COMPARATIVE LIFE CYCLE COST ANALYSIS OF CENTRIFUGAL AND POSITIVE DISPLACEMENT PUMPS FOR MINE DEWATERING

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COMPARATIVE LIFE CYCLE COST ANALYSIS OF CENTRIFUGAL AND POSITIVE DISPLACEMENT PUMPS FOR MINE DEWATERING

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ABSTRACT

COMPARATIVE LIFE CYCLE COST ANALYSIS OF CENTRIFUGAL AND POSITIVE DISPLACEMENT PUMPS FOR MINE DEWATERING

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In mining activities, there is water flow to mining environment which must be removed by mine dewatering method to provide suitable working conditions. One of the ways of mine dewatering is conducted via pumps there mainly two types of pumps are being used in mine dewatering operations, centrifugal and positive displacement pumps. Centrifugal pumps utilize the submersible as feeder to horizontal pumps in main stations for further pumping to ponds or collection dams at surface, while positive displacement pumps utilize single stage piston diaphragm pumps to remove water collected at mine bottom. Decision making in both of these system needs to be made by considering overall cost components rather than focusing merely on initial investment cost. This can be made by applying life cycle cost analysis to both of the system.

Main objective of this study is to develop a basic decision support tool for selecting the most economic pump type. Research methodology followed in this research study entails literature survey regarding pump types and case scenario data to be used in economic analysis. Decision support tool was developed by integrating graphical user interfaces (GUI) so that pump selection could be made by decision makers. At the end, the program was tested by implementing a case study data. Results of the four years operation data in the program show that total net present cost of positive displacement pump yields 828,389 $ USD less than centrifugal pump net present costs value despite of the fact that positive displacement pump has total investment 711,960 $ USD more than centrifugal pumps.

Keywords: Mine Dewatering, Life Cycle Cost Analysis, Decision Support Tool, Centrifugal Pump, Positive Displacement Pump.

ÖZ

MADEN SU ATIMINDA SANTRİFÜJ VE POZİTİF YER DEĞİŞTİRMELİ POMPALARIN ÖMÜR BOYU MALİYET KIYASLAMASI

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Maden operasyonlarında, maden sahasına su akışı olmaktadır. Bu su akışı operasyona uygun çalışma koşulları oluşturmak için maden susuzlaştırması yöntemiyle ortamdan uzaklaştırılmalıdır. Maden susuzlaştırma operasyonlarından birisi pompalar vasıtasıyla yapılmaktadır. Bu operasyonda kullanılan iki temel pompa tipi santrifüj ve pozitif yer değiştirmeli pompalardır. Santrifüj pompalar, dalgıç pompalar ve yatay pompaların kombinasyonu ile suyun maden alanından yüzeyde bulunan çökeltme veya toplama havuzlarına gönderilerek uzaklaştırılması yöntemini kullanmaktadır. Positif yer değiştirilmeli pompalar ise bu işlemi maden tabanında biriktirilen suyun pompalanması şeklinde gerçekleştirmektektedir. Bu bağlamda söz konusu iki farklı sistemin seçilmesinde sadece ilk yatırım maliyeti değil buna ek olarak tüm maliyet kalemleri değerlendirmeye alınarak yapılmalıdır. Bu seçim hayat boyu maliyet analizi yöntemi kullanarak yapılabilir. Bu çalışmanın amacı karar vericiler için temel bir karar destek programı oluşturmaktır. Bu çalışma kapsamında araştırma metodu ise pompalar ve hayat boyu maliyet analizi ilgili literatür çalışmaları ile birlikte ekonomik değerlendirme analizinde kullanılacak örnek çalışma verilerinin oluşturulmasıdır. Ayrıca sistemlerin ekonomik

değerlendirmesini yapacak bir program geliştirilmiş ve test edilmiştir. Program kullanılarak dört yıllık örnek verinin programda işlenmesi sonucunda, toplam güncel maliyet değeri pozitif yer değiştirilmeli pompa sisteminde 828,389 $ ABD daha az çıkmıştır. Fakat aynı sistem ilk yatırım maliyetinde ise santrifüj pompalar göre 711,960 $ ABD daha fazla çıkmıştır.

Anahtar Kelimeler: Madenlerde Su Atımı, Ömür Boyu Maliyet Analizi, Karar Destek Sistemi, Santrifüj Pompa ve Pozitif Yer Değiştirmeli Pompa.

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Finally, I owe my loving thanks to my family. Without their encouragement and understanding it would have been impossible for me to finish this thesis.

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CHAPTER 1

INTRODUCTION

1.1 Background Information

In mining and mineral processing, transportation of slurries and removal of water inflow are essential components of material handling and/or mine dewatering, which are achieved by means of pumps.

There are mainly two types of pumps that can be used in mine dewatering as centrifugal pumps and positive displacement pumps. Centrifugal pumps are classified into two groups as vertical (submersible) and horizontal pumps. Varying number of centrifugal pumps could be used in dewatering. As an alternative method to centrifugal pumps, single stage positive displacement pumps are utilized. Operating principles of centrifugal and positive displacement pumps are different. In a way that centrifugal pumps use centrifugal force to displace material to be pumped on the other hand positive displacement pumps utilize movement of piston to transport the material. Beside from this technical difference, positive displacement pumps are capable of handling dirty mine water unlike centrifugal pumps which are more compatible with pumping relatively clean water coming from sumps. Capacities of positive displacement pumps are greater than that of centrifugal pumps. This means that number of pumps could also be different for the same pumping requirement.

Although pumps are not the most expensive equipment on the basis of initial capital investment in a whole mining project, compared to the other heavy machines, cost of power consumption, maintenance, repair, and spare parts could account for the overall costs. Since overall costs are much higher than the initial investment throughout life cycle times of pumps, selection of correct type of pump is crucial for sustaining economic success of dewatering projects. For that reason, selection should be made by making a detailed Life Cycle Cost (LCC) analysis of both types of pumps. By doing this, economic feasibility of dewatering operation could be increased significantly.

1.2 Statement of the Problem

In mine dewatering system with centrifugal pumps, water flow is accumulated in substations at different levels and slurry is conditioned until particles are settled down. Then it is pumped by submersible pumps to the main pump station where there are horizontal centrifugal pumps to displace the clean water to surface. In this system, depending on the pumping requirement varying number of submersible pumps could be used in substations and cost of excavating of sumps associated with these substations could account for the significant portion of the overall cost due to large number of pumps in operation. Moreover, spare parts and maintenance of pumps are also very crucial due to large number of pumps are in operation. Enormous amount of spare parts need to be purchased and stocked every year to keep system in operation without any interruption. Cleaning of sumps several times a year is also another invisible cost in this operation

Positive displacement piston diaphragm pumps, on the other hand, generally use only one pump or two pumps depending on required output in a larger pump house in underground. All water is collected at mine bottom via piping and/or ditching and is pumped from mine bottom to surface. It requires less spare parts and maintenance period while initial investments of these types of pumps are greater than centrifugal pumps.

Appropriate selection between these two types of pumps can save money considering operating cost and initial capital investment cost than required. In order to select the most economically feasible pump type, an economic model can be constructed by applying life cycle cost (LCC) analysis as decision making support tool. By having such a model, better understanding in the two different pump's overall cost can be provided and decision can be made in a better way. Lack of such comparison study with model in the literature is the main motivation of this study.

1.3 Objectives and Scope of Study

Main objective of this study is to develop a decision support tool for selecting the most economic pump used in mine drainage operations for the given life using LCC analysis. In other words, economic comparison of centrifugal and positive displacement pumps should be conducted from LCC point of view and a decision support tool are aimed to be achieved. The elements of this main objective are:

i. To create an economic model to analyze all cost components of pumps throughout their life cycle,
ii. To implement LCC comparison for these two types of pumps, and
iii. To develop a program having graphical user interface (GUI) as a decision support tool

The scope of this study is limited by only the use-phase of pumps. Manufacturing and disposal of pumps are not included due to lack of available data regarding to these phases.

1.4 Research Methodology

The research methodology followed in this research study entails five main stages. At first, data involving economic information of pumps was acquired using extensive literature survey and personal communications in industry. Based on the acquired data, economic analysis was conducted using discounted cash flow diagrams and LCC analysis. After that the decision support tool was developed by integrating graphical user interfaces (GUI) to the developed economic analysis so that pump selection could be done at any time with different data. At the end, the program was tested and evaluated by implementing case studies and comparing the results with real data obtained from a underground mine operation located in Turkey.

1.5 Expected Scientific and Industrial Contributions

This study is expected to have several contributions from scientific and industrial point of view. This study may help to define total cost of pumps throughout their life cycles in operation so that end users could be able to find out total amount of economic costs for pumps when they purchase it and to choose the most appropriate alternative Moreover, decision makers could realize more clearly that initial investment alone is not of benefit to companies since capital investment, power, maintenance and spare part costs are also crucial in decision making. This part is especially crucial for Turkish mining market since majority of end users and decision makers believe that decision is the most sensitive to initial capital investment and not enough attention is given to life cycle cost of equipment in all operation life. This study may also help pump manufacturers to see overall costs of their equipment in industry by that they may be able to give more attention to their research and development studies to manufacture pumps at lower overall costs.

Since there is no any LCC-based decision support tool for mine drainage pumps, this study could be regarded as an original and a novel study and can fill the gap in this area in the literature.

CHAPTER 2

LITERATURE SURVEY

This chapter is organized in two main parts. Pumps used in mining industry, types and classification of pumps and costs associated with each type were explained briefly in the first part. Subsequent to the first part, Life Cycle Cost analysis used in decision making was presented comprehensively. At the end of the chapter, summary was given to present the way in which this study would fill the gap in literature in this research domain.

