aware of energy wastage produces large savings. Thumann and Mehta go on to describe that energy management in large organisations needs to be very visible and a focal point of much of the general management. Energy management teams and program members also need to interact with almost all divisions of an organisation.

Turner [5, pp. 3 – 5] confirms the importance of organisational management involvement in energy management by stressing that good energy management represents a real chance for creative management to reduce a component of product cost that has become a considerable factor of late. In the past organisations that have taken advantage of energy management drives have done so because of the obvious involvement, motivation and commitment from the top executive. Once this commitment has been understood, managers at all levels of the organisation can and do respond seriously to the opportunities of large savings. Tissink [6, pp. 10.2 – 10.3] also mentions that in order to minimise electrical energy costs, specifically in the mining environment, it is essential that line management is directly responsible for the energy consumed within its own area of responsibility.

It thus becomes clear that good energy management is a careful combination of management involvement and skills and technical methods and methodologies for actually implementing the changes which management have shown support for. The next very important component of effective energy management is quantifying what is being dealt with. Lord Kelvin said a century ago: "When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a

meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science." [7]. The importance of representing energy consumption numerically allows one to be able to mathematically analyse and manage consuming devices far more effectively.

Jacobsen [8, pp. 43 – 47] stresses the importance of technology in the process of energy management. He states that innovation of new technologies and improvements of existing technologies will be the dominant factor for survival in a future where proper energy usage and management will be of cardinal importance. The technological advances of specific interest are advanced methods of energy consumption modelling.

The study contained in this dissertation is intended to facilitate deep-level gold mining operations which do not have readily available power consumption data of their water reticulation systems. This is to be done by providing a method of determining the power consumption of various water reticulation system configurations. It will also be useful for the analysis of different prospective installations.

1.1.1 Overall Picture

In order to provide a clear picture of what is being addressed by this study, the following figure has been included at this point.
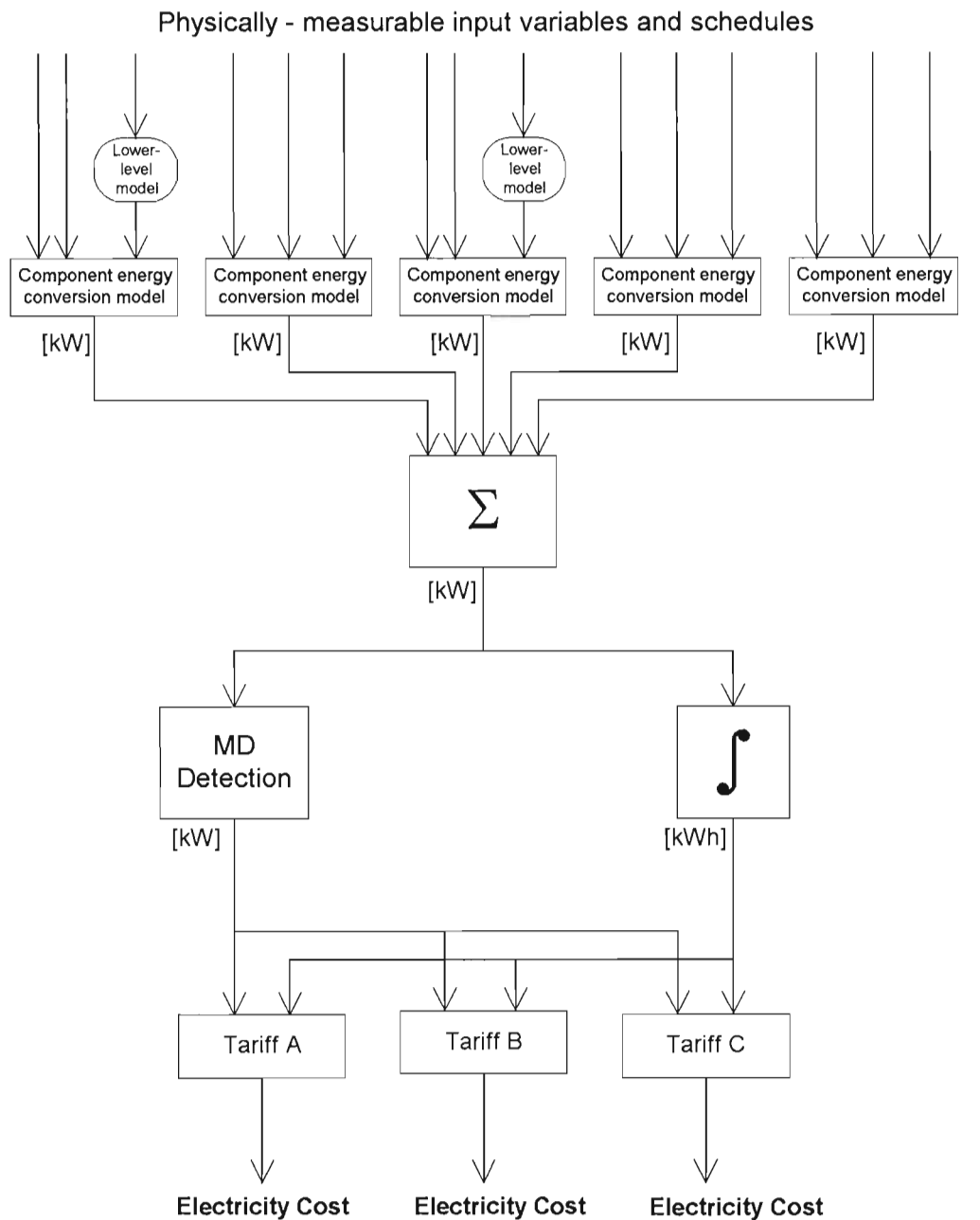
Figure 1.1: Path between physical variables and electricity cost

Figure 1.1 represents what is really being aimed at by this study. What broadly needs to be achieved is the development of a means of relating all input variables of the water reticulation system to respective electricity costs.

The heart of the study the development and verification of the component energy conversion models as shown in the figure. Once these have been satisfactorily

developed, it will then be a reasonably simple task summing their consumption, integrating and detecting the maximum demand to apply the energy usage to a number of different tariffs to find the most cost-effective.

The general aim of this study is thus to develop energy conversion models that will allow the user to experiment by changing inputs to the model such as physical parameters and schedules and observe the effect of the changes on electricity cost using different available tariffs and so find the most cost effective.

1.2 PRACTICAL ENVIRONMENT

1.2.1 Anglogold Introduction

The study was done with the support of Anglogold, which has a number of gold producing shafts in South Africa, many of which have sophisticated data capturing systems. Shafts which have full Supervisory Control And Data Acquision (SCADA) database systems are able to monitor much of the energy flow through the mine. Shafts without such systems are the intended true beneficiaries of this study.

Anglogold is a newly formed company which has taken over ownership and control of the Anglo American Gold Mines. The company is responsible for 3 main regions of Gold Mines in South Africa. These mines are situated in the Witwatersrand Basin, the largest gold mining region in the world with known and estimated reserves of 643 million ounces. All are deep-level operations, mining at an average depth of 2 100 metres below surface (6 900 feet) and in the West Wits region as deep as 3 777 metres (12 400 feet). In addition to the above, there is Ergo, a metallurgical operation using unique technology to extract gold from low-grade waste dumps.

The actual mines are as follows:

- Vaal River: Great Noligwa, Kopanang, Tau Lekoa and Moab Khotsong mines

- West Wits: Western Deep Levels and Elandsrand mines

- Free State: Joel, Bambanani, Tshepong and Matjhabeng

- Ergo: a metallurgical operation using unique technology to extract gold from low-grade mine waste dumps

- Driefontein: a prospective joint venture with Gold Fields Limited in which AngloGold is aiming to increase its level of ownership from 21,5% to 40%

The South African mining industry is one of the main electricity consuming sectors of the country. In the past, it has represented up to 27% in 1985 [9, p. 1] and 18.2% in 1999 [10, p. 96] of the country's energy consumption. Of this about 17,6 % of the energy and maximum demand usage is from the underground water pumping systems [9, p. 5].

1.2.2   Energy Policy

Anglogold, being one of the main electricity consumers of the country, have realised the importance of effective energy management as one of their main cost saving initiatives. An energy policy was developed in 1998 by Arnold [11], Anglogold's energy engineer. Any energy management changes or investigations, which are undertaken, must be done under any particular constraints stipulated in the company's official energy policy.

The Anglogold policy has two important subsections, namely economic considerations and environmental considerations. In keeping with international trends and possible legislation, it is very important for any industrial operation to pay careful attention to environmental impact from any of their activities. Anglogold has thus included environmental considerations in its energy policy, with particular interest in primary fuel availability.

The policy also clearly defines the organisational structure with reference to the line of responsibility of the energy manager. This emphasises the organisational involvement and awareness as mentioned earlier. It is very important in the whole energy management scenario of any organisation, to ensure that accountable parties are clearly identified. The Anglogold policy makes provision for various levels of this responsibility.

To standardise all measurements of various energy sources and consumers so that benchmarking can be done, the policy covers standard units, conversion and efficiency metrics. It then continues to define the system, format, and frequency that is to be used when measuring, recording and reporting energy use.

The final part of the policy defines the method the company will use for budgeting and billing the users of the various energy types.

1.2.3   Present data and tools available

A number of the Anglogold shafts such as Tshepong near Odendaalsrus in the Freestate have sophisticated SCADA systems. Others do not have any such data gathering systems and rely on rated specifications of system components and rudimentary mechanical measuring devices.

Tools which are used at present for energy management include load shedding, load shifting, historically-based load forecasting, power factor correction, cogeneration, alternative energy source usage, energy storage and tariff selection.

As can be seen from the list above, simulation and load forecasting based on system configurations are not readily available. This study provides a method for forecasting and simulating energy consumption for the water reticulation systems of deep-level mines, allowing different configurations, tariffs and schedules to be simulated whether the shaft has sophisticated data capturing systems available or not.

1.3   LITERATURE STUDY

1.3.1   Total Plant Study

Delport's Ph.D. [9, pp. i – ii, 1 – 5 & 38 – 40], entitled "Integrated electricity end-use planning in deep level mines" provides a comprehensive identification of major energy consuming sections of deep-level gold mines. The study suggests methodologies and strategies for mine-wide integration of energy management procedures. In order to do this all major energy consuming systems within the deep-level mining environment had to be identified and modelled to a certain degree, one of which is the water pumping system. Delport suggests mathematical models for pumps, friction losses and efficiency in the system, but does not provide for any other components, which may be found and thus does not refer to a water reticulation system as in this study. This study thus builds on Delport's models by verifying and refining what has been done and developing models for system components which have not been modelled such as turbines and Three Chamber Pipe Feeder systems. This study will also present models for multiple components and methodologies for integration of the different models. Delport provides for system delays and storage devices [9, pp. 69 – 71] qualitatively, but these components still need to be incorporated into the entire water reticulation system mathematically.

1.3.2   Component Study

A need exists to provide the deep-level gold mines of South Africa with a means of determining their energy usage for pumping under different operating conditions and configurations. Much literature exists relating the power usage of common water reticulation system components such as pumps, turbines and losses to other variables such as flow rate. This study will build on this knowledge and continue to include specific devices such as three chamber pipe feeder systems and integrating the different components in different configurations as one would find in the deep-level mining environment. With modern mathematical methods and technology having progressed as far as they have, an entire system can be treated as a whole once

analysis of individual components have been analysed and integrated [12, pp. 1 – 2]
Literature used for mathematical analysis of the common components include:

- Mechanical Technology [13]
- Pump Handbook [14]
- Introduction to Fluid Mechanics, 2nd Edition [15]
- Pump Application Desk Book [16]
- Solutions of Problems in Fluid Mechanics Part 1 [17]

This list of literature provides a reasonable overview of the mathematical derivations
and laws governing fluid flow relevant to most of the components of interest. They do
however not present methods of integrating the mathematics of different components
to be able to analyse a complete system. They also only present basic fundamental
facts, which will need to be used to generate models of system components that are
not common.

1.3.3   Inputs, Outputs and System Variables

In order to model different water reticulation system components all inputs, outputs
and different variables involved need to be identified and related to possible inputs
and outputs of individual system building blocks [9, pp. 46 – 51]. The methodologies
developed in this regard as discussed in full detail in the next chapter.

The literature mentioned in the previous section, provide clear guidelines for all
influences that may exist on the devices for which models need to be generated.
Usually the output of the models and of systems of models needs to be energy values.
Other variables, which typically need to be taken into account, are flow rates, gravity,
liquid density, device efficiency, pipe diameter, fluid velocity and other factors
associated with device energy losses.

For all components it must be remembered that they form part of and are in fact fluid-dynamic systems themselves. This means that in order to relate energy to the flow of liquids one needs to use a principle like Bernoulli's theorem [18, pp. 410 – 423], which will be dealt with in more detail in Chapter 3.

1.3.4   Overview of mine water reticulation system

Water, which is chilled on surface and passed down a mineshaft, has a number of uses. Chilling the water is mainly to control the ambient temperature within the mine, from bulk air cooling devices that form part of the air ventilation system [19, p. 11.3]. The water is also amongst others used to drive hydraulic rock drills and in some cases for water jet cleaning during the cleaning shift after blasting. Drinking water is a completely different system and so does not have any influence on the main reticulation system.

In order to ensure that there is enough water at all times mines generally have two sets of storage dams. One set on surface and one set approximately midway down the shaft, which is usually above most of the active mining levels. Each set consists of a hot water dam for water that has been used and a chilled water dam for water that is still to be sent to the workplace. All cooling is generally done on surface, by passing the hot water through evaporator towers for pre-cooling and then through a fridge plant to chill to obtain the desired temperature.

One main interest in the system from an energy point of view is the fact that the water which has been consumed in the workplace needs to be returned to surface by pumping. The other main interest is that the water, which is going to the workplace from the surface, gets there by flowing down the shaft and so obtaining kinetic energy. Considering that some gold mines in South Africa actively mine to a depth of 3700m, allows one to appreciate why as great a percentage of the mine-wide energy consumption is used for pumping, as well as how much energy is being wasted if the water going down the shaft is simply allowed to flow down.
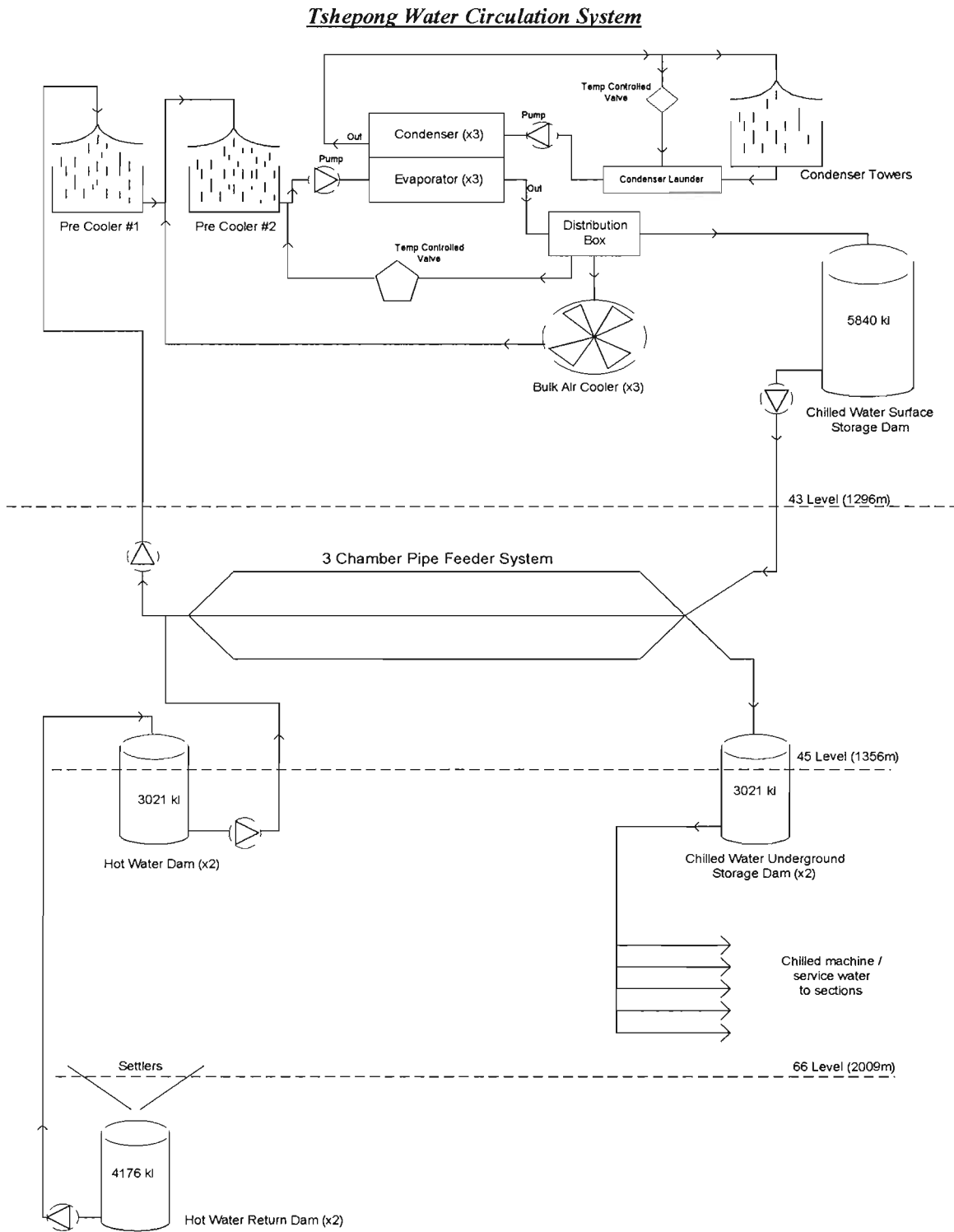
Figure 1.2: Typical Water Reticulation System

The layout shown in figure 1.2 is the basic layout of the water reticulation system of Tshepong mine in the Freestate. Tshepong mine was used to verify the models proposed in this study because of the advanced data capturing system installed there. There is also a three chamber pipe feeder system installed, which allows the verification of models for it. The three chamber pipe feeder system uses the head of cold water to balance the head of hot water that needs to be pumped to surface, thereby avoiding having to pump against the large head that normally exists.