2.1 Fundamentals of Mine Dewatering Operations

In mining and mineral processing, material transfer is required from one location to another. Wet material transfer in mining and mineral processing is fulfilled by means of pumps. Slurries are required to be transported in order to produce economically valuable metal or mineral. On the other hand, due to its nature, mining activities require handling of bulk tonnage. As a result of this material move, water tables and reservoirs are disturbed so water flow is seen towards to mining environment. Removing of this water from mining area is called as mine dewatering. This is an important operation in both underground and surface mining activities. Core of this operation is pumping activities. In surface mining operation water is accumulated at the pit bottom and then is pumped to the required location as shown in Figure 2.1. Mine dewatering in surface mining operations is also important for providing water for process facilities if there is water shortage in the area. Mine water may be used as process water in such cases. Mine water treatment plant may also be needed for such cases depending on the type of the process.

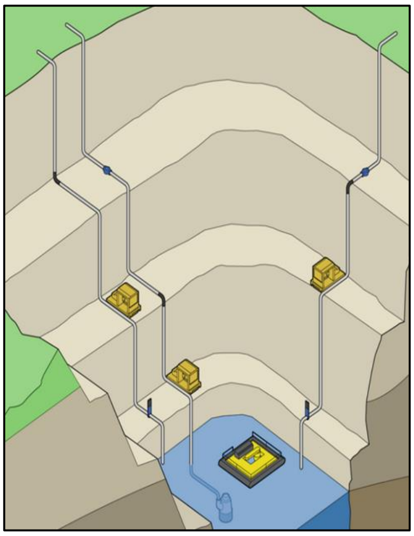


Figure 2.1 Schematic Diagram of Open Pit Mine Dewatering operation (Weir Minerals, 2015)

In underground mines, mine dewatering is done similar to that in surface mining. Yet, since underground mining is conducted in a confined area, water collection is made in a different location via sumps and transported to main stations for further pumping out to the surface as shown in Figure 2.2. Similar to surface mine dewatering, underground dewatering operation can facilitate the process water requirement.

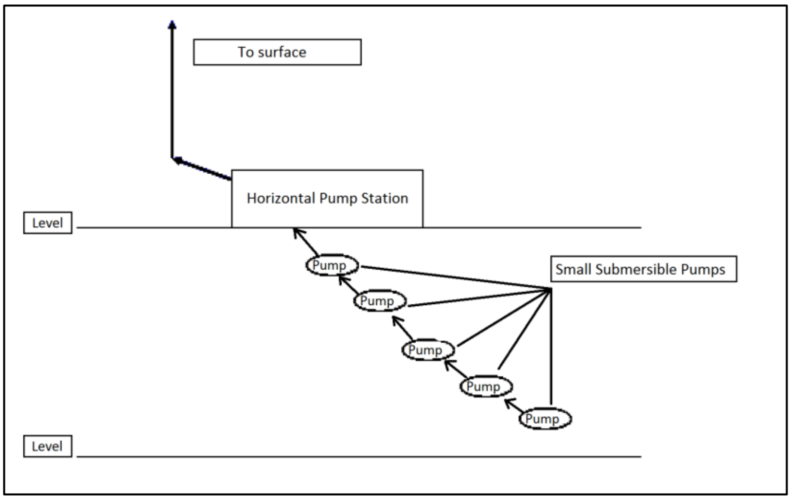


Figure 2.2 Underground Mine Dewatering

Mine dewatering is important since it may affect the mining activities negatively unless it is conducted in right way. Depending on the season of the year or size of the water reservoir, there may be increase in the water flow to mining environment. For that reason, each mine needs to have a proper mine dewatering system which is capable of removing water inflow from mining area. If there is a problem in mine dewatering system, advance rate in mining can be reduced which results in loss of production and money. If water accumulated in pit bottom cannot be removed effectively, material haulage and blasting practices will be affected in a negative way in surface mining.

For underground mining, mine dewatering is equally important as in surface mining. Given that, if water flow cannot be removed in a timely and an efficient manner in underground, it may cause accumulating of excess water in production galleries or flooding of mine as seen in two recent examples in coal mines in Turkey in 2010 and 2014. Modeling of water inflow is a major factor in mine dewatering but roles of pumps are also crucial. Deviation in water flow modeling can only be compensated with pumps with high efficiency and capability. As these pumps operate all day in the operation, there is a cost of dewatering associated with pumping. For that reason, appropriate pump selection should be made carefully in mine dewatering in order to reduce the risk in further advancement of mining as well as reducing the cost incurred due to pumping.

2.2 Pumps Used in Mining Industry and Their Classification

In this part of the study, basic pump classifications in literature were introduced. Basic information for particular types of pumps used in mine dewatering operation was presented. There are mainly two types of pumps commonly utilized in industry. These are centrifugal and positive displacement pumps. Many other different versions of classifications are made according to various specifications of the pumps. According to American National Institute Pump Standards (ANSI), pumps are divided into six subclasses. These classes are kinetic, vertical, rotary, reciprocating, direct acting, and sealless types.

According to Dickenson (1988) pumps could be divided into two main groups as dynamic pumps and displacement pumps. Dynamic pumps are further divided into two groups as centrifugal pumps and special effect pumps; while displacement pumps are divided as reciprocating pumps and rotary pumps. On the other hand, Nelik (1999) grouped pumps as kinetic and positive displacement pumps. Kinetic pumps were subdivided into three groups as centrifugal pumps, special effect pumps, and turbine pumps. Positive displacement pumps are grouped as reciprocating and rotary pumps in this classification. Another classification made by Bachus and Custodio (2003) such that pumps are divided into two types which are centrifugal and positive displacement. Centrifugal ones were further divided into: concentric, volute, and diffuser. A positive displacement pump, on the other hand, is grouped as reciprocating and rotating pumps. According to another classification made by Volk (2013), pumps were classified on the basis of energy transfer method, as kinetic and positive displacement. In the kinetic pumps, energy was given to liquid in a continuous manner while in positive displacement one, it is done as direct application of force as application of backward and forward operations of pistons or plunger.

Centrifugal pumps have more complex classification compared to positive displacement pumps. There are many different sub classifications of centrifugal pumps in literature. Classifications of centrifugal pumps according to flow type, bearing arrangement, and impeller, installations, suction types may also be found. For instance, centrifugal pumps are classified by Rishel (2002) such that pumps are defined as volute type pumps, axial flow types, and regenerative type pumps. Depending on the installation, slurry pumps can be dry, semi-dry, and wet types (Slurry Pump Basic, 2006). In the dry type, bearing and drive units stay out of the slurry while wet end bearings are in the slurry. It is classified as a wet type when all units are submerged in the slurry. Submersible pumps are only option for such operations. Another well-known classification is made according to the suction type of the impeller. More precisely it means that whether suction is made from one point or two points. This is called single suction and double suction types.

Since classification of the centrifugal pump is complex; after evaluating different pump classifications, a revised classification is suggested in below list to show the majority of the centrifugal pumps used in industry.

Pump classification according to:

- **Suction and Impeller:** Volute Pumps and Multistage Pumps
- **Coupling:** Closed Coupled and Flexible Coupled Pumps
- **Mounting:** Frame Mounted, Double Suction and Inline Pumps
- **Duty and Operation:** Vertical, Column, Vertical Turbine, Submersible and Slurry Pumps
- **Priming:** Self Priming Pumps
- **Flow Type:** Axial Flow and Regenerative Turbine Pumps

On the other hand, positive displacement pumps have slightly less variations in the classification when compared to centrifugal types. They have two main types: rotary and reciprocating pumps. After evaluating the different classifications on positive displacement pumps classification is given in below:

- **Rotary Pumps:** Sliding Vane, Sinusoidal Rotor, Flexible Member, Gear Rotary Lobe, Progressing and Multiple Screw Pumps
- **Reciprocating:** Plunger Pumps, Diaphragm Pump and Dual Disc Pumps

Among these pumps, the most commonly utilized in mine dewatering operations ones are:

1. Centrifugal slurry pumps commonly known as horizontal submersible pumps
2. Centrifugal submersible pumps
3. Positive displacement diaphragm pumps

In underground and surface mine dewatering applications; horizontal and submersible pumps are used in combination. In other words, submersible types are used as feeding pumps. They are positioned in sumps located in specific places and pump particle free-water to the main station which is equipped with horizontal pumps for further transportation of dirty water to final treatment plant or pod location. Given that only submersible pumps are used, dewatering is conducted by pumping water directly from sumps to surface where depth is 30-50 m.

Dickenson (1988) claimed that centrifugal pumps are used in pump stations installed in some levels with different elevations and were received water from sumps by submersible pumps since they are capable of pumping clean water of all system.

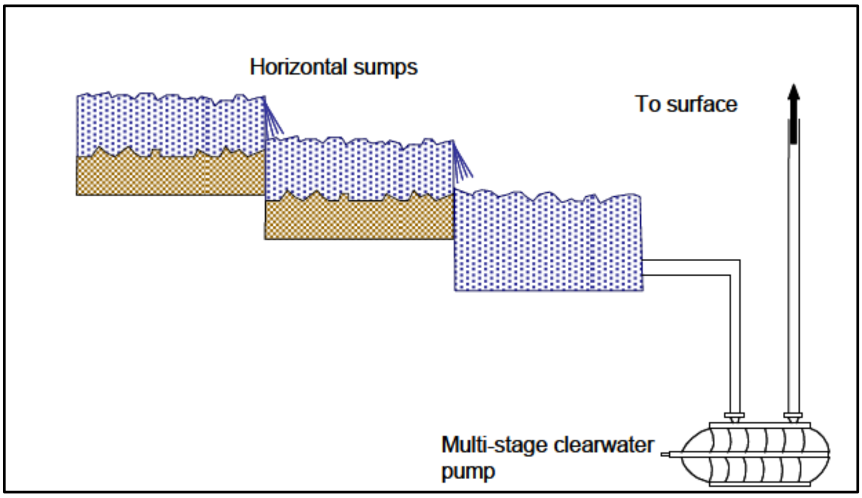


Figure 2.3 Centrifugal Pumps in Mine Dewatering (Weir Minerals, 2015)

Argall and Brawner (1979) stated that horizontal centrifugal pumps are used in pump houses as main pumps, pumping water to surface upon receiving clean water from submersible pumps at different levels as in Figure 2.3. For that reason, they defined submersible pumps as feeder. On the other hand, single-stage positive displacement pumps are used as an alternative to this conventional method. Positive displacement pumps can be used in dewatering of both surface and underground mine dewatering operations. However, in case of surface mines, submersible feeding pumps are utilized again. On other hand, in underground, system is different than centrifugal types. Mine water is collected in mine bottom in underground mines and then dirty mine water is pumped by diaphragm pumps as shown in Figure 2.4. In order to collect mine water at the mine bottom, water channels and pipelines are designed. There is a diaphragm pump located at the mine bottom and it pumps the collected water to the surface as shown in Figure 2.5. Depending on pump capacities and requirements, number of required pumps is determined.