Other factors that are important in the water reticulation system are the storage tank capacities and the delay for water to naturally flow from one point in the system to the next. It can for example not be assumed that the water, which has left the underground chilled water dam, is immediately available to be pumped.

1.4   PROBLEM IDENTIFICATION

1.4.1   Introduction

At this point it is clear that energy conversion models need to be developed to allow the user to be able to manage scheduling, configuration and tariff selection. This management will be done by allowing experimentation with different input conditions to a set of models. The questions now arise of who this user is? What exactly does experimenting with scheduling, configurations and tariffs mean? What needs to be modelled and how is everything going to be integrated?

The reason that it is beneficial to model the water reticulation system in particular is that it is one of the most flexible in terms of scheduling without negatively influencing production or worker comfort. The operators of the water reticulation system can adjust the timing of pumping and other related water flow controls within reasonably wide tolerances. The main concern is that there is sufficient water available for mining activities, along with a safety factor. The use of storage facilities are obviously one of the main reasons that this is possible.

1.4.2   End-user identification

Ultimately this study is of interest to the management of any mine, which is able to apply the models to their own environment. It has been done particularly with deep-level gold mines in mind. It is also of benefit to the management of prospective mines to decide on different configurations by testing to see which will be the most economically viable by comparing energy operating costs to initial installation costs.

Naturally other parties that this study is of interest to are parties responsible for costs savings, such as energy engineers if they exist in the particular mine or section engineers in charge of the water reticulation system.

1.4.3   The purpose of modelling

By generating energy conversion models for each component (device or integrated system of devices) in the water reticulation system of a mine, one is able to determine exactly how much power that component is using or delivering under different input conditions. Summing the power used by all the devices and integrating over the period that they are active for produces a value for the total energy consumed of the entire system [20, p.14]. Maximum demand and other dynamic values can then also be determined by integrating the power values over whatever integration period is of particular interest.

Once these models have been developed for general cases, they can be employed for systems where there is little knowledge of the usage of energy, by taking a few sample measurements to determine basic constant input conditions for the models such as flow rate. Employing the models over any scheduling and tariff conditions then follows this.

1.4.4   Future Systems

One of the main benefits as mentioned before is the fact that these models can be used to evaluate the energy consumption patterns of future installations. It may for example be of interest to a prospective mine to determine what kind of energy recovery system needs to be employed. Depending on individual circumstances installing a three chamber pipe feeder system may prove to be more economical than merely installing conventional turbines. It may also be necessary to decide between conventional mechanical turbine-pump drives and electrical turbines, which would allow the generated energy to be used by other users in the mine during Maximum Demand times.

Wagner and Oberholzer [21, pp. A78 – A80] confirm the importance of potential costs to mine managements when having to take capital expenditure decisions. Feasibility and cost studies are usually time consuming and costly. Modelling provides a very useful tool for examining prospective operating costs.

In prospective systems, one needs to evaluate the operating cost against the cost of installation by using accounting techniques such as the Internal Rate of Return (IRR), Minimum Attractive Rate of Return (MARR) and Net Present Value (NPV) of the initial investment [2, pp. 61 – 63]. The lifetime of the investment would generally be the expected gold-producing lifetime of the shaft. To this factors such as unexpected operation size reductions or expansions due to gold price fluctuations need to be kept in mind.

1.4.5   Scheduling and Tariffs

As mentioned a big advantage of modelling is to be able to experiment with different schedules and tariffs. Scheduling of the pumping functions in the water reticulation system can be rather flexible because of the storage facilities that mines have on surface and underground. Naturally the larger the storage capacity of the dams, the more flexible the schedules can become. In certain cases it may even be advantageous for the mine to investigate enlarging the size of the storage dams or at least ensuring

that they are clean, depending on the influence that this proves to have from the models.

The underlying constraints that exist for scheduling are the water requirements for mining operations, storage capacities and volume of water that can be pumped at a specific instance.

Along with evaluating different schedules, the user needs to be able to evaluate the influence of the water reticulation system on the entire electricity account of the mine, using different tariffs. The mines which are customers of Eskom, South Africa's electricity producer, have the choice of a number of tariffs, which include Nightsave, Megaflex [22] and Real Time Pricing (RTP).

1.5 OBJECTIVES

1.5.1 Main Objective

A means of relating physical parameters and scheduling of water reticulation systems in deep-level gold mines to electricity costs needs to be developed. This means must include energy conversion modelling and must be of such a nature that similar systems, configurations and schedules can be simulated to produce electricity costs of a set of particular conditions using different available tariffs.

1.5.2 Specific Objectives

Specific objectives for the achievement of the main objective are as follows:

Extension of Delport's Models

Delport's work as mentioned in section 1.3.1 needs to be verified and extended, paying particular attention to the shortcomings and discontinuities of his model propositions.

Modelling Methodology

A modelling methodology needs to be generated and closely followed in order to develop models systematically and ensure that they remain completely compatible and within the systems context.

Separate Modelling

Accurate mathematical models of all general energy producing, energy consuming and energy recovery components of a deep-level gold mine need to be developed and verified. These include pumps, turbines, pipe and other losses and three chamber pipe feeder systems.

Model Integration

Generated models need to be able to be coupled together in any configuration that is to be simulated. They thus need to be completely compatible. Energy values obtained from the individual components need to be summed and integrated over a relevant time frame. The output of the system of models with physical and test inputs, needs to be an accurate value for the cost of running the water reticulation system for a specified length of time.

External Compatibility

All modelling which is done, must be configured in such a way that it can be generally used in any typical deep-level gold mining configuration. This means that inputs and outputs must conform to formats and standards that are typically used in such environments.

Experimentation

Modelling must be done in such a way that different schedules, configurations and tariffs can be experimented with. This does not necessarily mean that the models need to have tariffs as an input, but final outputs must be of such a nature that they can easily be used to calculate costs from standard tariffs. Schedules typically would govern the periods in which the models are run. Configurations data would need to form direct inputs to a model system.

Future Systems

Models which are able to simulate the power consumption of the water reticulation systems of existing mines, should also be able to simulate proposed systems, allowing informed cost decisions to be taken before a mine is developed as described in section 1.4.4.

1.6   STRUCTURE OF DISSERTATION

This dissertation has been constructed in the knowledge that all mines have individual water reticulation systems that do not necessarily conform to any specific standards. The theory and practical examples presented within this dissertation are of a general nature and might require slight adjustments for systems that have specific individual components or operating conditions.

Chapter 2 addresses the methodology used to generate the energy conversion models. It elaborates in the types of models, criteria, approach, models contexts and constraints. In general, it defines how the bridge between the real and mathematical world will be crossed.

Chapter 3 deals with the actual mathematical development of models. This includes mathematical tools used to generate the models as well as the presentation of final models.

Chapter 4 focuses on the verification of models that have been developed by using data obtained from actual case studies.

Chapter 5 demonstrates how the developed models can used to examine and subsequently reduce electricity costs of pumping water around a deep-level gold mine.

2.   MODELLING METHODOLOGY

2.1   INTRODUCTION

At this stage it has become obvious that energy conversion model development, verification and integration form the heart of this study. It is important to have a structured approach to actually developing such models and for this reason a complete methodology has been developed for this purpose.

The theory and practice of energy modelling have made great advances recently [23, pp. 111 – 112], especially with the development of modern computer technology making complex calculations and model processing possible. Modelling contributes to the design and analysis process either directly, by enabling complex systems to be understood, so enabling the more complex and efficient systems to be designed, or indirectly by giving a greater degree of confidence to a design or process decision that would otherwise have to be made with a much higher degree of risk.

Modelling should not be purely mathematical and academic. In fact the art of modelling is to keep the subject as superficial but as broad as possible enabling proper results to be obtained. A process model can involve physical kinetics, engineering design, costing, accounting, mathematics, and programming [12, pp. 1 – 3]. Modelling therefore requires acquaintance with a wide range of subjects, some of which obviously need to be treated in more depth than others depending on the context of the situation.

2.1.1   Types of Models

Steven and MacLeod [24, p. 24] state that models can broadly be divided into two types, namely formal and conceptual models. Formal models are equation-based, mathematical models, whereas conceptual models are mental models or understanding about formal models.

Conceptual models are not expressible in formal terms and involve concepts such as quality or accuracy of the formal models and their applicability. Conceptual models thus really represent a basic non-mathematical understanding of a process, which is very important in the development of formal models.

Heuristic models are combinations of many different kinds of knowledge; cause-effect, spatial, temporal and taxonomic knowledge. Heuristic models are thus the most useful as they include a variety of different background and mathematical inputs.

2.1.2   Specific Criteria

The purpose of energy models are to represent low-level end-user groups reasonably accurately without being too complicated or creating unacceptable errors. In striving for a simple yet effective model, a number of development iterations will need to be done. A mathematical model is an abstraction of the real world system and will naturally require refinement after its initial development to ensure reliable accuracy [25, pp. 1 – 2].

Models must be relevant to the context in which the are found. This includes their inputs, outputs and all variables that have influence on them or are influenced by them. The theory used to develop models must be consistent and the models must be compatible to the surrounding system in which they are found.

The objective of the energy conversion models, which are to be developed, is to provide only the instantaneous, theoretical power consumption of each energy consuming or delivering component in the water reticulation system of a deep-level gold mine. These power values are to be summed to provide a combined figure for the entire system. The results can then be integrated to generate energy usage figures.

According to Roos [3, pp. 108 – 110], quantitative industrial plant models should be based on basic physical and economical properties of the plants operation. Used in a computer simulation, he continues that such models should represent the operation and functioning of the plant with fair accuracy without actually having to run the

plant. Roos proposes comprehensive modelling strategies including inputs from material flow, maintenance, management set points, MD set points and variable plant costs. Manichaikul and Schweppe [26, pp. 1439 – 1441], also mention that plant modelling should include physically based load models as well as economic analysis. For the purpose of this study however, only energy conversion modelling needs to be done to provide power usage values of the different components of a deep-level mine's water reticulation system. The only attention that is to be paid to economic properties, is the electrical cost calculation from the values obtained from the energy conversion models, using different available tariffs.

2.1.3 Methodological Advances

A number of studies have been in the development of energy modelling methods, as described by Griffin [23, pp. 115 – 123]. Griffin has proposed methods to quantify the actual methodological advances in energy modelling. In his research, he has come to the conclusion that more accurate models were not as a direct result of having more data available. The biggest advances have come from improved techniques of utilising the available data. This supports the requirement for an extensive modelling methodology in which all aspects relevant to the proposed models are taken into account.
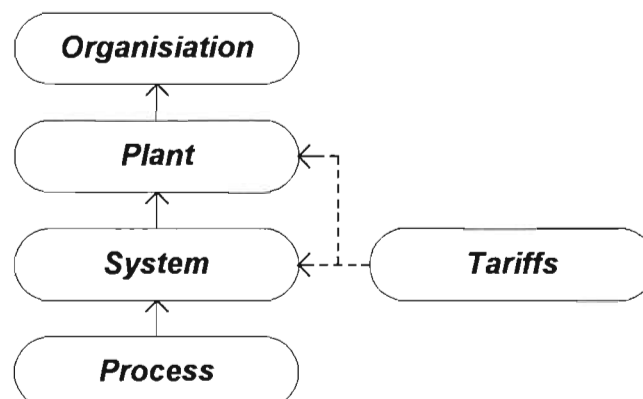
2.2 CONTEXT OF ENERGY MODELS

Figure 2.1: Context of models

In the hierarchy shown in Figure 1, *system* would represent the water reticulation system and *process* would represent all the functional components of the system. In the global picture, the *process* models will collectively have an output into the *system*. Energy usage values are outputs of the *system* and inputs to the *plant*, which in this case would collectively represent the entire mine's electricity consuming systems. Up to this point the flow of data from one level to another would be energy values. The data flowing to the organisation however, would be monetary values, the reduction of which would be the fundamental purpose of any such study. The *tariff* input shown may be an input to the *system* or *plant* level of the hierarchy, depending on the configuration and level at which most control can be done.

2.3   MODULAR APPROACH

In order to create versatile energy models, it is important to follow a modular, or 'building block' strategy as developed by Delport [35, pp. 46 – 51]. This allows one to use the developed modules in different configurations, and so make it practical for different mines to be able to use the models by fitting relevant components together. Referring to figure 2.1, building blocks can be generated for the *process* and *system* levels of the hierarchy.

The basic blocks for the *processes* would be of a more mathematical nature and the *system* blocks would consist of collections of process blocks and be used to couple different parts of the system, which would not be possible on the process level alone.
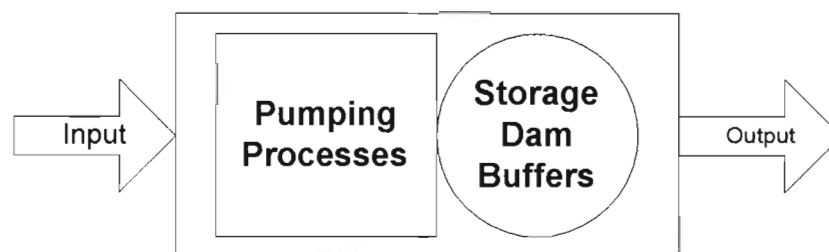

Figure 2.2: Example of a system building block for the pumping processes on a certain level of a gold mine, according to Delport's Building Block approach [9, p.46]

The underlying concept for this study is that a modular energy conversion model gets developed for each identifiable process, which will then form part of a system building block. Following this philosophy, many of the devices will consist of a number of sub-modules. Other components of the water reticulation system may have a module representing a physical device.

A crucial factor governing the development of any such modules (models), is that they are completely compatible to each other in any configuration. The inputs and outputs of each individual module must thus conform to a standard established for the entire system.

The models will be generated with the intention of automating them on computer to facilitate speedy simulation of different operating condition to find optimal solutions. For this reason it is even more important that the different 'building blocks' are completely compatible. If the models were to be used for manual calculations, one would still be able to alter values to provide compatible values. On computer however, it is naturally impossible to implement models that need to be individually checked during each calculation.