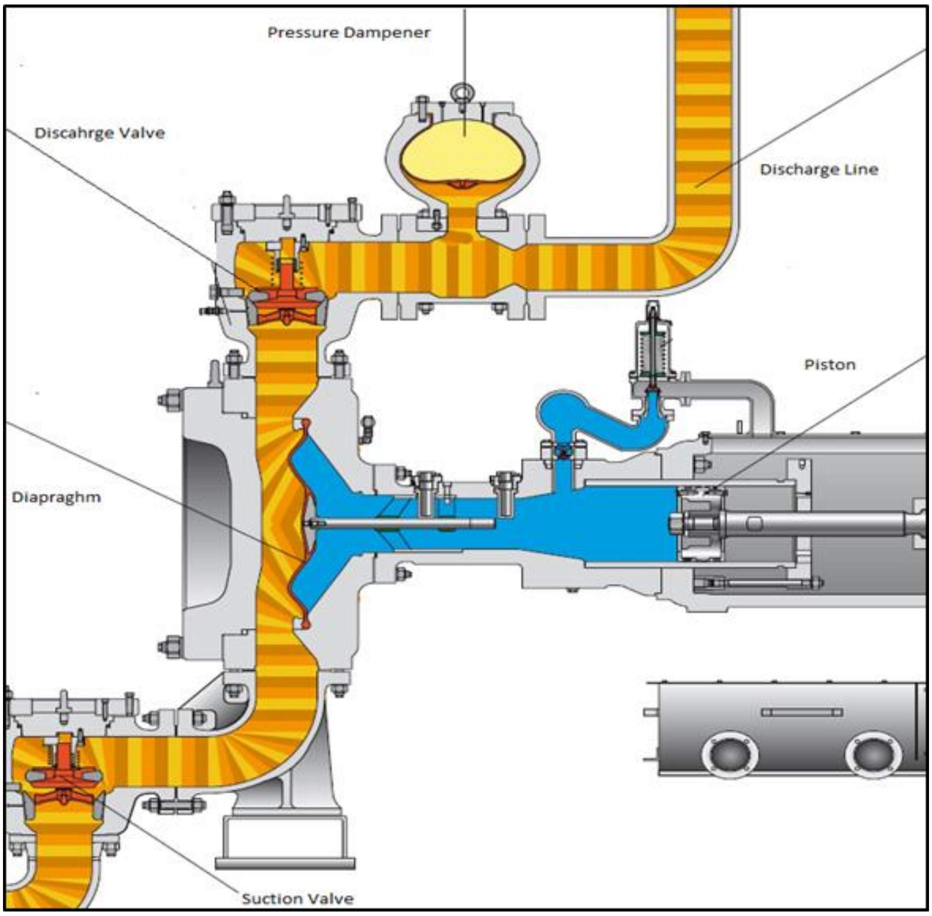


Figure 2.4 Single-Stage Positive Displacement Diaphragm Pump in Mine Dewatering

(Weir Minerals, 2015)

Figure 2.5 Dewatering with positive displacement pump (Weir Minerals, 1996)

The following section presents the technical details of centrifugal and positive displacement pump types used in mine dewatering.

2.2.1 Centrifugal Pumps Used in Mine Dewatering

Centrifugal pumps both slurry (horizontal) pumps and submersible pumps are widely used in almost all industrial applications including metal mines, industrial minerals operations, and coal slurries transportation, mine dewatering, power plant operations, ash transportation, and sand and gravel applications. In these operations slurries are accepted to be highly abrasive and to include various solid contents.

Operating principle of slurry pumps is a function of suction implied by impeller and energy conversion. For instance, centrifugal pumps are defined as equipment with spinning impeller that displaces liquid by momentum and types of them are defined with motion given to fluid by impeller (Improving Pumping System Performance, 2006). Moreover, Girdhar and Moniz (2011) stated that centrifugal pumps are types of equipment which increase pressure of liquid by imparting velocity first and converting it to pressure which is the same case in slurry pumps. Similarly, Karassik *et al.* (2008) defined major parts of these pumps as driver, volute, and impeller then summarized the operating principle as, upon spinning of the driver and associated shaft which has impeller mounted at the end, liquid enters eye of impeller and this pushes the liquid to discharge line by converting velocity to pressure. Outer casing of the centrifugal pumps can be seen in Figure 2.6.

Figure 2.6 Centrifugal Slurry Pump (Weir Minerals, 2015)

Submersible pumps have slightly different way of operation than slurry pumps. Bachus and Custodio (2003) stated that submersible pumps are one of the type of centrifugal pumps but impellers discharge into diffusers rather than volute. Argall and Brawner (1979) defined submersible pump as a type of pump which can operate in totally submerged conditions. Kristal and Annett (1953) classified these pumps according to their motor types which are dry and wet. They stated that dry motors are mounted on top of the pump while wet motors are mounted on the motor body. Wet type of motors could be oil filled, semi wet, and water filled types. Typical representative picture of submersible pumps are given in Figure 2.7.

Figure 2.7 Submersible Pumps (Weir Minerals, 2015)

Since there is such a variety in slurries like mine water, dewatering operations cause important wear on rotating parts and stationary parts of the pumps. Parts that are more subjected to wear and replacement can be given as casing, impeller, shaft, shaft sleeve, sealing, and bearings. Wear problems in rotation parts can be reduced by using rubber lined or hard metal in these parts. Rubber can be used in fine slurries having corrosive characterization while hard metal are used for coarser slurries. Metal types used in this type of pumps are high nickel-iron, stainless steel and cadmium-manganese in some cases. There is a competitive market for pump spare part market horizontal and submersible pumps. For instance, reputable pump suppliers are estimating that there is a 7.00 Million $ USD of spare part and maintenance supervision service market annually in whole industry. Same figure is 15.00 Million $ USD for pumps itself. (M. Katkay, personal communication, March 20, 2015)

2.2.2 Positive Displacement Pumps Used in Mine Dewatering

Positive displacement pumps have wider application areas in sludge slurries and similar heavy-duty slurries having relatively higher solid content. They are completely different than centrifugal pumps since they make use of the positive displacement of a piston or rotary action of a unit. Positive displacement pumps have their name from the movement of this positive displacement motion. These pumps take actions from crank shaft that is connected to positive displacement element like piston and plunger. As it is stated by Rishel (2002), positive displacement reciprocating pumps discharge a given volume of slurry at each stroke of piston. Positive displacement pumps over centrifugal pumps can be chosen when slurry being pumped requires high pressure together with high efficiency and high viscosity in operations. Given that viscosity is high, energy required to keep pumping on gets increased and in high viscous slurries it may not be economic to pump these slurries via centrifugal pump due to low efficiency as well as high power consumption.

Piston diaphragm pumps, also known as crank shaft-driven pumps, are mainly used in long slurry transportation. Piston diaphragm pumps can be utilized in many sectors. In mining industry they have a wide range of use such as, mine dewatering, mine backfilling, and tailing disposal.

Piston diaphragm pumps have the same operating principles. Movement of piston is achieved by the harmonic rotation of the crank shaft and connection rod. Self-actuated check valves opened and closed by the help of this reciprocating action so suction and discharge occur. During suction, suction valve is opened and slurry is sucked to diaphragm house, then suction valve is closed and piston is pushed from its original position. There is a diaphragm at the end of the piston and this diaphragm pushes the slurry to discharge line. Discharge valve is opened at the end of this and slurry is transported to pipe line. After this suction starts again. Purpose of using diaphragm is to protect piston and cylinders liners from slurry and abrasive effects of slurry. By doing that wearing off the parts is reduced and transportation of high solid content is achieved. Figure 2.8 shows the suction case of piston diaphragm pumps in operation

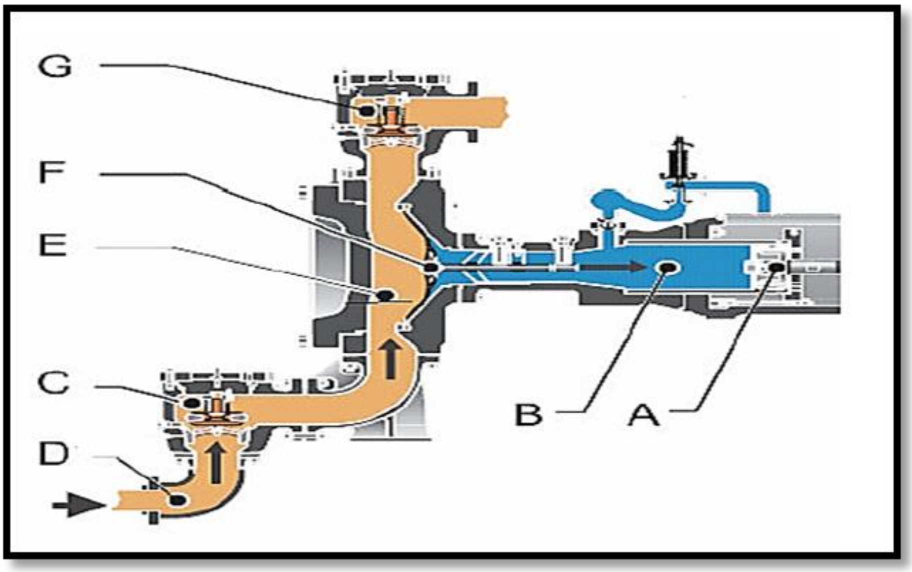


Figure 2.8 Suction Position of Positive Displacement Pump (Weir Minerals, 2012)

A: Piston, B: Propelling Liquid, C: Suction Valve, D: Suction Line, E: Slurry Chamber, F: Diaphragm, G: Discharge Valve

During suction process piston moves backward and diaphragm moves backwards with them. This results a low pressure in slurry chamber and discharge valve is closed, suction valve is opened. Following this slurry fills slurry chamber. After that discharge stroke is started. Piston moves forward and diaphragm moves forward with it. This results in high pressure in slurry chamber and causes to close of suction valve and open of discharge valve. Slurry leaves chamber through discharge line.