Godfrey [27, pp. 23 – 25] emphasises the importance of the integration of the electrical distribution systems, management information systems and energy management systems in a typical mining environment. This is done to be able to keep a global control on the entire operation. In the same way, it is important that models generated for different components of any of the electrical system within a mine are completely compatible to be able to be able to give overall results of any simulated conditions.

2.4   DEVELOPING MODELS
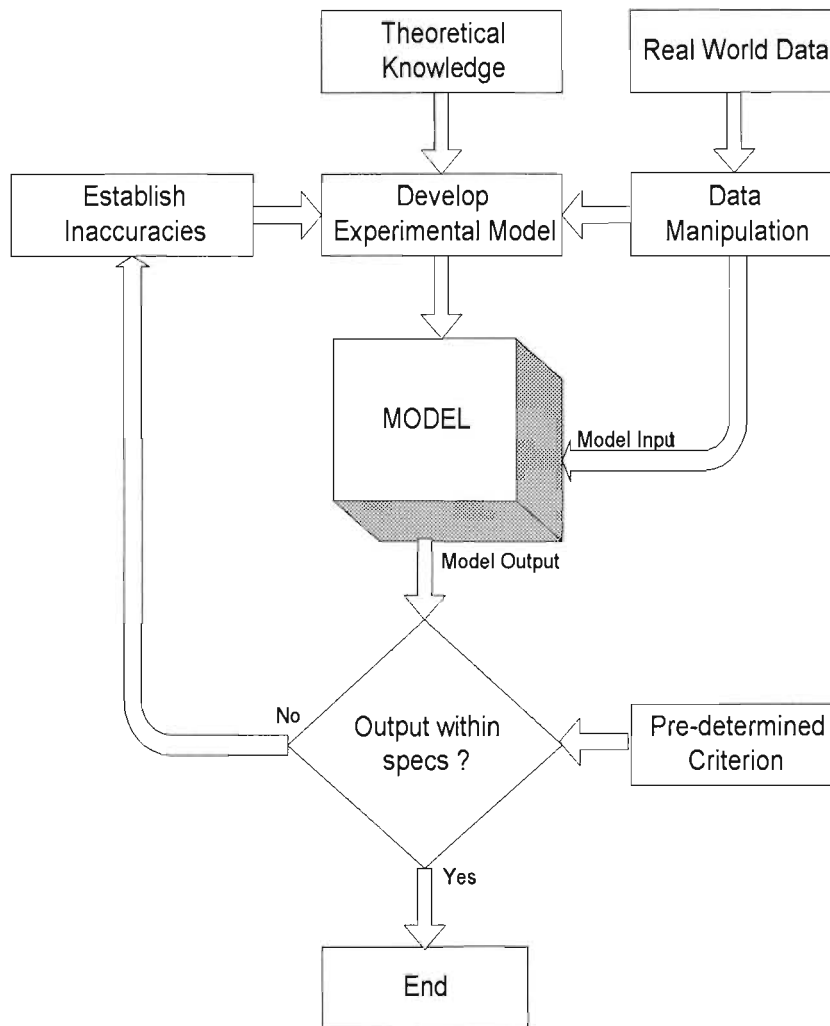
Figure 2.3: Model Development Flow Chart

Figure 2.3 is a graphical representation of the process of developing models in this methodology. The heart of the process is naturally the actual development of the model. As shown, the development stage has a number of inputs, namely theoretical knowledge, manipulated real-world data and a refining input from previous model trials. The development output is of course the actual model, which can then be tested.

The "theoretical knowledge" input represents all scientific theory of the system for which the module is being developed as well as all factors which may influence the system that have been experienced or witnessed in the practical environment. This includes basic physics and applied theory for whichever device the model is being developed. Roos [3, pp. 108 – 110] mentions that the functioning of processes in the plant should be modelled according to basic principles. Part of this input to the model development process is the set of engineering assumptions that should be made intelligently to keep the model simple but effective.

Any real-world data that is used will essentially not conform to a standard format, which is to be implemented to allow total compatibility between any modules developed. It is therefore necessary to manipulate data that may enter the development stage of such a model, to ensure that it is presented in a format, which will be used for the input of the working model. It is imperative that all data conforms to the standard laid down. For this reason, the particular assumptions, aggregations and simplifications that will be employed need to be stipulated clearly as well as the format and units of all data in the system.

In essence the model will be developed predominantly from the "theoretical knowledge" input, but the manipulated "real-world data" input is important to establish the ranges of values such as efficiencies and conversion constants that may be used. Meredith [28, pp. 16 – 18] mentions that in any particular circumstances, idiosyncrasies of the system being worked with must be taken into account. The "real-world data" input is instrumental in identifying any such idiosyncrasies in the development stage of any model. By tailoring the model at development, it reduces the process of refining the model later rather significantly.

Once the experimental model has been developed, it needs to be tested. The model represents a process and therefore has certain inputs and outputs. The inputs will naturally be the same as the manipulated data, described earlier. These are the real-world measurements that need to be processed in the artificial mathematical world, which has been generated. The outputs of the model need to be compared to the real values of the system that has been modelled. This will involve actually measuring the

physical values such as power, which the model may have as outputs. These outputs then need to be within a predetermined tolerance of the actual values. This is represented by the "pre-determined criterion" and "output within specification?" stages.

If the outputs are not within the pre-determined criterion, the process needs to be repeated with the inaccuracies established now also forming an input to the development stage. The process may have to be repeated a number of times before a model is established successfully which conforms to the laid down criteria.

According to Snow [29, pp. 1.2/8 − 1.2/9], the monitoring of results is of crucial importance to the success of any energy efficiency operation. This has been proven all over the world in many areas, not only models used for energy management. In addition to this, it must be realised that the monitoring of results is not purely for the verification of models after they have been developed, but should be an on-going process to continually verify that models remain valid under operating conditions that may not stay constant.

Snow continues that once models have been developed and employed successfully, they should not simply be forgotten about and accepted that they are the optimum solution. New technologies are constantly being developed and one should keep abreast of developments, in terms of physical technologies that can be installed to improve profitability as well as technologies that can be used to develop more accurate models.

2.5   MODEL INPUTS AND OUTPUTS

2.5.1   Process Inputs and Outputs
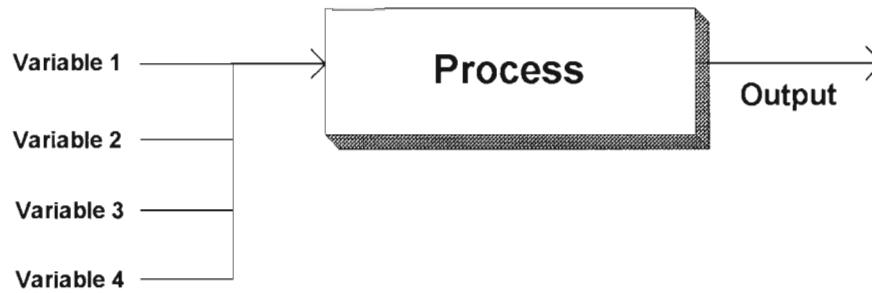
Figure 2.4: Any process that is modelled has a number of inputs and one output

Figure 2.4 represents the methodology regarding process identification. Each process that is to be modelled needs to be identified in such a way that it has a number of variable inputs, but only one output. This simplifies the modular approach and avoids situations of complicated interdependencies of different modules. One would expect the output of a process to be an energy value to facilitate the energy modelling of the system, but seeing that the processes are being broken down to a level of single output modules, only the output of a number of stages would be an energy value. Certain processes may have inputs consisting only of outputs of lower-order processes.

All variables that may influence a certain process need to be considered. Any assumptions or simplifications must be made consistently throughout the modelling process. This implies that the entire modelling process uses a consistent level of detail.

Typical inputs to a process may include physical values such as water flow rate as well as outputs from other processes such as friction head.

2.5.2   System Inputs and Output

The process models mentioned up to now really provide mathematical relationships between physical variables, which may be the outputs of other models and an output value. In the system level however, in addition to manipulating physical values, most of which are outputs of other process models, the model needs to make provision for a number of other kinds of variables.

The system-level models need to include other inputs such as electricity tariffs, production schedules, system and process limitations and constraints, management rules and buffer systems [25, pp. 10 – 12]. Seeing that not all of these values are technical, it is natural to expect that the outputs of these models are not purely technical either. The main outputs of this level of models are electricity usage values, which may be profiles or simply total figures, depending on the required level of detail, as well as buffer checks and final levels.

2.6 PROCESSES, DELAYS AND THE SYSTEM BOUNDARIES
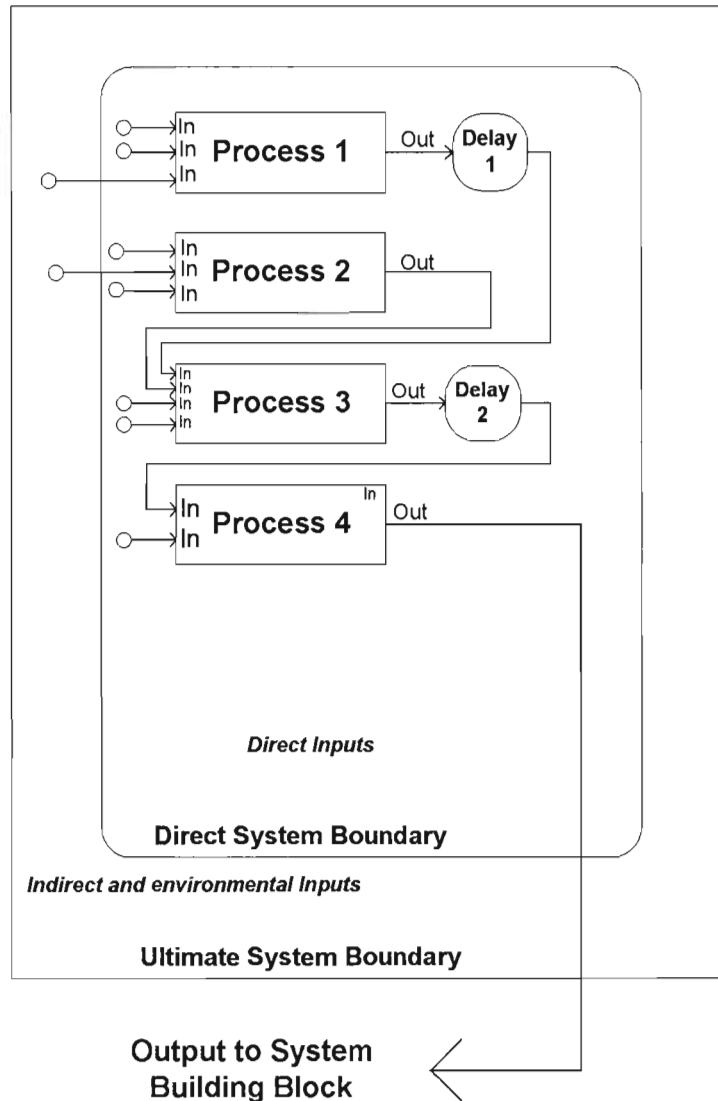
Figure 2.5: Models in context of the system boundaries

In order to keep a clear perspective of the system being modelled, finite system boundaries must be identified. Any system, which is being modelled, has certain inputs, which are obviously part of or relevant to the system. These inputs are represented in Figure 5 as falling within the direct system boundary. Complementing these inputs, are inputs from the ultimate system boundary, which would mainly consist of environmental factors and indirect influences such as management limitations on the specific system.

The general philosophy which is followed is that any delays in the system such as energy storage devices, typically dams, get represented by a process with a single input and output. According to Schweppe and Manichaikul [30, pp. 1439 – 1441], storage structures connected to individual processes are very important processes in their own right. These processes do not perform any function besides buffering. They do however form an integral part of the modelling of the system and so fall within the direct system boundary. An alternative to this is to include a buffer stage with each process for uniformity. If no buffering is relevant to a particular process, the process would then contain a "zero" buffer.

In order to once again maintain a consistent standard, once the ultimate system boundary has been established, it must not be crossed. All inputs and influences on the system that may come from outside the ultimate boundary must be neglected. It is therefore important that careful planning is done when these boundaries are established.

The output indicated is the input to the system level of the hierarchy as shown in Figure 2.1.

2.7   CONSTRAINTS

The models, which are to be developed, are intended to provide instantaneous power values that can be used in whatever mathematical way necessary. Up to now, no mention has been made of the fact that these models can only be valid under certain circumstances. If a dam is empty for example, it is impossible for a pump, which pumps from that dam to operate.

In the mining environment, all models that are developed need to comply with two major sets of constraints, namely physical constraints and management constraints. For the purpose of this study, management constraints do not play a technical role. However, for the models to be valid, they must conform to system and process limitations and constraints.

When a model is implemented it is very important that its operating conditions are verified to be valid for the entire duration of its operation. This ties in very closely with the concept of buffers mentioned earlier. Buffers tend to form one of the main constraints on models. Often buffers have safety limits built in, in case of problems. When the models are executed, it is necessary to ensure that the buffer values will always be within these set tolerances before the models are executed. A practical example of this is the checking of dam levels for the entire time that the models are to operate on the levels of the dams, before providing energy usage outputs.

3.   MODEL DEVELOPMENT

3.1   INTRODUCTION

This chapter describes the mathematics used to develop energy conversion models for all relevant components of the water reticulation system in a deep-level gold mine. In keeping with the input output methodology, models need to be developed to a low enough level for them to have a single output. Most of the developed models have a "friction head" input, and for this reason the "Darcy" model will be dealt with before actual models for physical components.

3.1.1   Fluid-Dynamic Background

The fundamental law that governs any system of fluid flow is Bernoulli's Theorem [31, p. 85], which states that in any system of fluid flow, the total energy in the system at any two points is the same provided that the energy is neither given to nor extracted from the system. When energy losses due to friction and other causes play a role, the theorem makes provision in quantifying the losses as well as energy that gets added to the system in an equation known as Bernoulli's equation [32, pp. 410 − 423]:

$$\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + h_1 + h_w = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + h_2 + h_f + h_{misc-losses} \qquad (3.1)$$

Bernoulli's Equation quantifies all variables in a fluid flow system in terms of equivalent heads that get calculated and equated. Pressure for example is equal to the product of density (ρ), the gravitational constant (g) and water head (h). By making h the subject of the formula, the first term of Bernoulli's equation is found. The terms of the equation represent (from left to right), pressure head before the process, velocity head before the process, natural head before the process, energy added to the system represented by head, pressure head after the process, velocity head after the process, natural head after the process, friction head calculated using the Darcy formula described below and other miscellaneous losses which may be incurred in isolated cases.

3.2 FRICTION HEAD

Friction head is a mathematical means of representing losses incurred in a fluid-dynamic system from physical friction of the fluid within a pipe. These losses are called the system's "friction head", due to the fact that they are represented as an equivalent natural head that could be added to the system to have the same effect. This is in keeping with the Bernoulli Theorem, which equates "head" values.

In order to calculate the friction head of a system, the Darcy formula needs to be used. This formula is such a fundamental part of these systems, it can be seen as a model on it's own which serves as in input to the pumping model defined later. The friction head (Darcy) model is [32, p. 440]:

$$h_f = \frac{(f.L.Q^2)}{3.d^5}$$

with inputs f, L, Q, d and output h_f.
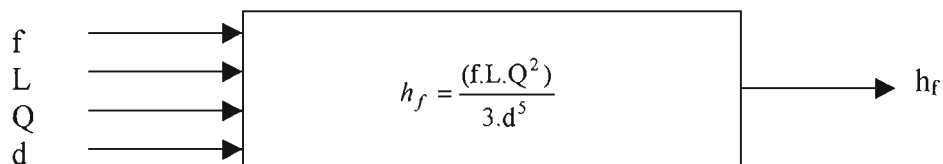
Figure 3.1: Model of Friction Head in Fluid Systems

From this model, one can see that influences on the value of the friction head are the length of the pipe, the flow rate through the pipe and the diameter of the pipe. f represents a constant, dependant on the material of the pipe, which usually needs to be determined experimentally. However applications for which this model will be used are limited to smooth steel pipes used in mining applications. f thus remains constant and can be approximated to 0.02 [33, p. 1271].

3.3 PUMPS

The most fundamental model that needs to be developed in any water-reticulation system is for pumping. In order to generate a pump model it is necessary to examine the function that pumps perform in processes such as the water reticulation system of deep-level mines.

In essence pumps are moving water from one level of the mine to a higher one. This means that the pumps are adding potential energy to the water and so should be seen as devices, which are adding energy to the fluid-dynamic system in which they are present.

The first step in the process of developing an energy conversion model for pumps is to examine which of the heads in the Bernoulli equation will have an influence on the power which needs to be injected into the system. In doing this, a number of approximations can be made.

The first approximation that can be made from the Bernoulli equation is the ignoring of the pressure head. This can be done because the pressure heads in the Bernoulli equation represent the pressure of the fluid before it enters the process and the pressure of the fluid after the process. In other words, referring to equation 1, p_1 would be the pressure of the water in a dam in the mine before it gets pumped. This means that for example, if the dam is 30m deep and the column of water that the pump is pumping up the shaft is 600m high, then the pressure at the outlet of the dam represents a mere 5% of the pressure due to the natural head. The pressure at the outlet at the upper level, p_2 would reduce this value even more, although the pressure at the outlet will not have any head to increase it above atmospheric pressure, seeing that the outlets are generally placed at the top of the dam.

The next approximation that can be made is the omission of the velocity head. This is because the head will not change at all between the two conditions that the system is working. In typical water reticulation systems of deep-level mines, the cross-sectional area of the pipe remains the same from the suction at the lower dam to the outlet at the higher dam. This implies that for a constant value of mass movement, there must be a constant velocity and so the velocity head does not change.

Miscellaneous losses would include added losses in systems that may for example have a number of pipe bends and orifices. These losses will not be included in the pumping model due to the fact that most mining applications have mainly straight, vertical columns of water to pump against and so have most of their losses in pure

frictional losses. This does not mean that these losses should be forgotten about. Some systems may have many different piping configurations and would then need to have the associated losses taken into account. It is not possible to list the losses associated with all the different components that may be found in water reticulation systems and so it would be necessary to research the losses associated with the different devices present in systems where they appear. An example of the head loss that would be present at the widening of a pipe would be calculated using the following formula [34, p. 174]:

$$h_{loss} = \frac{(v_1 - v_2)^2}{2g} \tag{3.2}$$

Where v_1 is the velocity in the narrower part of the pipe and v_2 is the velocity in the wider part of the pipe.

There are thus 2 fundamental heads which play a role in the power that needs to be added to the system by any pumps, namely the natural head, h and the friction head h_f. In order to relate these to the power that needs to be injected by the pump, we need to define power in a fluid system. The power delivered by a pump in fluid system in defined as [35, p. 80]:

$$Power = Q.P \tag{3.3}$$

This simple relationship tells us that the power is equal to the product of the flow rate and the pressure. Defining pressure will complete the model of a pump. The fundamental definition of pressure is [36, p. 3.1/5]:

$$P = \rho.g.h \tag{3.4}$$

Including natural and friction head in h in equation 4, substituting equation 4 in equation 3 and including a factor for the efficiency of the pump leaves us with a rather

robust model of a pump which can be used in the water reticulation systems of deep-level mines:

$$P_{in} = \frac{\rho.g.Q.[h_f + h]}{\eta}$$

Inputs: ρ, h_f, h, g, Q, η → Output: P_{in}
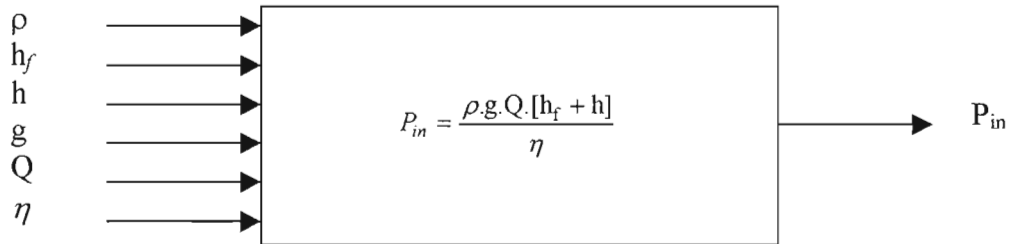
Figure 3.2: Pump Model

The model above requires density, pump efficiency, flow rate, friction head and natural head as inputs. If all of these are not available but delivery pressure, flow rate and efficiency are, then the following model can be used per pump:

$$P_{in} = \frac{Q.P_D}{\eta}$$

Inputs: Q, P_D, η, k → Output: P_{in}
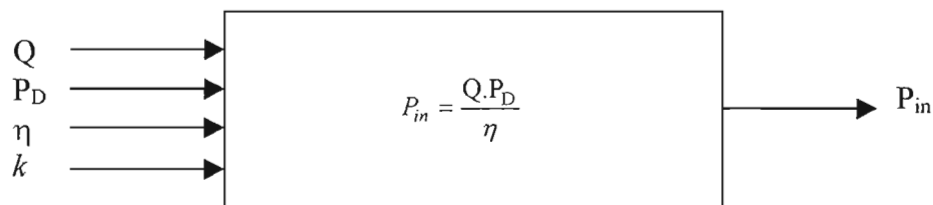
Figure 3.3: Alternative Pump Model

3.4   MULTIPLE PUMPS IN ONE LINE

In configurations where multiple pumps are used to pump water up a single pipe in a mineshaft, one must be aware of the fact that even if identical pumps are used, the increase in flow rate is not proportional to the increased number of pumps. The reason for this is that the flow rate increases with more pumps; friction losses are proportional to the square of the flow rate as shown in figure 3.1. Thus a higher flow rate means a much higher friction head.

From experimental data, it has been determined that the increased flow rate is a bounded exponential relationship. This means that the power used by the system also does not increase linearly with flow rate when more pumps are added.

If more than one pump is present in a single pipeline, and one needs to model the power used in such a system, the flow rate needs to be measured and reduced to the flow rate of a single pump using an equation of the form of equation 3.5. The values of A and k must be determined experimentally by running one and then two pumps alone to generate two separate sets of test figures. Once the equivalent flow rate of a single pump has been determined, the power of a single pump can be found using the pump model and then multiplied by the number of pumps to find the total power used.

$$Flow = A(1 - e^{-k.(pumps)})$$ (3.5)
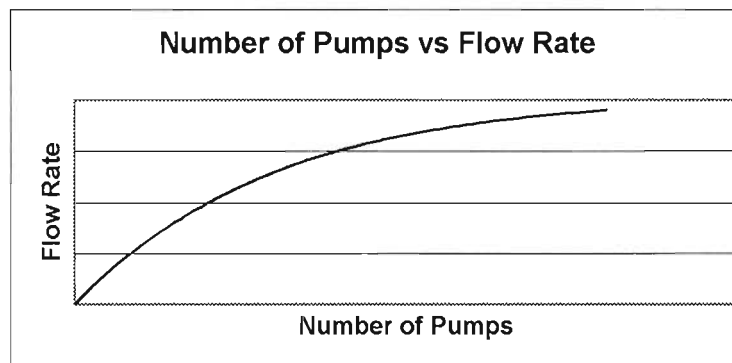
Figure 3.4: Illustration of bounded exponential effect on flow rate when adding parallel pumps in a single line

3.5   TURBINES

Energy recovery is very important in any water reticulation system. The easiest way of performing energy recovery is by using a turbine. The power, which is regained by a turbine, can then be used to either directly drive a pump or first be converted to electrical energy using a generator and then driving an electrical pump. If the power is

converted into electrical energy, it does not only have to be used for pumps, but can be utilised in a number of ways.

Turbines are very similar to pumps in the sense that they convert power in fluids to mechanical and then electrical power, where pumps convert electrical and mechanical power into power within a fluid. It thus makes sense that the same factors influence the turbine model as the pump model. The system is still a fluid system for which the Bernoulli equation must hold. Only in this case the energy is not being added to the system, but removed as an additional loss.

The same simplifications hold for the generation of a turbine model as for the generation of a pump model. Velocity and pressure heads can be ignored. The value for f can still be assumed to be 0.02. In this configuration however, the heads cannot be added. The pump model requires the natural head to be added to the friction head. For turbines the turbine is using the natural head to generate power and the friction head is still a negative influence to the available power. For this reason the friction head needs to be subtracted from the natural head and the efficiency factor needs to be moved to the numerator of the model as the power obtained from the turbine will be less than the power available in the fluid system.

ρ
h_f
Q
h
η_t
g

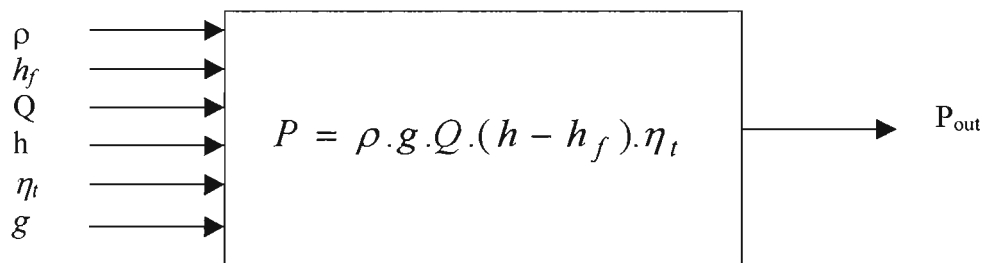$$P = \rho . g . Q . (h - h_f) . \eta_t$$

P_{out}

Figure 3.5: Turbine Model

If the turbine is directly coupled to a pump, then the power produced by this model can simply be used as the pump input power. If the turbine however drives a generator, the generator will have a single input and output, both being power, and therefore merely add an efficiency factor to the output power of the turbine, as follows:

P_{in}

η_m

$$P_{out} = P_{in} . \eta_m$$

P_{out}
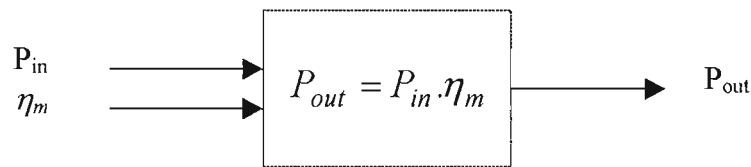
Figure 3.6: Motor Model

Baker-Duly, Ramsden and Mackay [37, p. 384], mention that part of the potential energy of the water passing down the shaft is in thermal form. They continue that this means that an added benefit of using energy recovery systems such as turbines is that it reduces the energy required to cool the water in the fridge plant of the mine.

3.6   THREE CHAMBER PIPE FEEDER SYSTEM

The 3 Chamber Pipe Feeder System (3CPF), is not very widespread due to its complexity and cost. This system goes a step further from the directly coupled turbine-pump configuration, in that it actually uses the head of chilled water passing down the shaft to balance the head of warm water which needs to be pumped up the shaft, using the U-tube principle [13, p. 422]. At present the only fully-functional 3CPF system in South Africa is used in the Tshepong mine in the Freestate. The system consists of 3 high-pressure chambers located on 45 level of the mine, each having a capacity of 16 kl. In a process of sequential pressurising and depressurising, the chambers are filled with the warm water that needs to be drained to the surface. This warm water then gets pressurised to 13,7 MPa, the chilled water, which is at the same pressure due to its head, is allowed to flow down the shaft and into the chamber. This displaces the hot water to the surface with the help of two 800 kW pumps, which are used to overcome friction and other losses. At the same time the other chambers are being filling with warm water and emptying chilled water at low pressure

[38, pp. 10 – 20]. One of the pumps is on surface and the other on 45 level of the mine, at the same level as the underground hot and chilled water dams.
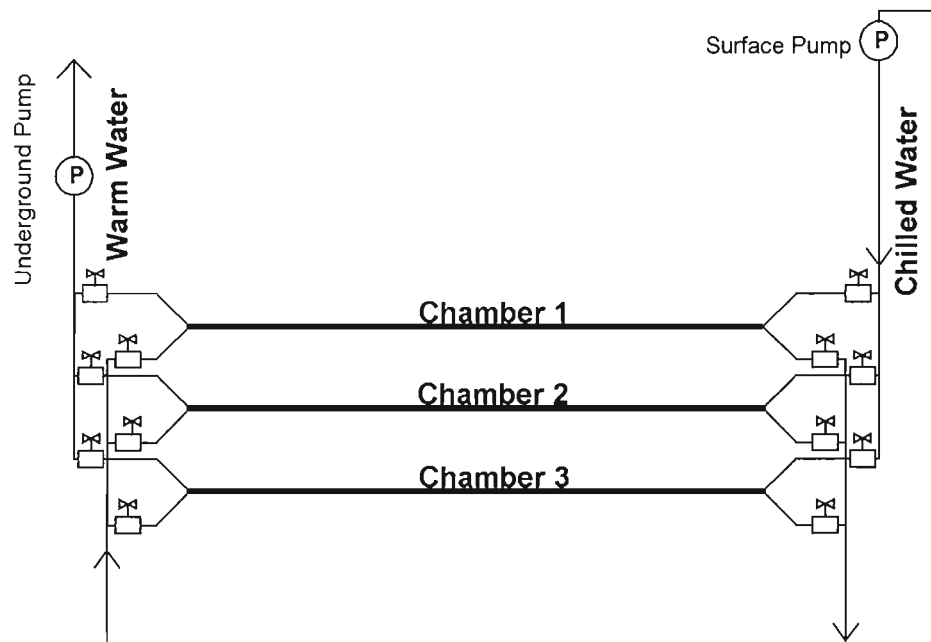
Figure 3.7: Three Chamber Pipe Feeder System

The head of chilled water is used to balance the head of warm water that needs to be drained up the shaft. Relatively small pumps are used to overcome friction and other losses in the system. These pumps can be modelled using the standard pump model shown earlier.

In order to model the 3CPF, it must be realised that it uses potential energy in the downward chilled water column to balance the warm water head. This prevents the need for most of the energy in conventional pumping systems, namely to overcome the head, h. The purpose of the pumps are to overcome the friction head. The same simplifications hold as for normal pumps regarding being able to ignore pressure head and assuming f in the Darcy equation to be 0.02. The pumps are also there to overcome all other losses such as the imperfect efficiency of the entire system, due to amongst others the pressurising, depressurising and valve switching. The model for the pumps would thus be:
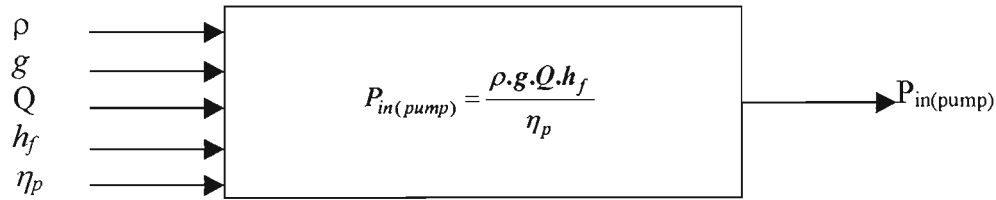
Figure 3.8: 3CPF Pump Model

Note the absence of the natural head, h in the pumping power model. The friction head can be calculated using the friction head (Darcy) model, it must be remembered that the downward and upward pipe lengths must be added; the heads balance out but total friction and other losses still need to be taken into account.

In general, one would expect more than one pump per 3CPF due to the size and associated flow of the system. In a system such as the one installed at Tshepong mine, two pumps are in place, one on surface pumping chilled water down and the other on the same level as where the 3CPF is installed – in this case 45 level of the mine. These pumps are thus not in parallel, the way pumps are generally added to increase flow rate, but in series. This means that the total flow of multiple pumps cannot be calculated using the bounded exponential model described earlier for multiple pumps. In this case, the pumps must be treated individually and the total load shared proportionally between them. In the Tshepong example, this means that the downward friction head gets used as an input to the model that will be used for the surface pump and the upward friction head gets used for the 45 level pump.