A piston diaphragm pump is composed of two main components:

1. Water End
   - Suction-Discharge Valve,
   - Piston and Diaphragm, and
   - Air Vessels-Dampeners,

2. Drive (Power) End

- Crank Shaft,
- Cross Head,
- Connecting Rod, and
- Oil Sump

Figure 2.9 presents a typical view of water and power ends as in below.

(a) (b)

Figure 2.9 (a) Water and (b) Power Ends (Weir Minerals, 2012)

When it comes the volume of the market for positive displacement pumps, total of 3.00 Million $ USD of spare parts and service can be estimated annually. When it comes to pump capital cost budget, volume of the market is changing depending on the economic structure of end product price and general economic conditions. However, annual volume of Turkish market can be estimated around 5.00 Million $ USD. (E. Hakan, personal communication, March 20, 2015)

2.2.3 Comparison of Centrifugal and Positive Displacement Pumps

After evaluating technical features of both types of pumps, following basic advantages and disadvantages of horizontal and vertical centrifugal pumps and piston diaphragm positive displacement pumps on basis of mine dewatering can be summarized as in Table 2.1.

Table 2.1 Comparison of Pump Types

	Centrifugal Pump	Positive Displacement Pumps
Advantages	• Low Initial investment • Low Pumping House Requirement • No Suction Piping • Easy to Install	• Higher efficiencies with more than 85-95% • Constant speed, Constant Flow • Lower Power Consumption • Less Spare Parts and Maintenance Period • Slurry pumping capability
Disadvantages	• Lower efficiencies around 45-75 % • High Power Consumption • Pump-Sump Arrangement • High number of Pumps and Parts in Mine Dewatering • Clean water obligation	• High Initial Cost • Large Pump Station Requirement • Pressure Fluctuations • Detailed and Complex Engineering

Summary of pump classification is introduced in Figure 2.10 as in below.

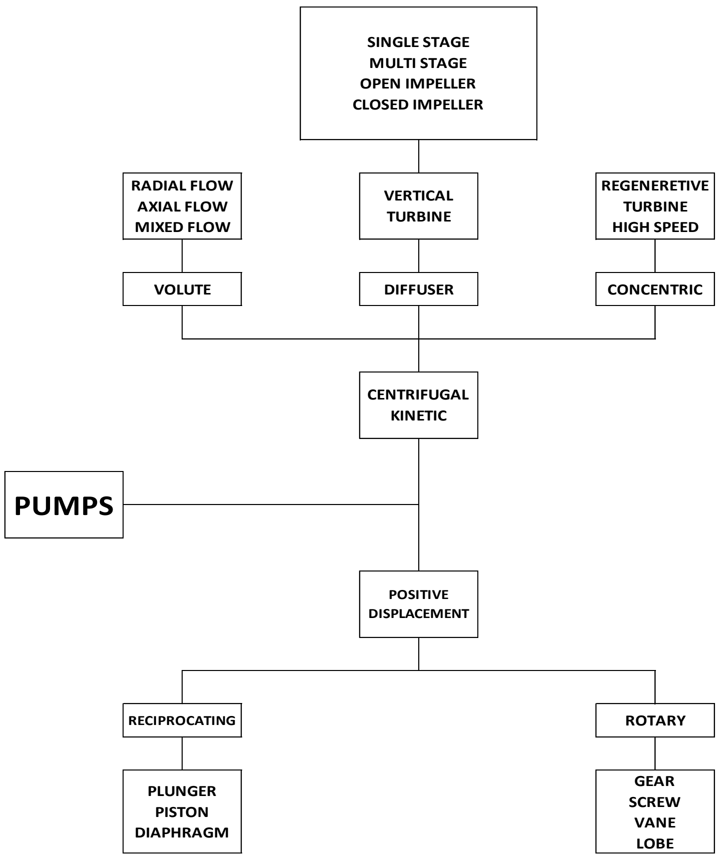


Figure 2.10 General Pump Classification (Modified after Bachus and Custodio, 2003)

2.2.4 Selection Criteria between Pumps

General pump selection is made in two stages. The first stage is the selection of alternatives based on technical properties and evaluation of the alternatives. After this stage, economic evaluation of the different alternatives from budget quotations and firm bid quotations gathered from different suppliers. In order to make technical selection and design the system, pressure and flow requirements are calculated. Based on these figures, selection criterion together with operational factors of wear rate, pump material selection, particle size distribution of the slurry, solid shape, temperature and solid content of the slurry, impeller speed, pH and metal content of the slurry are formed. These parameters are used to size and select the pump type and to design the system. Selection can either be made by decision maker or by supplier based on the data sent to supplier. In some cases, supplier may ask samples to be tested in their labs in order to size the right type for particular slurry characteristics. This enables the supplier to understand the pumping requirement and correct material selection since material used in pump construction is cast iron, white iron, steel, rubber and ceramic as well. Particle size is another limitation in pump operation.

Maximum particle size to be pumped is given as 300 mm (Sicard, 2006). After investigating these parameters, pumps are selected depending on the pump performance and system curve. If pump is not selected carefully, wear rate will increase and power consumption will be higher. Moreover, pump may be damaged and may be out of function. Pump curve is a graph showing the pressure and head. In centrifugal pumps curve is always downward slope since head and flow are inversely proportional. System curve is a graph showing the required head of system at different flow rates. In positive displacement pumps it is linear since capacity is directly related to speed of the pump. Figure 2.11 and Figure 2.12 are typical pump curves of positive displacement and centrifugal pumps, respectively.

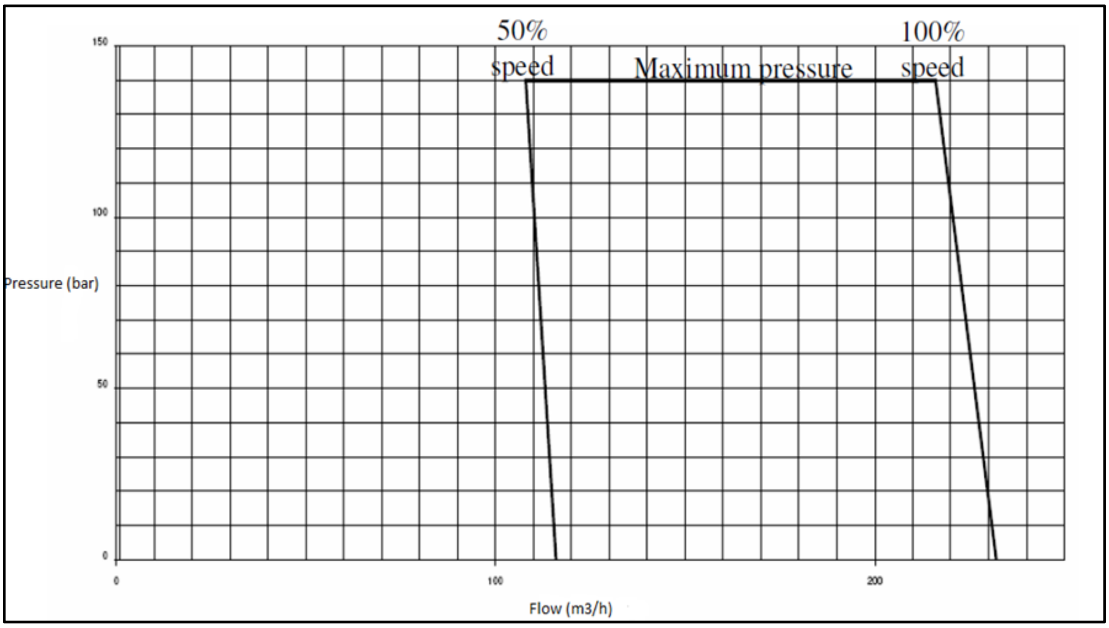


Figure 2.11 Positive Displacement Pump Curve (Kuenen, 2010)

Operating speeds relative to fixed impeller diameter, head at different flow regimes, required power for duty different efficiencies, net positive suction head can be found in performance curves. Straight after process is defined and selection is made, pricing of the pumps is made and sent via quotations to decision makers. After this point technical evaluation is completed and economic evaluation starts.

Current perception both in state and private sector is quotation with the lowest initial investment is the most economically feasible option. However, this approach can lead the decision maker to face with unforeseen overall cost of overall system. This fact is emphasized by several studies in the literature. Sahoo *et al.* (2014) emphasized on the total energy consumption of the pumps in total life cycle analysis. They studied a mine dewatering operation by modeling the water fluctuations as mining advances and associated pumping requirement. They also added that 27 % of the total energy consumption in mining industry belongs to pumping. For that reason they suggested that specific energy requirement for dewatering needs to be modeled such that mining planning and advance is carried out.