The 3CPF model however does not consist of only friction heads and pumps. It has a number of other losses associated with its operation. The causes of these losses include the switching and the many bends found in the 3CPF system. All such additional losses can collectively be quantified in an efficiency factor for the 3CPF as follows:

$$P_{in} = \frac{P_{in(pump)}}{\eta_{3CPF}}$$

$P_{in(pump)}$

η_{3CPF}

P_{in}
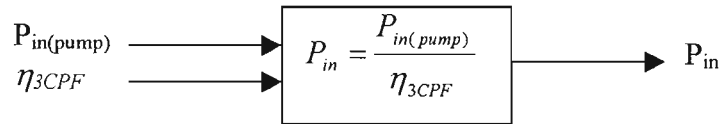
Figure 3.9: 3CPF Model

The model shown above is very useful in keeping with the modular methodology. This however may not always be possible. In fact, in systems such as the one installed at Tshepong Mine, available data is not precise and defined enough to be able to precisely determine all the variables of the pump models. This complicates properly distinguishing between the efficiencies of the pumps and the efficiencies of the 3CPF system. For this reason, it simplifies circumstances by simply including the losses of the 3CPF in the pump efficiencies.

3.7   STORAGE / BUFFER MODEL

In any system that is being modelled, it is important to take careful note of all constraints present. Before any models can be implemented successfully, it is important to verify that they will be valid for the entire period that they are proposed to operate.

The main constraints that can be mathematically represented in the modelling of the water reticulation system of a deep-level gold mine are the dam levels. The system component models all operate with the assumption that there is enough available water from their source and that they are not overfilling any dams.

Summing the inflow, outflow and initial level of all storage devices and ensuring that the results obtained are within set tolerances before calculating the energy usage, ensures that the models will in fact produce reliable, valid results.

Roos [3, p. 121] quantifies this in a model he developed for any general storage process. The following is a slightly modified version of Roos's model:

$$Contents = \sum \int InflowRate - \sum \int OutflowRate + InitialContents$$

Figure 3.10: Storage / Buffer Model

This model is general enough for it to be able to be continuously implemented. It is important to ensure that the integration period used is a small enough interval for the buffer not to exceed its limits during that time. Using the small enough interval in the model, means that the model will need to be repeated a number of times to completely verify the other models for the full duration of their operation. The summations in the model are in case a storage device has more than one input and output.

Giles and Wunderlich [39, pp. 40 – 45], point out that storage devices such as dams have more inputs and outputs than initially meet the eye. In addition to the conventional inlets and outlets to dams, one must keep track of other factors such as ground water being added as well as seepage losses occurring from the dams.

Giles and Wunderland continue to stress the importance of the storage model as it is not only a constraint which must be adhered to, but if utilised correctly, can form a reasonable cost saving tool. When energy recovery systems such as turbines are in place, stored water can be used to add energy to the water reticulation system in times of high demand and so reduce total energy costs.

4.   MODEL VERIFICATION

4.1   INTRODUCTION

The purpose of this chapter is to prove that the mathematical models developed in the previous chapter are in fact valid. This is to be done by using live data gathered at Anglogold's Tshepong and Kopanang mines.

4.1.1   Measurement Accuracy

In order to successfully verify mathematical models, it is imperative that test data used is accurately measured and gathered. According to Dressler, Ferenczy, Olver and Turner [40, pp. 6 – 7], the ultimate accuracy achievable in South Africa, for any kind of measurement, is limited by the quality of the national measuring standard for the relevant unit of measurement. Since the most important user of calibrated measuring equipment is industry, the accuracies of the various national measuring standards are determined by industry's stated demands.

Measurements taken on the water reticulation systems in the gold mining industry vary greatly depending on the size, age and budget of the individual mines. These measurements range from crude plots on graph paper to electronically gathered data stored to four decimal places on SCADA systems. One such mine is Tshepong. Tshepong's SCADA system stores comprehensive data of the water reticulation system. The mine also has a three chamber pipe feeder system installed, making it the perfect case study to verify the generated models.

Kopanang mine in the Vaal River Region makes extensive use of turbines. They also have data available on-line, which can be used to verify the turbine model.

This study is aimed at a 90% accuracy so mines such as these which regularly maintain their systems to ensure that they are within the national measuring standards will easily provide data accurate enough to verify models aimed at a 90% accuracy.

4.1.2 Case Study Details

The philosophy, which is to be followed in the verification of the models, is to use two different time case studies of Tshepong Mine for all models except the turbines. The individual turbine models are to be verified using two different time case studies of Kopanang mine. Two full day's data is used for each case study. The particular case studies chosen were chosen randomly from sets of available archived data:

Case study 1 dates: 27 – 28 July 1999.
Case study 2 dates: 16 – 17 May 2000.

4.2 INDIVIDUAL MODEL VERIFICATION

4.2.1 Introduction

The individual models developed are building blocks of a much greater system. For the models to be valid in any configuration, it is important to verify that each one is individually valid. For this reason, this section confirms the validity of each model developed in chapter 3 with the exception of the Darcy model, which by definition must be used as an input to one of the other models. There is numerous literature validating the Darcy model, as mentioned in section 3.2.

4.2.2 Pumping Model Verification

A problem, which one is faced with when attempting to verify the pumping models, is the fact that the efficiencies of the pumps are not readily available. For this reason it is necessary to use one set of test data to determine the efficiency of the pump and then another set of data for the actual verification using the efficiency already determined. The second set of data should be of a similar pump, allowing the efficiency determined for one pump to still be valid. According to Garay [41, pp. 198 & 258], a range of efficiencies of 55% - 75% is seen as normal for centrifugal pumps.

Referring to figure 3.1 and figure 3.2, the following data was used to determine efficiencies:

Table 4.1: Tshepong 66-level pump 1 data to determine pump efficiencies

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	640.1 m
	Flow Rate	Q	0.103 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*8.6 m*
Pump	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.103 kl/s
	Natural Head	h	640.1 m
	Input Power	P	1015 kW
Model Result	*Efficiency*	η	*65%*

Using the pumping and Darcy models, one can see from the table that the efficiency of the pump is well within the range mentioned above. This efficiency will now be used as an input to a pumping model verified on a similar pump working under different conditions.

Table 4.2: Tshepong 66-level pump 2 data to verify pump model

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	F	0.02
	Pipe Length	L	640.1 m
	Flow Rate	Q	0.142 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*16.4 m*
Pump	Water Density	ρ	1 kg/l
	Gravitational Constant	G	9.81 m/s^2
	Flow Rate	Q	0.142 kl/s
	Natural Head	h	640.1 m
	Efficiency	η	65%
Model Result	Input Power	P	*1,407 kW*
Actual Value	Input Power	P	*1,379 kW*

Table 4.2 shows us that using the generated model depicted in figure 3.2, the power of 66-level pump 2 is calculated to be 1,407 kW. This represents an accuracy of 98%.

4.2.3   Multiple Pump Model Verification

The multiple pump model can be verified using values obtained with different numbers of similar pumps pumping together on 66-level of Tshepong mine. In order to test the validity of this model, the unknown constants, *A* and *k* of bounded exponential equation 3.5 need to be determined. There are two unknown variables in this equation and therefore two data points need to be used to determine the unknowns. The result can then be verified by using a third data point as a test point.

The two data points decided upon for determining the two unknowns, are data for running only one of the 66-level pumps, and data for running three of the 66-level pumps simultaneously. Once the unknowns have been determined, they are to be tested by substituting data for running two of the 66-level pumps into the bounded exponential equation, and comparing the flow rate calculated to the actual measured flow rate when two of the 66-level pumps are running. Equation 3.5 is repeated for ease of reading:

$$Flow = A(1 - e^{-k.(pumps)}) \tag{4.1}$$

The unknowns are *A* and *k*. The following data is used to solve these two unknowns as described above:

Table 4.3: Data for multiple pumps

DATA SET 1	DATA SET 2
Flow = 102.5 l/s	Flow = 270.5 l/s
Number of Pumps = 1	Number of Pumps = 3

From these values it was found that A = 817.3 and k = 0.314

When the model was tested using two pumps and the determined values of *A* and *k*, it predicted that that the flow rate would be 192.1 l/s. The measured flow rate of two pumps running together was 195.1 l/s. This represents an accuracy of 98.5%.

4.2.4   Turbine Model Verification

Tshepong mine does not make use of turbines at all due to the three chamber pipe feeder system in use there. For this reason data to verify this model had to be obtained from Kopanang mine. Kopanang does not have the same level of accurate, on-line data as Tshepong, but it does have accurate, manually measured data of the turbuines present on its 38-level. The data available from Kopanang, is basically flow rate through and power delivered by the turbines. This is sufficient for the model shown in figure 3.5 as all other required values are physical values, which can be measured or calculated.

The same philosophy will be followed as was in the verification of the pumping model to verify the turbine model. One set of data will be used to determine the typical efficiency of the turbines installed at Kopanang. This efficiency will then be used as an input to verify the turbine model using data of another turbine.

Table 4.4: Kopanang 38-level turbine 1 data to determine turbine efficiencies

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1161 m
	Flow Rate	Q	0.125 kl/s
	Pipe Diameter	D	0.4 m
Darcy Result	*Friction Head*	h_f	*11.8 m*
Turbine	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.123 kl/s
	Natural Head	h	1161 m
	Output Power	P	986 kW
Model Result	*Efficiency*	η	*70%*

This efficiency will now be used as an input to a turbine model verified on a similar turbine working under different conditions. In the configuration present in Kopanang the turbines are used to directly drive pumps. This means that the 986 kW produced by this turbine can be used as the input to a pump model once all the other inputs are available. The next table shows data using the 70% efficiency, proving that the turbine models are accurate.

Table 4.5: Kopanang 38-level turbine 2 data to verify turbine model

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1161 m
	Flow Rate	Q	0.180 kl/s
	Pipe Diameter	D	0.4 m
Darcy Result	*Friction Head*	h_f	*24.5 m*
Turbine	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.180 kl/s
	Natural Head	h	1611 m
	Efficiency	η	70%
Model Result	Output Power	P	*1,404 kW*
Actual Value	Output Power	P	*1,361 kW*

When the output value of the turbine model is compared to the actual value obtained when it was measured, we see that it is 97% accurate.

4.2.5   Three Chamber Pipe Feeder System Model Verification

The principle of the 3CPF system in that it does away with the natural head, *h*, that pumps usually have to pump against. Verifying this model promises to be very interesting due to the fact that the only remaining head is that of friction, which is usually much less that the natural head in similar vertical applications. This verification should help to prove whether or not the major loss in vertical-load pump applications can really be eliminated if it is balanced out.

Seeing that the 3CPF has two pumps in series, and the proposed model states that the load must be shared proportionally between the pumps, half the total friction head will be used for each pump. The 3CPF by definition has to have an equal amount of water moving up and down the shaft at any given time. Data from Tshepong mine however shows that on average that the chilled water flow rate passing down the shaft is 25 l/s higher than the warm water being pumped up the shaft. The reason for this is that a certain amount of extra water is allowed to flow down the shaft and emptied into the chilled water dams on 45-level through dissipaters. This water is used to make up water, which is lost to earth absorption. This water is continuously replaced by

purchasing additional water from the Rand Water Board. This additional water passes through the surface pumps, increasing the flow rate of the surface pumps. The additional downward flow rate also confirms that the mine also does not have an increase in total water volume due to fissure water. Water is also lost due to evaporation in the pre-cooling towers. This loss however does not result in any additional flow rates because the Rand Water gets added at the same point in the system.

Once again, the philosophy of the verification process will be to use measured data to determine the efficiency of one pump. This efficiency will then be used as an input to the model to be verified when employed on a similar pump. The 3CPF system has two similar pumps installed and so this process will be possible. The data for the surface pump is as follows:

Table 4.6: 3CPF system surface pump data to determine pump efficiency

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1372 m
	Flow Rate	Q	0.299 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*155.7 m*
Pump	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.299 kl/s
	Natural Head	h	0 m
	Input Power	P	660 kW
Model Result	*Efficiency*	η	*69.1%*

As mentioned previously in paragraph 4.2.2, this efficiency is well within the reasonable range for centrifugal pumps. This efficiency will now be used as an input to the model when it is employed on the underground pump:

Table 4.7: 3CPF system 45-level pump data to verify 3CPF pump model

MODEL	INPUT	SYMBOL	VALUE
Darcy	Constant	f	0.02
	Pipe Length	L	1372 m
	Flow Rate	Q	0.274 kl/s
	Pipe Diameter	D	0.35 m
Darcy Result	*Friction Head*	h_f	*130.7 m*
3CPF Model	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Flow Rate	Q	0.274 kl/s
	Natural Head	h	0 m
	Efficiency	η	69.1%
Model Result	Input Power	P	*508.4 kW*
Actual Value	Input Power	P	*505.0 kW*

The model predicts an input power of 508.4 kW and the actual value measured was 505.0 kW. This represents an accuracy of 99.5%.

4.2.6   Storage / Buffer Model Verification

The process followed in verifying the storage and buffer model shown in figure 3.10 was to simulate the level of a number of the dams in Tshepong mine and then to compare the simulated results to the actual measured dam levels of the same time. The model basically integrates the total inflow and outflow rates of any storage device. In order to realistically implement this model in the mining environment, a computer algorithm was developed which integrated the resulting flow rate every minute and kept a running total of the resulting dam level. The algorithm makes provision for rather versatile scheduling and flow rate inputs. Operating schedules for the days that were simulated were obtained from Tshepong as well as actual data of the dam levels of interest.

The first set of conditions used to simulate this model were the 66-level hot water dam of Tshepong mine, over a period of 24 hours from 00:00 on 28 July 1999 to 23:59 on 28 July 1999. The results are as follows:
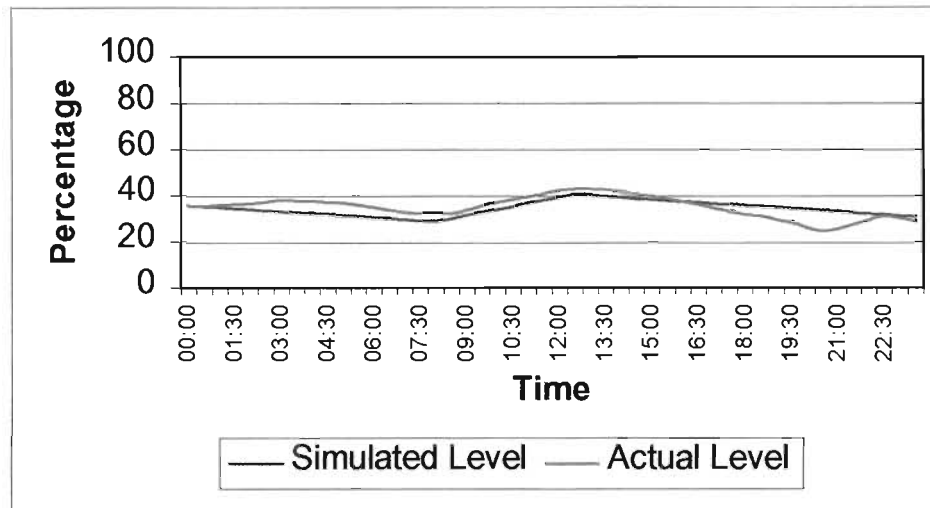
Figure 4.1: Simulated and actual Tshepong 66-level hot water dam level

As can be seen from the graph the simulated dam level is far more linear than the actual level. The main reason for this is that the flow rate from production, which actually fills the dam is not linear. It is dependent on a number of factors such as the delay time for the water to reach the shaft bottom from each different level and physical path, which the water has to follow from each level. In the simulation a constant flow rate into the dam was accepted. The overall simulated profile of the level seems to be reasonably similar to that of the actual profile. In fact, the average value of the simulated dam level is 34.53%, while that of the actual level is 35.36%. This represents an error of only 2.35%. Another important success of the simulation is that the final values of the actual and simulated conditions are very close. The actual final dam level is 29.1% and the simulated value is 30.8%.

The second set of conditions used to verify the model were the 45-level hot water dam of Tshepong mine, over a period of 24 hours from 00:00 on 16 May 2000 to 23:59 on 16 May 1999. The results are as follows:
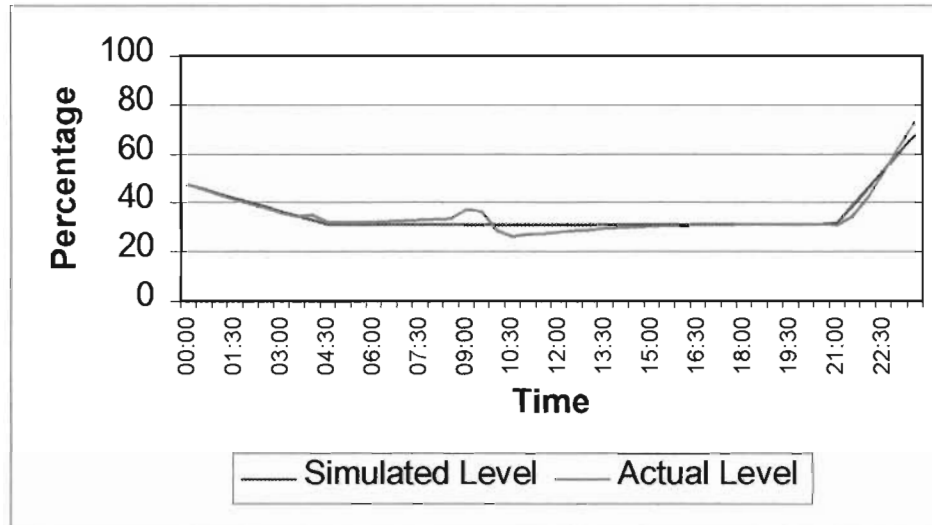
Figure 4.2: Simulated and actual Tshepong 45-level hot water dam level

From figure 4.2 it is apparent that the simulated profile follows the actual profile much more closely than the previous verification using the 66-level dam. The main reason for this is that the 45-level hot water dam does not have nearly as many unknown inputs as the 66-level dam. The profile of the 66-level dam is very subject to the delay of water from the workings as well as losses and gains from ground water. The 45-level hot dam basically has the 66-level pumps as an input and the three chamber pipe feeder system as an output. For this reason, as long as the flow rates of the pumps which are involved stay constant, the change in dam level will remain linear.

It is interesting to note that the average simulated level of the 45-level hot dam is 35.19% and the actual average level is 34.67%. The final level of the dam was once again also very successfully simulated. The simulated final level is 73.63, while the actual final level is 72.46%. Having a simulated value higher than the actual value is more desirable than visa versa. This is because the safety factor of the dam will be reached sooner, preventing overflows sooner.

It must be remembered that the main purpose of this model is to verify that the conditions for the rest of the models, which have been developed in this study, are valid. It is thus important for this model to in itself be accurate. From the findings in this section, it is clear that this is indeed so and the rest of the models developed in the study can be used with confidence once their operating validity has been checked by this model.

4.3   INTEGRATED MODEL VERIFICATION

4.3.1   Introduction

At this point, we have established that the models developed are indeed accurate when used individually. The point of the study however is to be able to use these models in any combination. This section provides verification that these models can indeed be used together to form a powerful tool.

The method used to verify the models working together is to use the models in a combination representing the entire water reticulation system present at Tshepong mine in the Freestate. Once all the relevant model inputs have been obtained for a period of operation, the corresponding power usage values for the system will be determined from the models. These power usage values will then be summed together and applied to the tariff applicable for Tshepong mine. The total electricity cost will then be determined and compared to the actual electricity cost for pumping experienced by the mine for the relevant month.

Both case studies mentioned in section 4.1.2 will be used to ensure that the models work with entirely different sets of data.

4.3.2   Case Study: Tshepong 27-28 July 1999

Two full production days' data was used for this case study. The flow rates responsible for energy consumption are shown in the following graph:
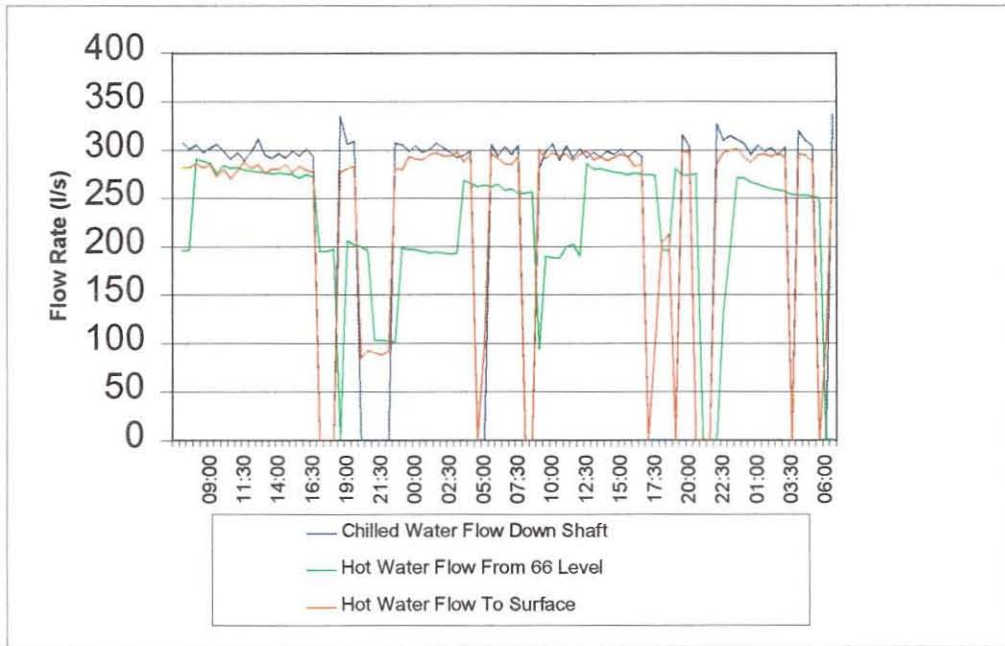
Figure 4.3: Flow rates responsible for energy consumption at
Tshepong mine for 27 – 29 July 1999.

It can be seen in Figure 4.3 that the profiles of the water flowing to and from the surface correspond. This is naturally because they are both as a result of the operation of the three chamber pipe feeder system, which by definition has the two flows running together.

The number of pumps operating together on 66-level at any time is determined by inserting numerical filters at 150 l/s and 230 l/s. The number of pumps is then used in the bounded exponential relationship of equation 3.5 to determine the equivalent flow rate of a single pump. The energy consumption of one pump is then multiplied by the total number of pumps to obtain the total energy consumption at any particular time.

Using the models developed with the flow rates shown in figure 4.3 as well as all the other relevant physical model inputs, the following demand plot is obtained:
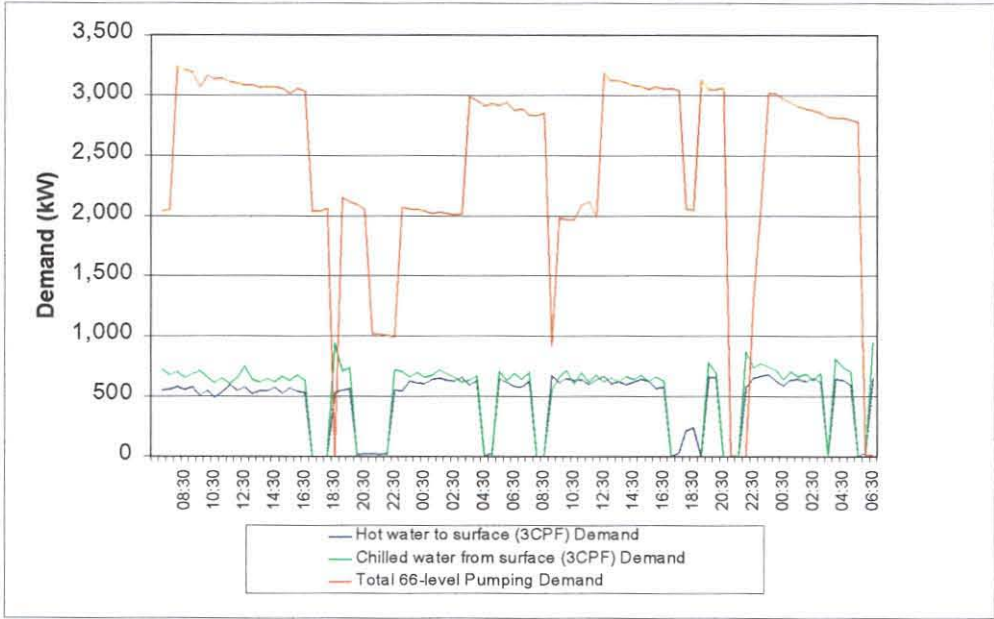
Figure 4.4: Demand plots of pumps for 27 – 29 July 1999

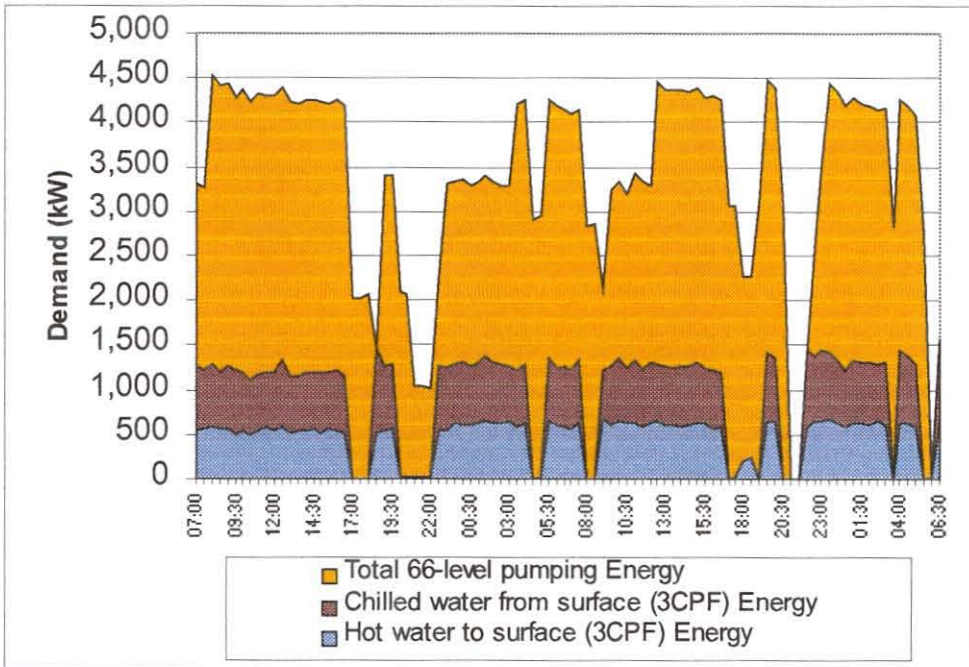Summing these profiles produces the following disaggregated pumping load profile:

Figure 4.5: Total Disaggregated pumping energy profile for 27 – 29 July 1999

From the data presented in figure 4.5 one can see that the highest value is 4,520 kW, which represents the pumping maximum demand for the two days. Integrating the profile produces 163,435 kWh of energy used in the two days.

The energy that has been calculated is for two consecutive full-production days. To approximate a full month, this needs to be multiplied by 11 (for 20 full-production days and 2 half-production days per month). The total energy consumed per month for pumping at Tshepong under these typical conditions is thus:

163,435 x 11 = 1,797,785 kWh

The maximum demand should not change from the two typical sample days and so 4,250 kW will be used, seeing that it occurred in a peak time. At the time of the test data, Tshepong mine was on Eskom's Nightsave tariff. The following is a calculation of their total electricity costs:

1,797,785 kWh x 7.46 c/kWh	R134,114
4,520 kW MD x R46-26 / kW	R209,095
Sub Total	*R343,209*
Total After Voltage Discount (3.3%)	**R331,884**

Figure 4.6: Total simulated electricity costs

The actual cost of electricity used for pumping by Tshepong in July 1999 was R330,908. This figure is 99.7% accurate.

4.3.3   Case Study: Tshepong 16-17 May 2000

Once again two full-production days were sampled to obtain typical profiles of the flow rates that are responsible for most of the energy consumption of the water reticulation system of Tshepong.

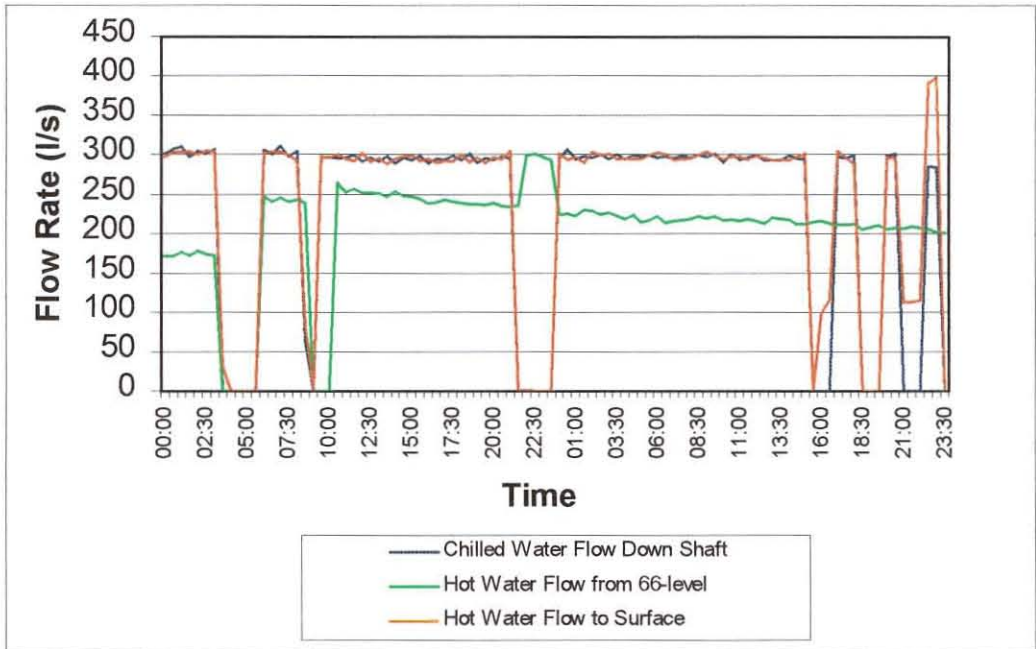The following is a plot of these flow rates:

Figure 4.7: Flow rates responsible for energy consumption at the indicated times on
16 – 17 May 2000

Again, it is interesting to note that the flow rates of the cold water flowing down the shaft and the warm water flowing to surface match almost exactly because of the three chamber pipe feeder system.

The sudden rise in the hot water flow to surface shown in figure 4.7 at approximately 22:00 on 17 May 2000 can only be ascribed to a possible error in the data.

The number of pumps operating together on 66-level at any time is once again determined by inserting numerical filters. The numerical filters have been inserted at 190 l/s and 270 l/s for this case study. As before the number of pumps is then used in the bounded exponential relationship of equation 3.5 to determine the equivalent flow rate of a single pump. The energy consumption of the equivalent one pump is then multiplied by the total number of pumps to obtain the total energy consumption at any particular time.