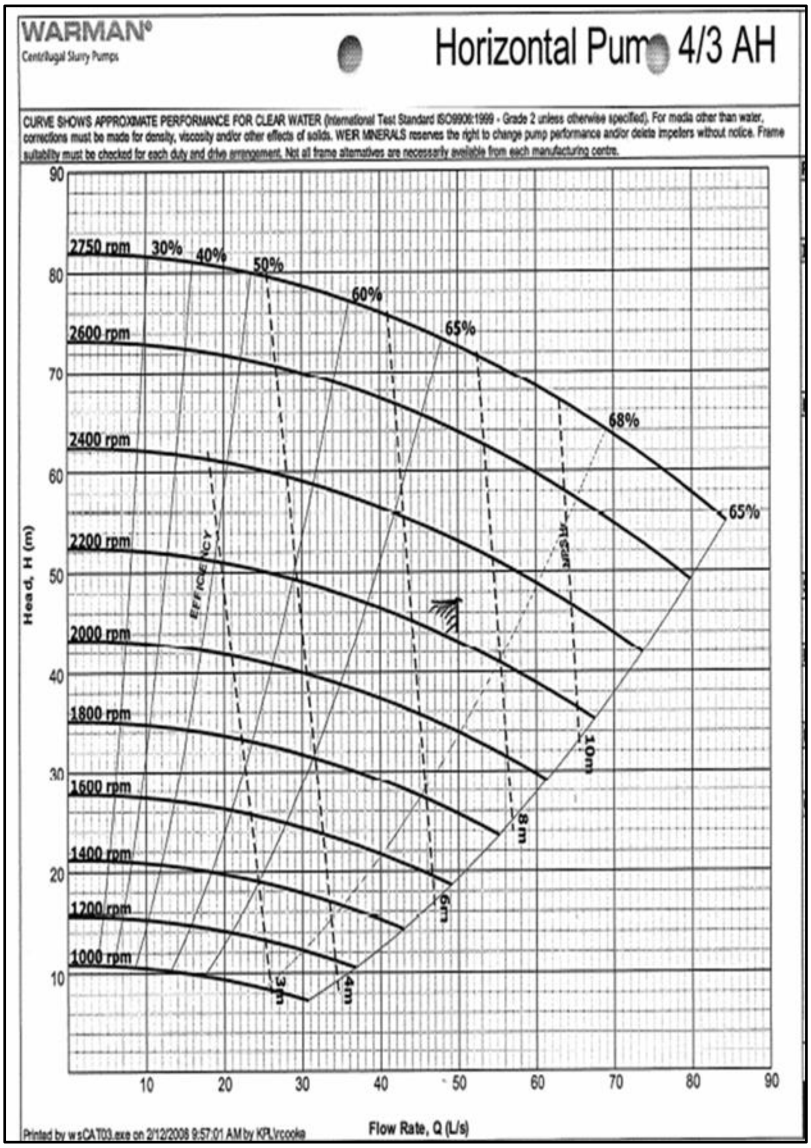


Figure 2.12 Centrifugal Pump Curve (Kuenen, 2010)

Moreover Liebenberg and Velleman (2012) studied the pump energy consumption in mine refrigeration system in a deep gold in mine in the South Africa. The reason of optimizing the refrigeration system is the fact that 42% of the whole total energy consumption is spent for the refrigeration system. Pumps with motor 2 MW motors are used in order to recirculate the water from mine to pond for cooling of the ventilation air. Since electricity tariff is varying during different times of the day, pumps are optimized such that pumping is made more in cheaper time frame by optimizing the water requirement. Overall 2 % electricity reduce is achieved and it contributed to 13 % reduce in the annual operation cost. This study is another illustrating example of energy requirement of the pumps in the total owner ship concept and one always need to look for a solution with more efficient way to save money from energy. Moreno *et al.* (2010) studied the optimization of energy consumption of pumps utilized in underground water reservoirs. The authors also stated that the minimum total cost on the basis of initial investment and operating cost can be met by optimizing the pump curve, pump efficiency and pipe diameter. They emphasized correct sizing of pumps and importance of energy consumption. They stated that if pumps are not sized correctly or used in wrong environment without optimization, energy consumption could be very high that takes operation far away from feasible point. Graham (2007) supported LCC analysis in the centrifugal pumps in water applications. He stated that total ownership cost can easily outweigh the initial investment of the pumps and in order to solve this problem detailed cost analysis is required to make the pump efficiently running and maintenance free. He also suggested that this analysis needs to be addressed such that it may be used as marketing purposes. Nimser and Naumann (2004) analyzed the coal refinery pump maintenance problems since they believed that maintenance factor is a major cost item in the life cycle of the pumps. Total annual maintenance cost of targeted plant turned out to be around 1.2 Million Euro by proving that maintenance cost can be a significant problem. They analyzed the failures and found that 25 % of the total annual maintenance cost can be reduced in changing the material type and sizing characteristics of problematic areas. This article was important since it showed that right pump type with right material can save money at the beginning of the projects. Barringer (2001) emphasized on the reliability analysis and importance of it in LCC analysis. They claimed that maintenance and reliability data is as importance as the initial cost of systems and they suggest that all cost components together with maintenance make decision makers to choose the right option. Moreover, they presented a case study for comparison of high temperature pumps to overcome increased production. They believed that accurate information from maintenance and reliability concerns help necessary bodies to make right decisions in LCC including net present value (NPV) and Internal rate of return (IRR). However, depreciation analyses are not included in this study. Lam and Chan (2001) made empirical heat loss analysis for swimming pool in hotels and make LCC comparison of heat pumps and conventional system. LCC analysis was conducted in order to find option with the lowest energy consumption. Hennecke (1999) studied the LCC of pumps in chemical industry. The author stated that initial investment of pumps in processing industry was small portion of total life cost of pump in whole operation. In order to prove this the author made LCC analysis of pumps for 10 years. Cost components used were initial investment, maintenance cost, and energy consumption. The author used NPV method with discounted cost flowed to show that investment cost merely was not significant since it accounts for the small portion of total cost of pumps in operation.

2.3 Life Cycle Cost Analysis

When market conditions, economic growth rates, and fragile economic conditions are considered, it may be claimed that making investments for small- and large-scale projects are getting more tedious for industry. Decision makers find themselves in the limited budgetary conditions with a short period to make the right selections while investors and shareholders do not find themselves in a comfortable environment since they believe that they may lose money with wrong decisions. On the other hand, suppliers and manufacturers try to improve new designs and new technologies including illustrating innovations to increase their market shares and seeking for new clients and investments to make business with them. Furthermore, all possible options are required to be analyzed closely to see what possible savings and profits may be gathered out of them.

These conditions and facts have brought engineering and economy together and formed Life Cycle Cost (LCC) which is widely used almost in economic comparison of investment alternatives. LCC term was introduced to literature for the first time in

1965. Since then it has been started to be used by decision makers in selecting alternatives giving the lowest total cost.

Dhillon (2013) defined LCC as a relatively new method in estimating the total ownership cost of the systems and equipment including all cost components of the system. According to another definition, Bull (1993) stated that LCC was a method that concerns resources, consumables, and personal finance, acquiring, purchasing, disposing costs during service life of system. By analyzing similar definition in the literature, it may be alternatively defined as the total amount of cost incurred during whole operating life of system under evaluation. By having these features, LCC can be a strong decision making support tool which may be utilized in early stage of acquisition, during requirements, feasibilities studies as well as after investments studies. In pre-investment studies, it may help end users to choose right options before procurement. In order to bring LCC to such wide scope, cost, time as well as performance should be considered in the course of life cycle costing processes.

LCC can be much higher than the just initial cost of system or equipment. This fact could be seen in many cases. For example Dhillon (2011) claimed that there were many examples in the U.S.A. Defense Department that total anticipated and allocated budgets are exceed by operational and maintenance cost of the item whose initial investment was the lowest at the decision stage. Bull (2003) stated that total portions of majority of costs in any equipment or system occur in service life and this portion could be in the range of 50-80% of the total life cycle cost of the system.

Operating and maintaining of equipment put significant awareness as a result of high monetary impact associated with them, they prove that initial cost is not only an factor in decision making process as shown by Figure 2.13. In other words, it may be said that any service or product that are planned to be procured at the lowest initial investment cost may not be the most feasible option when total cost of all options are brought into together. This difference in cost between capital and total service life is the reason why LCC getting reputation both in academy and industry since it is space for improvement and optimization.

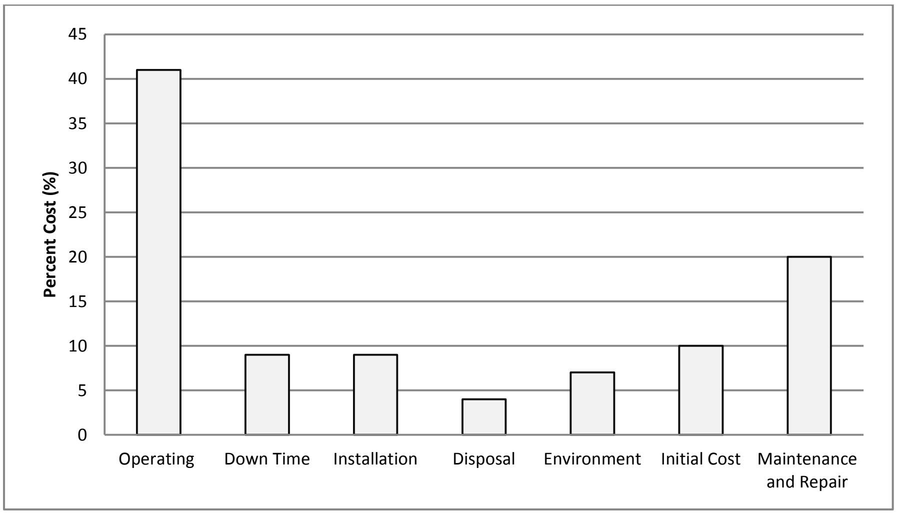


Figure 2.13 Life Cycle Cost Structure of a Pump (Kernan, 2013)

LCC analysis can be consisted of three main phases such as; the system itself, manufacturing of the system, and the system support. All these three areas are considered together to find the most efficient and the least cost during operation. Since the aim of LCC analysis is to determine the most feasible option in any of the process, it is quite logical to apply it to systems and projects at the design stage, during and after operation or even before manufacturing stage of the system. Several important operations that LCC analysis method can be used are:

1. Selection and decision making among different alternatives
2. Efficient and cost effective system selection
4. Renewal and revision of the investment
5. Marketing of new products to industry,
6. Monitoring of operating and maintenance costs,
7. Budget planning and allocation fur upcoming requirements of systems
8. Forming the cost break down structure and cash flows

9. Past budget track down of the systems in operation
10. Controlling of the existed projects and,
11. Forecasting the future operational costs and budgets for new investments.