Using the models developed, the following is a plot of the demand for the two sample days of the water reticulation system of Tshepong:
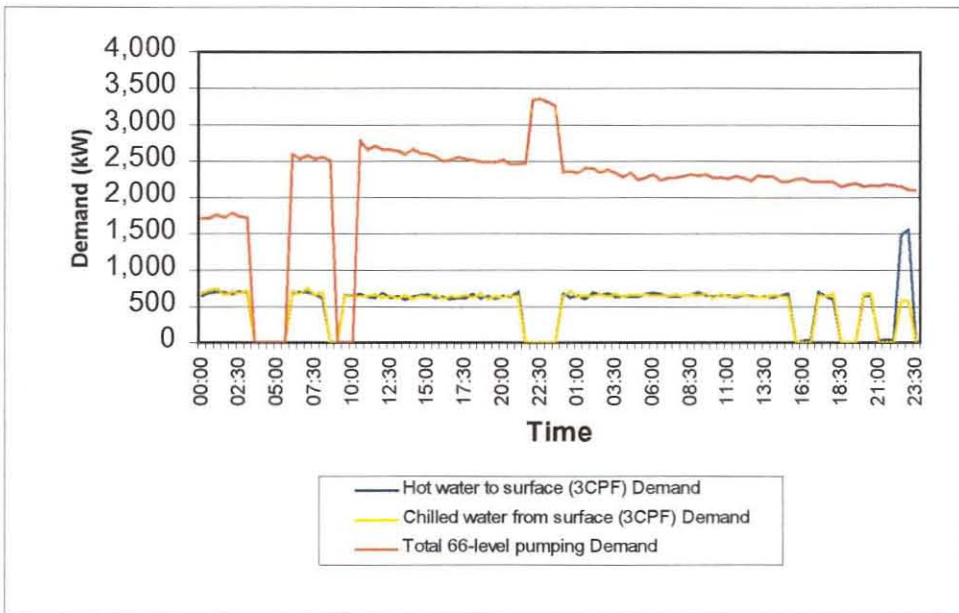
Figure 4.8: Demand plots of pumps on 16 – 17 May 2000

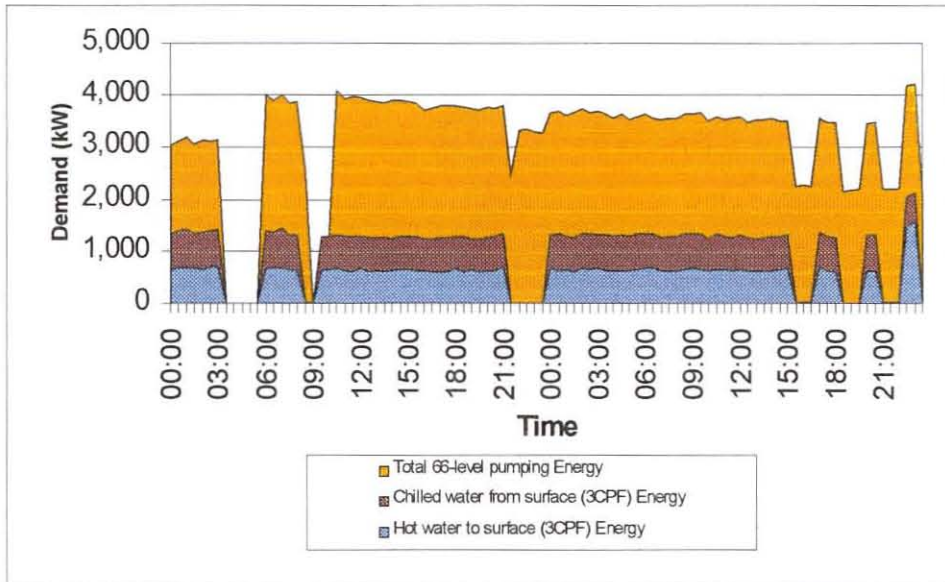Summing these profiles produces the following disaggregated pumping load profile:

Figure 4.9: Total Disaggregated pumping energy profile for 16-17 May 2000

At the time of the case study, Tshepong mine was using the Eskom Nightsave tariff. According to this tariff, MD is only charged for load during peak times. As can be seen from Figure 4.9, the maximum demand of the water reticulation system during peak times occurred at 10:30 on 16 May 2000. This maximum demand was 4,087 kW. Integrating the profile produces 152,997 kWh of energy used in the two days.

As before, the energy that has been calculated is for two consecutive full-production days. To approximate a full month, this energy is multiplied 11 (for 20 full-production days and 2 half-production days per month). The total energy for the May 2000 is thus 152,997 x 11 = 1,682,967 kWh

The maximum demand is accepted to be 4,087 kW. The following is the calculation of the mine's total pumping electricity cost for May 2000:

1,682,967 kWh x 7.87 c/kWh	R132,449
4,087 kW MD x R49-46 / kW	R202,143
Sub Total	*R334,592*
Total After Voltage Discount (5.33%)	**R316,758**

Figure 4.10: Total simulated electricity costs for May 2000

The actual cost of electricity used for pumping by Tshepong in May 2000 was R327,460. This represents an accuracy of 96.7%.

4.3.4   Contribution to Maximum Demand

In both case studies (4.3.2 and 4.3.3), it was accepted that the maximum demand of the pumping profile can be used as the maximum demand figure used to calculate the cost of the maximum demand. This is in fact not entirely correct because the water reticulation system electricity usage is not billed separately to the rest of the mine. A more accurate method would be to calculate the *contribution* to maximum demand at the time that the whole mine experiences a maximum demand. This ties in with the adherence to the context of the models.

For the purpose of the case studies used in this verification however, the maximum demand of the pumping system occurs during the main production cycle of the mine. The energy consumption stays at reasonably constant maximum level for much of the production cycle and for this reason, using the maximum demand of the pumping system in these cases produces accurate results. Shifting this pumping maximum demand should be addressed for cost savings.

5.   APPLICATION EXAMPLES

5.1   INTRODUCTION

Energy conversion models have been developed and verified for different components in a water reticulation system that could be found in a deep-level gold mine. It has also been verified that they operate together successfully. What becomes important now, is to demonstrate what use these models actually are to us by using examples of how they can be employed to save electricity costs to the mine.

This chapter uses case study data presented in the previous chapter to show examples of how the models can be used to reduce the cost of electricity. This is not only done by adjusting schedules, but also by showing the effect on the cost of pumping that changing physical parameters could have. Depending on the cost of changing physical components, it becomes possible to decide if it will be viable making such changes. This also extends to how these models can be used to evaluate different proposed systems for future installations.

In installations where data of flow rate and power consumption are available, these models can be altered to have the efficiency as an output. This will aid the mine in determining the condition of the pumps by monitoring the efficiencies of the pumps. Once the efficiencies drop below a specified level, the pumps would need to be seen to. This may used to indicate the need for routine servicing or damage to the pump.

The examples used in this chapter are all based on data obtained from the Tshepong mine case study of 27-28 July 1999. For demonstration purposes, in each example, all variables will be kept constant apart from the variables that are specifically being changed.

The variables that have been used as inputs to the models for this chapter are summarised in the following table. Naturally the variables relevant to each example are not kept constant.

Table 5.1: Summary of variables used in examples

COMPONENT	VARIABLE	SYMBOL	VALUE
Shaft Bottom Pumps	Constant	f	0.02
	Pipe Length	L	640.1 m
	Flow Rate	Q	0.250 kl/s
	Pipe Diameter	D	0.35 m
	Number of Pumps	No	3
	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Efficiency	η	65%
	Natural Head	h	640.1 m
3CPF	Flow Rate	Q	0.295 kl/s
	Pipe Length	L	1372 m (x2)
	Water Density	ρ	1 kg/l
	Gravitational Constant	g	9.81 m/s^2
	Constant	f	0.02
	Natural Head	h	0 m
	Efficiency	η	69.1%
	Pipe Diameter	D	0.35 m

The pumping profiles used for all the examples presented in this chapter are the same as those shown in figure 4.5, which represents two days' actual data. The only variations to the profiles will be in the illustration of savings, which can be brought about by schedule changes.

5.2 THE EFFECT OF PIPE DIAMETER ON ELECTRICITY COST

Tshepong mine has 350 mm pipes installed up and down the shaft for its water transportation. According to Darcy model shown in figure 3.1, the friction head incurred by these pipes is proportional to the 5th power of the diameter. The following figure demonstrates the effect that changing this would have on the cost of electricity at a mine such as Tshepong. All other variables and schedules remain the same.
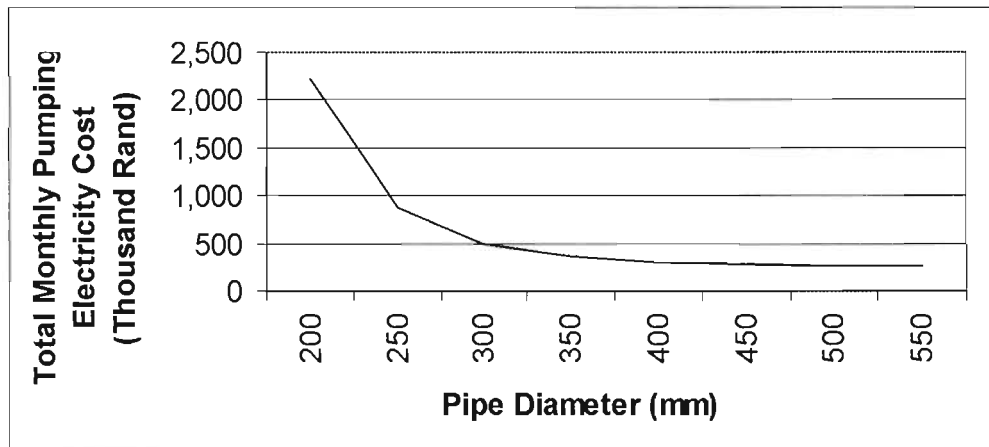
Figure 5.1: Total monthly pumping electricity cost as a function of pipe diameter

As can be seen from the figure 5.1, the 350 mm pipes, which Tshepong have installed are reasonably efficient. Depending on the cost of changing the diameter of the pipes, they can now decide if it would be worthwhile doing this. Once the pipe diameter is above 300 mm, the friction head becomes reasonably small compared to the natural head. It is also very informative to notice how enormous the cost of electricity for pumping would be if the pipe diameter were too low.

5.3 THE EFFECT OF EFFICIENCY ON ELECTRICITY COST

McKechnie [42, p. 3.2/5] mentions that dirty water pumps in underground operations are very large consumers of electrical energy. This can be explained by the low efficiencies of such pumps.

In the water reticulation system of Tshepong mine, two efficiencies are identified, which have the greatest effect on the cost of electricity. These are the efficiencies of the shaft bottom pumps, which are assumed to be identical and the efficiencies of the pumps driving the three chamber pipe feeder system. The efficiencies listed in table 5.1 were determined in the model verification process. For the purpose of this example, the two efficiencies will be varied individually while keeping the one not being varied constant at the value shown in table 5.1.

5.3.1   Shaft Bottom Pump Efficiency effect

The following figure shows the effect of varying the efficiency of the shaft-bottom pumps on the total cost of electricity for pumping.
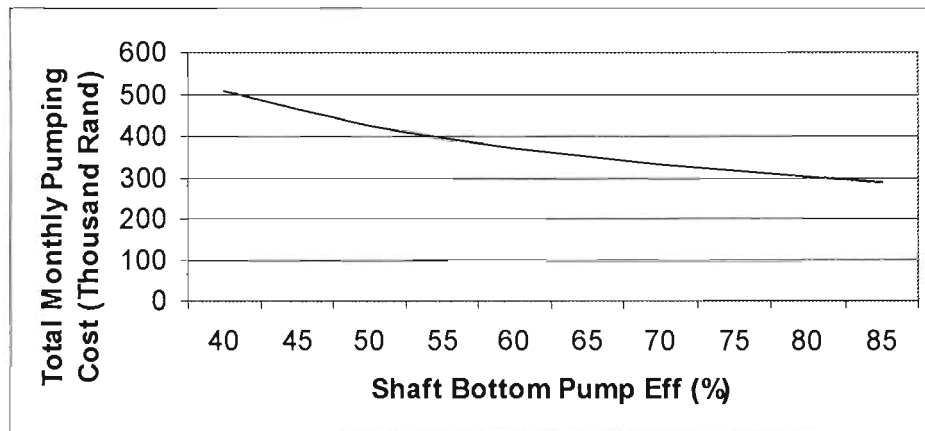
Figure 5.2: Total monthly pumping cost as a function of shaft bottom pump efficiencies

By ensuring that there is no wear on the pumps and that they are using very efficient impellers, a rather significant difference can be made to the monthly pumping costs. Presently the pumps are operating at approximately 65%. If this efficiency could be raised to the region of 75%, approximately R35,000 could be saved per month. Again the investment of implementing any such changes should be weighed against the returns.

5.3.2   Three Chamber Pipe Feeder Efficiency

Changing the efficiency of the entire three chamber pipe feeder system is not possible. For this reason the efficiency of the pumps alone will be varied, as this is the only realistic variable that can be changed.

The three chamber pipe feeder has a single pump on surface as well as a single pump on the mine's 43-level. The effect of varying the efficiencies is investigated by varying the efficiencies of the two similar pumps simultaneously.

The following figure is a graphical representation of the effect of varying the efficiency of the three chamber pipe feeder pumps on the total electricity cost of pumping in the mine.
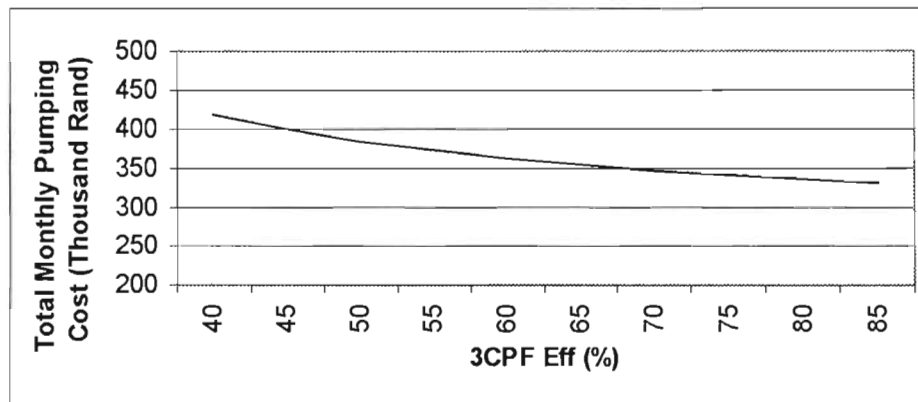

Figure 5.3: Total monthly pumping cost as a function of 3CPF efficiency

Figure 5.3 shows that varying the efficiency of the three chamber pipe feeder pumps, has a similar effect to that of varying the efficiency of the shaft bottom pumps. Presently the three chamber pipe feeder pumps are operating at approximately 70%, which is reasonably good. If the efficiency were to be increased to for example 75% as speculated in the last example, a saving of approximately R7,000 per month would be achieved. This is much less than that of the savings which could be achieved by making the shaft bottom pumps more efficient, it is however still a considerable sum. If both sets of pumps had their efficiencies raised, the total monthly saving would be approximately R42,000. Again, a decision would need to be taken keeping the capital expenditure in mind that any efficiency improvements would require. Investment criteria were also dealt with in section 1.4.4.

The reason that the efficiencies of the three chamber pipe feeder pumps do not have nearly the same effect on the total pumping cost as that of the shaft bottom pumps, is that the pumps are much smaller. The whole idea behind the 3CPF system is that it does not need to pump against a natural head. It thus uses much less energy than the shaft bottom pumps, even though there is a natural head of more than double that which, the shaft bottom pumps have to pump against.

5.4   EFFECT OF NUMBER OF SHAFT BOTTOM PUMPS ON ELECTRICITY COST

Investigating the effect of the number of shaft bottom pumps operating in parallel is perhaps not as useful as the other studies because the constraints present make changing the number of pumps rather difficult. The pumps, which have been installed, have been installed for a certain designed flow rate. Keeping all variables (including flow rate) the same while varying the number of pumps, implies that the pumps will not be operating in their most efficient area in their respective pump curves.

The following figure indicates how the total cost of electricity for pumping will vary when the number of pumps are varied.
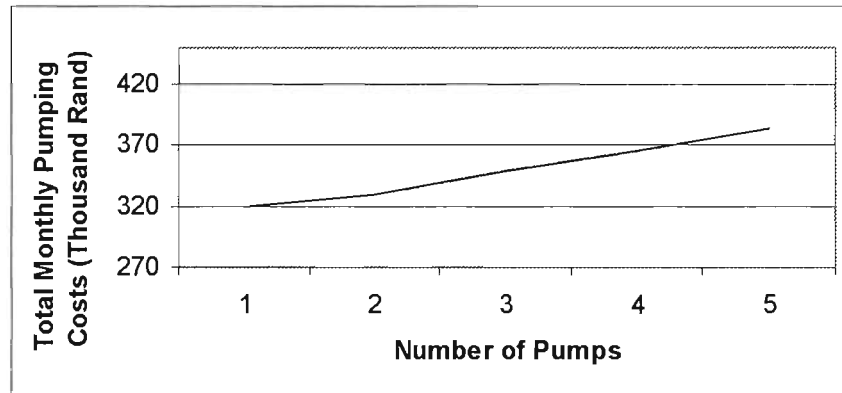
Figure 5.4: Total monthly pumping cost as a function of number of shaft bottom pumps while maintaining the same flow rate

Figure 5.4 shows that as more pumps are used, the cost of electricity also increases. For this reason it is important that there is a balance between the number of pumps (and so the electricity cost) and size of the pumps (initial costs). Efficient pumps that can handle much larger water volumes obviously cost much more than smaller pumps, which would be used in parallel. It is also pointless simply adding pumps in parallel due to the fact that the flow rate increases in a bounded exponential fashion as described in section 3.4.