Time value of money is considered in LCC analysis. Value of the money changes over period under effect of a certain interest rate that means some amount of money today does not equal to the same amount in the future. Present value method is computed by using present value discounting methods. In other words, the time value of money is useful tool in decision making process since it gives an idea regarding monetary conditions of the present and future status of investments and decisions. By using the time value of money concept together with LCC method, comparison among different selection options can be made. In other words, given that time value of money and LCC analysis are utilized in engineering economic analysis and decision-making process, all alternatives should be considered and only one selection is to be determined as the most feasible one. In scope of this study, LCC in usage phase of the pumps will be covered by applying net present value of technique. Manufacturing and disposal phases are not included in the scope of study.

2.4 Life Cycle Cost Studies in Decision Making

There are many studies in the literature regarding utilization of LCC in decision making. In literature some of the studies are focused on the general decision making process and its importance while others are focused on comparisons of different product using life cycle costing and engineering economy methods. On the other hand, another group of researchers are giving importance of the maintenance issue and reliability of the system which can make energy savings together with money. Typical structure of LCC is given in Figure 2.14

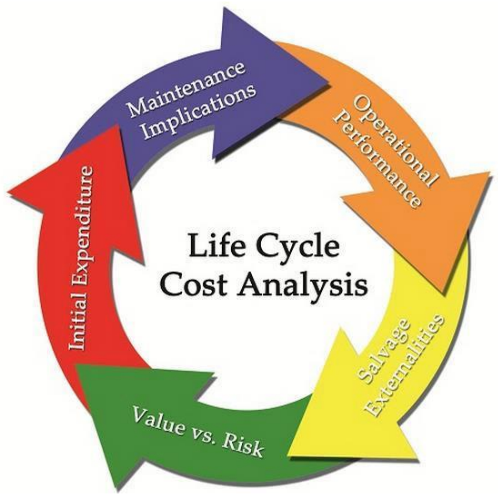


Figure 2.14 Life Cycle Cost Structure (Eco-Shift Power, 2015)

Valentin *et al.* (2012) analyzed the process of cost and benefit analysis in general. They outlined the basic steps in the cost and benefit analysis as economic model that is used in investment projects as a decision tool to see overall cost and benefit of project. They divided cost and benefit analysis into two types. First type was cost and benefits analysis before investment while second type is after project is completed. Cople and Brick (2010) concerned with simulation frame work general LCC analysis for industrial usage. The program framework they offer consisted of all cost components from purchasing to disposal including all operational costs. The author defined the most suitable way of dealing with this problem is to use LCC analysis. They believed a program was necessary for covering such a wide range in overall operating life of systems. On the other hand Jiang *et al.* (2004) suggested that LCC analysis can be used to determine the most feasible alternative among various sets of choices. They conducted an analysis with random variable due to uncertainties in estimating costs. They developed a model using randomly treated data for this selection. This study was useful since it gave a clear example of statistical model upon random variable data. Jiang *et al.* (2003) defined LCC analysis as a useful tool in decision making process in their study but they also refer that modeling of cost elements and systems were usually conducted via estimation. They summarized the statistical methods being generally used in these applications and they formed two new methods to be used for the same purposes. Cutt *et al.* (1997) claimed that cost control and gathering detailed cost component was useful in decision making process in any part of the heavy industry like mining. They pointed out that detailed cost analysis in a system together with unit cost and benefits should be analyzed in detail in order to achieve better decisions. On the other hand, Jin *et al.* (2003) pointed out that a methodology in selecting equipment is dependent on reliability and failure rate as well as maintenance and repair of equipment. Park *et al.* (2002) suggested an alternative LCC estimation method with contribution of the neural networks algorithms in order to compare different products from economic points of view. According to authors, by doing that best selection could be achieved by comparing all benefits and loses.

Some researchers study LCC in detail i and they emphasize that operating cost of system together with maintenance and repair issues which are crucial functions in a system under operation or planned to be procured. They believe that individuals need to understand the importance of maintenance and repair conditions of the systems that are necessary to be dealt in detail with LCC analysis. For instance, Pascual *et al.* (2008) studied effectiveness of system from maintenance points of views during its LCC. They classified the maintenance costs into two main components which are intervention and downtime costs. Former one is the cost of labor and material while latter one is the cost occurred when equipment fails. Barringer and Weber (1997) defined a well-constructed procedure for LCC assessment together with reliability analysis. The author stated the LCC as cost summarizing of a system from starting to disposal date. Monte Carlo simulation in calculating the annual maintenance cost was also introduced in the study. The author claimed that only procurement cost should not be used in decision-making process since sustaining and operating cost of equipment is much higher than purchase cost. For that reason the author stated that long term ownership concept equipped with LCC, reliability and maintenance costs over whole service life of a system is a better approach.

Johnson and Solomon (2010) made a cost and benefit analysis of wind turbine investment. They classified the cost and benefit of the system over 20 and 30 years of periods. Cost items were initial investment, operating costs, and maintenance costs while benefit was only limited to the electricity generation. Chen and Keys (2009) defined economic analysis of hauling equipment in mining from client and manufacturer point of views. They claimed that manufacturers make economic analysis of manufacturing process and considered warranties only while clients or end users put initial investment on top of priority list in their analysis. The authors argued that operating cost of heavy equipment is much higher than initial investment of equipment in most cases. On the other hand, Lutz *et al.* (2006) examined different types of boilers and furnaces used to generate heat in houses in the U.S.A. They examined operating and initial cost of these equipment according to amended design with a higher initial investment gives better efficiencies which is also a sign of giving less total ownership cost in the long-term base. In addition to this, Aktaçir *et al.* (2006) made economic analysis of constant air and variable air volume air conditioners in Adana in Turkey using present worth cost method. Author showed that energy consumption was more important than initial investment. Furthermore, Gustavsson (2002) studied air filters which were important part of the ventilation system in indoor air quality. For that reason, they stated that purchasing cheap options did not bring efficient operation and even sometimes they could cause the worst scenario when compared to expensive ones. They defined the cost components as energy, maintenance, investment, and disposal costs. The developed software calculated the energy cost according to analytical formulas for filters and for maintenance. Wei *et al.* (2001) compared the sewage sludge systems from economic point of view. They analyzed the different operating systems at different capacities and operating conditions. They applied NPV method to find the total cost of system. They collected costs from hypothetical models and divided costs into three categories, as fixed cost, capital cost, and operating cost. Similar to others, Chen and Wang (2001) made cost and benefit analysis of conventional cyclone and electro cyclone which were utilized in power plants for separation of fly ash particle from air. They defined that initial investment of electro cyclone was higher than conventional ones but when operating cost was also included in the cost of and benefit analysis, they found out that usage of electro cyclone was more feasible than conventional cyclones.

2.5 Rationale of This Thesis Study

Mine dewatering is an integral unit operation of the mining and it utilizes the pumps for sending water away from the operation area. Two different pumps types used in the mine dewatering are centrifugal pumps and positive displacement pumps. Both of these pumps have advantages and disadvantages. In order to understand the technical differences between two pumps, technical details are already given in literature survey of the study. Moreover, general information of pumps is also introduced and a new classification is made for pumps in previous sections.

Life cycle cost (LCC) technique is an economic analysis used to model and see the all associated cost component of a system. Total ownership cost of a system be sourced may be way higher than the initial investment of the same system. For that reason, investor or owners need to put effort in understanding the invisible cost of the system under evolution rather than just comparing the capital. By having this feature, LCC is studied by many researchers in various applications. As it can be seen in previous sections, decision making can be conveyed via LCC analysis to find the most feasible option.

It was interpreted that common point encountered in these studies is that initial investment alone does not reflect LCC of the equipment. Long-term cost structure of energy consumption, maintenance-repair activities are also as important as initial investment cost. It may be observed in the literature that there is lack comparative LCC analysis comparison with decision support tool in mine dewatering methods. For that reason, this study addresses the problem of LCC analysis of the pumps used in mine dewatering operation from decision making view. Suggested software was developed to make detailed cost break down structure and LCC for decision making which forms the main novelty of this study. It may be observed in the literature that there is lack of direct economic comparison of centrifugal and positive displacement pumps by using LCC. This study can be regarded as filling this gap by focusing on the importance of pump systems with associated overall costs.

CHAPTER 3

DATA OBTAINED FOR THE CASE STUDY

Mine dewatering is an important phenomenon since there is water flow to mining environment due to structural geology and topography. Unless this water inflow is removed from mining environment, it may cause severe problems. Lack of efficient mine dewatering can even lead to a mine owner and workers facing with production loss or safety concerns. It has already been seen a very dramatic mine flooding problems very recently in Turkey. Two examples from a large metal producer and one coal enterprise can also be regarded as illustrating examples to this problem. Former one has stopped the operation due to problem in mine dewatering pumps, latter one suffered from the same problem and stopped the gallery driving activity in underground.

Since aim of this study is to look for a comparison method between a conventional and relatively new mine dewatering method on basis of cost analysis, a real case data has been requested from a metal mine located in Turkey. This is a copper and zinc mine. It has been in operation since 1983. Yearly mining production is $1,2x10^6$ tonnes of ore. This mine suffers from mine dewatering design in 2007 and it ended up with replacing all its design to a different technique. They have started operation with conventional technique but due to operational problems they have replaced the system in 2004 with relatively better system. However; problems in mine dewatering system forced mine operator to replace the whole design in 2007. Total four years data available in the mine has been received and it is in two main formats. First one is submersible and centrifugal pump cost components while second one is positive displacement pump cost data including initial investment. Data for the years of 2004 to 2007 has been received. Cost components for the submersibles are as given below:

- Number of submersible pumps together with investment amounts,
- Pump specifications,
- Number of horizontal pumps together with design specs and initial investments, Table 3.1 and Table 3.2 represent the tabulated form of the data for submersible and horizontal pumps used in mine dewatering operations. This data will be used in manual LCC analysis as input to see the overall cost details of the submersible and horizontal type mine dewatering.
- Number of sumps and sump construction cost,
- Sump cleaning costs for submersibles,
- Maintenance and Repair Cost for submersibles and horizontal ones
- Spare Part Costs for submersibles and horizontal ones

On the other hand, second data set is gathered for positive displacement pump option. System has been replaced to positive displacement option upon making extra investment. Data for the years of 2004 to 2007 has been received. Data received for this option can be listed as:

- Total initial investment cost for single positive displacement pump,
- Pump specifications,
- Sump construction and operational costs for this,
- Maintenance and spare past costs.