Tshepong mine typically runs three shaft bottom pumps in parallel, so obtaining a reasonable balance between energy cost and initial pump cost.

5.5   TYPE OF ENERGY RECOVERY AND TARIFF COMPARISON

Using the models that have been developed, it has become possible to examine different kinds of energy recovery systems that can be used within a certain water reticulation system. For the purpose of this example, the system used in Tshepong mine was used. The simulation was done using the three chamber pipe feeder system as well as turbines and finally with no energy recovery. The entire system remains the same apart from the energy recovery system changing. As is the case in many mines where turbines are used, it was accepted that a system such as this would use three turbines in parallel and three pumps pumping the water to surface in parallel.

For the purpose of the example, it was accepted that the mine-wide maximum demand occurs at 9:30. The costs listed in the following table are based on Eskom's Nightsave and Megaflex tariffs as in 1999. The reason for this being that the case study's profile used for this simulation was measured in July 1999.

Table 5.2: Energy recovery and tariff comparisons

	3CPF	TURBINES	NO RECOVERY
Energy (Total Monthly)	1,865,559 kWh	3,478,699 kWh	3,776,007 kWh
Maximum Demand	4,366 kW	8,477 kW	10,561 kW
Monthly Nightsave Cost	R349,495	R667,238	R788,588
Monthly Megaflex Cost (Summer)	R283,200	R445,078	R599,961
Monthly Megaflex Cost (Winter)	R305,480	R457,897	R629,983

Table 5.2 demonstrates a further benefit of the modelling in that it can be used to evaluate different tariffs for the same or different systems. If for example Tshepong mine was a proposed mine, it would now be possible to determine how much power would cost for different installations and then decide in the energy recovery configuration while keeping available tariffs in mind.

One can furthermore determine how much power would be saved by the different energy recovery systems and use this information to decide if it would be economically viable to install the various systems. In the example shown in figure 5.2, one can see that using Nightsave, which is the tariff Tshepong are presently using, a typical saving of R439,093 per month is brought about by using the three chamber pipe feeder system. A saving of R121,350 per month would have been realised if they had installed turbines.

Naturally one must keep in mind that the figures mentioned assume that the maximum demand occurs at a given time. This is not necessarily the case, and may vary due to many other factors in the mine. The water reticulation system of a mine is not billed separately to the rest of the mine and so the choice of tariff must take the entire mine load profile into consideration. The values presented in table 5.2 are given as an indication of what the cost contribution of the water reticulation system would be if the mine had to be on the Nightsave or Megaflex tariffs.

5.6   SCHEDULING

Using the models developed, it is possible to use flow schedules as an input to the system of models to determine the electricity cost for that particular schedule. Once again the Eskom Nightsave and Megaflex Tariffs are of interest [22].

5.6.1   Nightsave Tariff

Apart from the basic charge, monthly rental, voltage discount and transmission percentage surcharge, Nightsave charges customers for total energy used per month as well as a maximum demand charge for either kW or kVA integrated over a 30 minute period. The maximum demand charge for Nightsave is only applicable between 6:00 and 22:00 on weekdays.

A customer such as a mine naturally has reasonably high maximum demand on this tariff as their main production shift occurs within the Nightsave peak time. This means that if the water reticulation system, which as can be seen from figure 4.7 is operating for most of the day, including the peak times, it is contributing a substantial amount to the maximum demand of the mine. From table 5.2 it can be seen that a typical maximum demand for the water reticulation system of Tshepong mine is 4,366 kW.

Theoretically, if the mine were to avoid using the water reticulation system at all during the times that they experience maximum demand, they could realise a potential saving of R213,628 (based on 1999 rates). Naturally this is only possible if there is absolutely no contribution to the mine's maximum demand from the water reticulation system.

Apart from this no saving can be made from scheduling changes. The energy used for pumping a certain amount of water remains constant and so Nightsave cannot be of any further benefit.

5.6.2   Megaflex Tariff

Customers using the Megaflex tariff are subject to a basic charge, monthly rental, reactive energy charge, voltage discount and transmission percentage surcharge. In addition they have to pay an active energy charge as well as a maximum demand charge. The main difference between Megaflex and Nightsave is that the energy cost varies depending on the time of use. The maximum demand is applicable all the time

and varies according to two set seasonal rates. The time of use rates also vary according to two respective set seasonal rate groups. The two seasonal rate groups broadly represent winter and summer.

In order to use Megaflex most economically, it is not only important to minimise the contribution to the mine's maximum demand, but also to avoid using energy at all during expensive times. In summer as little energy as possible should be used between 7:00 and 12:00. In winter energy usage should be avoided between 7:00 and 10:00 as well as between 18:00 and 20:00. Energy is typically the cheapest in the evenings and so as much load as possible should be shifted to night time (after 22:00).

Again referring to table 5.2, if Tshepong were on Megaflex, they would typically be spending R283,200 for pumping in summer and R305,480 on pumping in winter. Potentially, this figure can be reduced to R244,207 for summer and R271,478 for winter rates. Again, these figures are based on the 1999 figures. Furthermore the amounts represent only the potential saving that can be brought about by shifting load to reduce energy costs. In addition to this saving, a saving can also be made by avoiding operating the components of the water reticulation system at mine-wide maximum demand times.

The 4,366 kW of maximum demand from the water reticulation system of Tshepong, represents a potential saving of R52,000 in summer and R57,675 in winter. One must keep in mind that this saving is dependent on when the mine-wide maximum demand occurs and that one may need to weigh up the cost effectiveness of shifting load to avoid maximum demand or to avoid high energy costs. Typically Megaflex has its expensive energy charges during a mines production shift. For this reason, it may be possible to avoid high energy costs and maximum demand contribution be reducing pumping during the main production shift as far as possible.

5.6.3 Constraints

For any schedule changes that are brought about for electricity cost reduction, it is imperative that the buffers in the system are checked. This means that schedules can only be adjusted once it has been established that there will be sufficient water for production when it will be needed and that none of the dams in the system will overflow. Depending on the particular system, it may be necessary to compromise on some of the potential cost savings to ensure that the system operates properly. The constraints must ensure that an acceptable safety tolerance is adhered to in all cases as well.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

Chapter 1 mentions the main objective as well as a number of specific objectives to be achieved by this dissertation. This chapter concludes the dissertation by linking these objectives to what has been achieved. It globally focuses on the main objective and also concentrates on details of the specific objectives. The value of the work done in this dissertation is discussed and recommendations are made along with suggestions for future extensions and diversification to this study.

6.2 CONCLUSIONS ON THE OBJECTIVES

The main objective of this study was to develop a means of simulating the cost of electricity associated with the operation of a typical water reticulation system of a deep-level gold mine. Models were to be developed and integrated in such a way that they allow experimentation with scheduling, configuration and tariffs in order to minimise electricity costs associated with water pumping.

This main objective was achieved by employing a structured, systematic approach to identifying and solving all relevant issues. These issues were addressed by the different specific objectives and overall by constant referral back to the main objective. In addition to dealing with issues directly related to the objectives, it was also necessary to include much detail about the environment for which this study is intended to add an appreciation for the importance of what has been achieved.

Much of this dissertation concentrates on the methodology used in generating the models. This is intended to enhance the reader's comprehension of procedures and thought processes used to develop the models. In addition to adding total comprehension by doing this, it is intended that this study can be extended upon in the future to include other components or even a set of models for other systems found within mines. Using the same methodology will ensure compatibility; this will however be discussed later.

The introduction of chapter 1 provides a brief overview of theory and history of energy management as applicable to the mining environment in general. The main point, which is put across in this section, is that energy management in any form is aimed at reducing energy costs to enhance competitiveness. This does not necessarily mean using less energy, but rather reducing the cost of electricity per product.

Chapter 1 continues to deal with the practical environment, for which this study is intended, including global technical and non-technical constraints, which the results would need to adhere to.

6.2.1   Conclusion on extension to Delport's work.

One of the fundamental reasons for conducting this study was for the continuation of research initiated by Delport. Delport's research suggests methodologies and strategies for mine-wide integration of energy management procedures. As mentioned in section 1.3.1, this was to be achieved by modelling all major energy consuming devices within a deep-level mine. Delport however does not develop refined models for all components found within a typical water reticulation system. He proposes energy conversion mathematics for typical pumps, friction losses and efficiency.

This dissertation provides structured models for all common components found within the water reticulation systems of deep-level gold mines. It also makes provision for multiple components and ensures that all models are compatible. Models were verified to ensure that they are valid under typical conditions.

6.2.2   Conclusion on Modelling Methodology

Chapter 2 is solely devoted to explaining the methodology used in the generation, integration and constraints to be considered, when developing energy conversion models. It is important that one realises that modelling is not purely mathematical and academic. In fact the art of proper modelling is diverse and must consider a number influences such as physical, mathematical and financial factors. The use of conceptual models to generate mathematical models is also very important.

Models are in essence bridges between the real world and mathematical world, the methodology presented in this dissertation addresses the importance of providing a proper structured means of building such bridges. This is done by examining types of models and specific criteria of models.

The methodology addresses different contexts which models can fall into. This is important to ensure that different levels of models are compatible. The next part of the methodology presents a modular strategy to develop models to allow separate processes to be individually modelled and integrated into a global system.

The actual model developing process is also dealt with by the methodology, which provides a step-by-step mechanism used to produce each individual model. In addition other factors in the development such as the relevant inputs and outputs of models and system boundaries are addressed. The methodology also makes provision for constraints, which need to be kept in mind in the development process.

The methodology presented in this dissertation proved to be a reliable, robust guideline for model development, while at the same time, being simple enough to avoid confusion.

6.2.3   Conclusion on Separate Modelling

Accurate separate mathematical energy conversion models were developed in chapter 3. A large part of chapter 4 is devoted to verifying that the individual models are valid. Producing models for each common identifiable component of the water reticulation system allows for easy simulation of numerous different systems by simply plugging models for relevant components together.

Due to the mathematical nature of the models at this level, chapter 3 derives the mathematics for the models by starting with basic fluid-dynamic theory. By describing the derivation of the models, it is intended that the reader will be in the position of being able to derive similar models for any specific related components for which models have not been generated in this study.

6.2.4 Conclusion on Model Integration

In order to successfully simulate any water reticulation system, the individual models that have been developed need to be able to be integrated and thus be completely compatible in any configuration. This was achieved by generating models in such a way that the format and units of any inputs and outputs conform to a set standard. The success of the models operating together was evaluated in chapter 4, where it was proved that the models indeed function well together.

The integration of the models working together was verified using two separate sets of case study data. This data was used as an input to a set of models, which represented the configuration of an existing mine. The final simulated cost output of the system of models was compared to the actual cost value supplied by the mine for the cost of pumping at the specific times. The outputs of the system of models proved to be very close to the actual values quoted by the mine.

6.2.5 Conclusion on External Compatibility

Developing models that conform to a set of pre-determined standards ensured proper model integration. This integration strategy was however not limited to only ensuring integration of models with each other. In order to produce models that can be applied to any general water reticulation system, the models were developed using input and output variable formats and units that are commonly used in the mining environment.

An important part of ensuring external compatibility is also covered in the methodology. It is very necessary to adhere closely to the various system boundaries as described in chapter 2 to avoid stray influences.

6.2.6   Conclusion on Experimentation

The models and their applications in systems of models as described in this dissertation are of such a nature that their final output value are energy values. This means that if profiles of flow rates and other inputs for a pre-determined time are used, the output of the system of models will be an energy profile which allows one to examine the cost of electricity using different tariffs. It is thus also possible to vary the input profiles to observe the effect energy usage profiles and so also the cost associated with each set of input conditions.

6.2.7   Conclusion on Future Systems

Using the 'building block' approach described in the methodology of this dissertation, it is possible to simulate any general configuration of a water reticulation system. This naturally does not imply that the system must exist. In fact one of the benefits of this study is that it is now possible to create a number of different water reticulation systems which could be used in a proposed installation and evaluate the energy usage of each. This allows experimentation with a number of different energy recovery configurations.

Proposed installations could now for example determine the energy costs of a system using a three chamber pipe feeder system versus turbines or no recovery at all. The reduction of energy costs can then be weighed up against the capital outlay required for a three chamber pipe feeder system of the cost of turbines using a number of present value of money techniques as mentioned in section 1.4.4.

6.3   EXTENDED VALUE OF THIS STUDY

In addition to the obvious financial savings to individual mining business units, studies such as this may have much further reaching benefits. The national department of minerals and energy [43] is continuously evaluating ways and means of environmental pollution reduction. Using the models developed in this study to manage the energy demand of the water reticulation systems in a number of mines

will ultimately mean the capacity of the supplier will not need to be as great, thereby having a positive influence on the environment.

In 1999 Eskom sold 31,505 GWh of energy to the mining sector of South Africa [10, p. 96]. This represents 18.2% of the country's total energy consumption. Section 1.2.1 mentions that water pumping in typical mining operation in South Africa is responsible for about 17.6% of the total energy costs. This means that the water pumping in South African mines uses in the order of 3.2% of the country's total energy supply. If one considers the typical potential saving of up to 51% of the energy and 59% of the maximum demand as shown in table 5.2, it becomes clear that if energy-aware decisions are taken, especially when deciding on energy recovery systems in prospective mines, it can have a significant influence on the South African environment in the future. It must be noted that if only scheduling changes are brought about, only the maximum demand can be changed. A certain amount of water needs to be pumped in any cycle and this will require a specific amount of energy. This means that if no energy recovery changes are made by a particular mining shaft, reduction of maximum demand will be the only way that they can contribute to the environment.

In current installations, decisions may need to be taken about energy recovery system installations. Reducing the energy requirements of the water reticulation system, especially the maximum demand will be of benefit to the environment.

6.4   RECOMMENDATIONS AND FUTURE WORK

6.4.1   Implementation Recommendations

The models presented in this dissertation are robust and simple to use. They provide a way of simulating changes to existing water reticulation systems and the way they are operated with reasonable ease. It is thus highly recommended that all deep-level gold mining operations make use of the models presented and integrate them into their overall energy management policies and procedures. It is also highly recommended that these models be used to evaluate the prospective systems.

A great benefit of modelling the water reticulation system of deep-level gold mines as suggested is that there is no need for capital expenditure to be able to do this. Models can easily be implemented in spreadsheet applications commonly found on personal computers. It is however suggested that this dissertation be read in its entirety before any attempt at modelling is made. This is to ensure that the reader is aware of all factors and influences that must be kept in mind such as contexts, system boundaries, buffers and other constraints.

6.4.2   Future Work

The next step in the entire quantified energy management approach at deep-level mines would be to model all other systems and processes found within a mine in a similar way to this study. This includes the compressed air system, fridge plant, vertical transport system, ventilation system and all other essential and support systems.

Once complete modelling of all the systems found within a deep-level mine has been done, it will be possible to prioritise systems in schedule generation and be able to simulate schedules of the entire mine. Once the entire mine can be simulated, a number of different tariffs can be experimented with and the entire mine's scheduling can be geared towards specific tariffs. Evaluation using Real Time Pricing (RTP), should also form an integral part of such a study.

Following the extension to this work just mentioned, a further study should be undertaken into the development of customised tariffs. These tariffs should be developed for internal billing purposes. By billing each energy consuming system found within a mine in a fashion relevant to that system's operation will ensure that personnel responsible for each section make an effort to reduce electricity costs.

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