Tabulated form of the data set for positive displacement pumps are given in **Error! Reference source not found.**. Manual LCC cost will be constructed with the help this available data to show the feasible option between two different systems. Calculations and results of manual LCC analysis given in following chapter is based on these data set. In submersible pumps, there are two types of pumps in different capacities . These pumps are named as Type 1 and Type 2. The difference in these types is mainly in head specification. First one is pumping mine water to 10 m with capacity of 20 l/sec while second type is conducting same duty for 20 m with capacity of 25 l/sec in operation. All cost units are in USD currency.

Table 3.1 Data Set for Mine Dewatering Operation with Submersible Pumps (Ofluoğlu, 2011)

Type of Data	Years							
	2004		2005		2006		2007	
Pump Type	**Type 1**	**Type 2**	**Type 1**	**Type 2**	**Type 1**	**Type 2**	**Type 1**	**Type 2**
Number Submersible Pumps	11	3	13	5	16	8	20	10
Installed Power (kW)	8	37	8	37	8	37	8	37
Number of Sumps	4	2	5	3	7	4	10	5
Sump Size (m^2)	25	50	25	50	25	50	25	50
Maintenance Costs ($ US/pump)	5,220	10,120	5,321	10,230	5,525	11,330	6,550	12,550
Spare Part Costs ($ US/pump)	1,020	2,950	1,120	3,100	1,230	3,210	1,733	3,530
Pump Design Head (m)	15	24	15	24	15	24	15	24
Pump Design Capacity (l/sec)	20	25	20	25	20	25	20	25
Head in Operation (m)	10	20	10	20	10	20	10	20
Capacity in Operation (l/sec)	15	20	15	20	15	20	15	20
Initial Cost of Pump for ($ US/pump)	3,650	11,070	13.200	12,000	4,400	13,200	5,000	14,300
Cost of advance ($ US/m^2)	622.60		626.40		660.00		670.00	

Table 3.2 Data Set for Mine Dewatering Operation with Horizontal Pumps (Ofluoğlu, 2011)

Type of Data	Years			
	2004	**2005**	**2006**	**2007**
Number of Horizontal Pumps	2	2	2	2
Pump Design Pressure (kPa)	4,500	4,500	4,500	4,500
Pump Design Capacity (m^3/h)	65	65	65	65
Capacity in Operation (m^3/h)	60	60	60	60
Pressure in Operation(kPa)	4,000	4,000	4,000	4,000
Motor Power (kW)	75	175	175	175
Maintenance and Spare Part Cost ($ US/pump)	32,120	33,890	35,630	38,750
Sump Size (5x5 m)	25	-	-	-
-Initial Cost of Pump for ($ US/pump)	43,200	47,500	47,500	47,500
Total Piping Cost ($ US/year)	95,350	32,978	39,467	45,236
Fuel Cost for Sump Cleaning ($ US/year)	150,010	151,610	170,150	179,200
Truck-Shovel-Man-Spare Part-Maintenance ($ US/year)	110,010	112,020	123,120	127,550
Cost Electricity ($ US/kWh)	0.101	0.106	0.107	0.109
Specific gravity of water in sumps	1.2	1.2	1.2	1.2
Operation Time (h/year)	6,000	6,000	6,000	6,000

Table 3.3 Data Set Mine Dewatering with Positive Displacement Pump System (Ofluoğlu, 2011)

Type of Data	**Years**			
	2007	**2008**	**2009**	**2010**
Number of Positive Displacement Pump	1	1	1	1
Designed Pressure (kPa)	6,500	6,500	6,500	6,500
Designed Capacity (m^3/h)	90	90	90	90
Actually Capacity (m^3/h)	65	65	65	65
Actually Pressure (kPa)	6,000	6,000	6,000	6,000
Rated Power (kW)	150	150	150	150
Maintenance of Pumps ($ US/pump)	10,000	15,000	25,000	30,000
Spare Parts ($ US/pump)	20,000	35,724	56,617	130,018
Sump Size (m^2) (10x5x10)	50	10	10	10
Screen Cost ($ US/pump)	15,000	-	-	-
Dewatering Channel Cost ($ US/pump)	100,000	-	-	-
Agitator Cost ($ US/pump)	20,000	-	-	-
Pipe Line Cost ($ US/pump)	100,000	-	-	-
Initial Cost of Pump ($ US/pump)	600,000	-	-	-
Fuel Consumption ($ US/year)	55,760	55,870	56,880	57,894
Cleaning Operation and Maintenance ($ US/year)	38,122	38,732	39,622	39,967
Additional Dewatering Pipe Line Cost ($ US/year)		32,750	41,510	50,160

3.1 LCC Comparison of Dewatering Systems

Based on input data, calculations are conducted and cash flow and cost break down structure are formed for both centrifugal and positive displacement pump options. During the calculations, interest rate was taken as 10 % and straight line depreciation method was applied for the cash flow formation.

In order to make a comparison common year was taken as 2007 when centrifugal system was replaced with the existing system. Cash flow and cost break down structure of the systems can be seen in Table 3.4 and Table 3.5. In cash flow table following items were calculated for each year:

- Initial investment costs,
- Maintenance and spare part costs,
- Total power demand of all pumping activities,
- Sump construction and total sump cleaning cost, and
- Total piping cost.

Depreciation was also calculated and used in the cash flow analysis. Initial investments were calculated based on the unit capital cost and number of pumps per year. Maintenance cost was given figure for each data set and it included the total man-hour spent by staff as well as consultants from suppliers.

Spare part cost was calculated based on the required spare part cost per pump and number of each pump type. Sump construction calculation was made according to sump sizes, number of sumps, and advance rate per meter square as given in data set.

In addition to this, sump cleaning cost was also considered. Sump cleaning cost is the total annual cost spent for transportation of the accumulated mud in the sumps made by two trucks, loader, and required operators and maintenance of the equipment specifically assigned for mud removal. Energy cost was calculated as product of pump shaft power and energy cost per year as given in Table 3.6. Pump shaft power, on the other hand, was determined as multiplication of pump pressure and flow rate. In order to make this calculation, units of flow rate and pressure need to be m^3/sec and kPa respectively. Piping cost was taken as total figure per year in the data set. Manual calculations can summarized is in below list :

- Initial investment: For centrifugal system, overall cost of investment is total of horizontal and submersible pump investment cost. Number of each pump type and associated initial investment on this year are available in the data set. Horizontal pumps are not replaced and invested only at the beginning of project. Submersible Type 1 and Type 2 pumps are procured every year due to requirement of operation. Total initial investment is found by multiplication of pump type number and initial investment of it. For Positive displacement pump initial investment is not merely for pump itself. There are items that are invested together with pump at the beginning of project. These items are pump, pump house, screen, agitator, and drainage channels. For that reason, initial investment of positive displacement pump system is calculated by taking summation of all these items at the beginning of project.
- Maintenance and Spare Part Costs: These cost items are given as unit cost for both of the pump types and are calculated by multiplication of unit cost by pump amount in that year. Spare part cost stands for the all purchased spare part inventory invested per year. Maintenance cost is given as total figure of labor and supervision and consultant cost born while maintaining the equipment per year.
- Total Power Cost: Power cost is calculated by product of pressure (kPa), quantity (m^3/sec), operation time (h/year), and electricity cost ($ US/kwh).
- Sump Construction and Sump Cleaning Costs: Sump construction is the cost of advance per meter square per sump area in the underground and it is calculated by product of sump area, advance cost, and number of sump per year. Advance cost is the total amount of cost to excavate a unit area of a sump including associated labor and maintenance cost of sump excavation equipment. Sump cleaning cost is total amount of cost incurred in order to clean mud accumulated in the cost and it is calculated by total cost of fuel,

maintenance and spares of cleaning equipment as well as labor costs for this operation

After all sub cost components were calculated, total net cost for associated year was found as summation of each cost component. Following this, in order to find and compare LCC analysis of the system, common year of 2007 was taken as base. In submersible and horizontal system, all total cost per year was discounted to 2007. The same operation was also done for positive displacement pump option. Table 3.4 shows the tabulated form of cash flow diagram for system with positive displacement pumps. On the other hand same tabulated table is also given in Table 3.5 for the dewatering system with centrifugal pumps. In these tables, cost breakdown structure is given, In addition to this, cost component in year of 2007 also given by discounting the figures by interest rate of 10%. In Table 3.5 Net present value is also given. This figure will be used to compare the hand calculations with program results.

Table 3.4 Cash Flow and Cost Breakdown Structure for PD Pump System

Type of Data	2007	2008	2009	2010	Total
Initial Investment ($ US)	1,070,000	0	0	0	1,070,000
Maintenance Cost ($ US)	30,000	50,724	81,617	160,018	322,359
Power Cost ($ US)	70,850	90,350	89,700	91,000	341,900
Sump Cleaning Cost ($ US)	93,882	94,602	96,502	97,861	382,847
Piping Cost ($ US)	100,000	32,750	41,510	50,160	224,420
Depreciation ($ US)	-18,000	-36,000	-54,000	-72,000	-180,000
Total Cost Component ($ US)	1,346,732	232,426	255,329	327,039	
Value in 2007 ($ US)	1,346,732	211,296	211,016	245,709	2,014,753

Table 3.5 Cash Flow and Cost Breakdown Structure for Centrifugal Pump System

Type of Data	**2004**	**2005**	**2006**	**2007**
Horizontal Pumps Investment ($ US)	86,400	0	0	0
Vertical Pump Investment ($ US)	73,360	32,000	52,800	48,600
Power Cost ($ US)	101,718	116,051	129,609	142,803
Maintenance-Spare Parts Cost ($ US)	172,090	218,163	295,660	403,960
Sump Cost ($ US)	140,085	46,980	66,000	83,750
Sump Cleaning Cost ($ US)	260,020	263,630	293,270	306,750
Total Piping Cost ($ US)	95,350	32,978	39,467	45,236
Depreciation ($ US)	-20,981	-47,722	-83,966	-128,959
Total Net Cost ($ US)	908,222	662,081	792,839	902,140
Value in 2007 ($ US)	1,208,844	801,118	872,123	902,140
Net Present Cost ($ US)	908,222	601,892	655,239	677,791

Table 3.6 Price Index of Electricity used in Cash Flow Analysis (Ofluoğlu, 2011)

Year	**Price ($ US/kWh)**
2004	0.100
2005	0.106
2006	0.107
2007	0.109
2008	0.139
2009	0.138
2010	0.140

When both options are discounted to common year of 2007 as shown in table 3.7 for manual calculations, it is seen that total figure of centrifugal system is 3.78 Million $ USD while same figure is 2.01 Million $ USD for positive displacement pumps. Total difference is 1.77 Million $ USD is less in positive displacement. This difference between two different systems can be used by decision makers to understand the feasibility of both options. In this case, system with positive displacement pumps yield less total cost when compared with centrifugal system.

Table 3.7 Comparision Table of Cash Flows

Type of Data	**Positive Displacement in 2007**	**Centrifugal Pumps in 2007**	**Centrifugal Pumps NPV**
Initial Investment ($ US)	1,070,000	358,041	269,001
Maintenance Cost ($ US)	263,789	1,222,215	918,268
Power Cost ($ US)	295,488	561,181	421,623
Sump Construction and Cleaning Cost ($ US)	333,162	1,694,314	1,272,964
Piping Cost ($ US)	201,764	255,464	191,934
Depreciation ($ US)	-149,450	-306,991	-230,647
Total Cost in 2007 ($ US)	2,014,753	3,784,224	-
Net Present Cost ($ US)	2,014,753	-	2,843,143

When cost figures in Table 3.7 are compared from total investment amount made in 2007, it may be seen that positive displacement pump system requires 0.71 Million $ USD more than centrifugal pump system.

It is also interesting to note that if these investments are compared on the NPV base by assuming that these investments are made at the same time for two different projects having similar mine dewatering specifications. It was resulted that total net present value of 2.84 Million $ USD of total LCC is calculated for centrifugal pumps. On the other hand, the same figure is 2.01 Million $ USD. Total LCC is 0.83 Million $ USD less in the positive displacement pumps.

The same case study was also considered using LCC based program, created for pump selection to support the decision makers at basic level in the next chapters. Output of the program addresses the question of feasibility of the both systems given that investment is made at the same time. Another main objective of next chapter will be to show the validation of program by comparing the total LCC of manual calculations and program results. Manuel LCC will be total net present cost of the both options.

3.2 LCC Program for Mine Dewatering Systems

In this section of the thesis, a program to calculate LCC of pumps will be introduced. As it has been pointed out that aim of this study is to form basic decision support tool that can compare the cost component of two different pump types in order to support the decision maker. By having this decision support tool, end user can calculate the LCC components of two pump types, centrifugal pumps and positive displacement pumps. As mentioned in various parts of this study, mine dewatering is conducted mainly in two different ways. First one is via combination of submersible and horizontal centrifugal pumps while second option is to make this operation by means of single positive displacement pumps. The developed program analyses two options differentially and finds out the total net cost based on NPV. Java programming language was used in construction of this program and Graphical User Interfaces (GUIs) were integrated. A flowchart algorithm was introduced in Figure 3.1. A part of source code of the software is also included in the A.1.

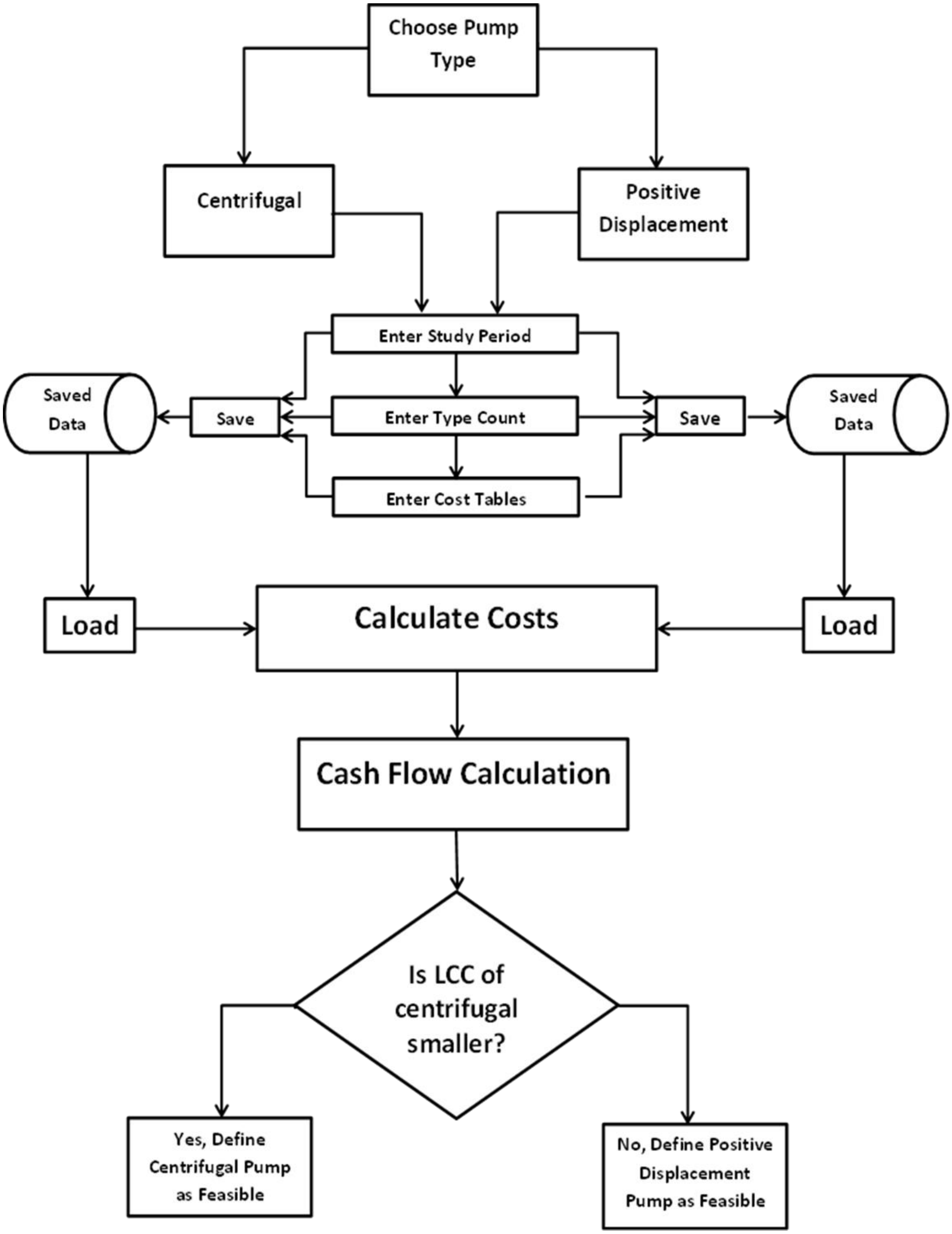
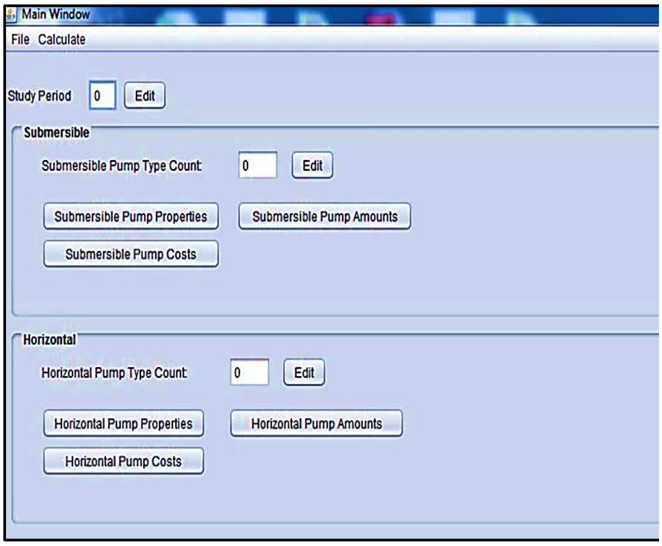


Figure 3.1 Flow chart algorithm of program

3.3 Input Data for Program

Like all similar programs, this software requires end user to enter data for forming a data base and for calculating all cost components. Program starts with asking the pump type. In this study pumps types are centrifugal and positive displacement ones. Centrifugal pumps are divided into two main sub components. These are submersible and horizontal pumps. After selecting the pump type two similar and separate windows are activated for end user. In these windows, given below, tool bars are activated and asked for end user to fill study period and pump types, pump properties, pump amounts, and pump cost center. Typical initial interface and the first segment of the selection part of the software is given in Figure 3.2 (a) and (b) below.



(a) (b)

Figure 3.2 (a) Main Window and (b) Pump Selection Window

Project period is entered and can be modified as requested by pressing edit button. Pump types button enables end user to enter the total number of different pump types in total life time of the pumping project. Pump type refers to any particular type. The reason for this is the fact that different types of pumps handling different volumes and alternating heads are used in the life cycle of the mine dewatering operation. For that reason in this part, number of different types of the pumps is entered. Pump properties of each pump type need to be entered another button to enter the following pump properties:

1. Pressure in kPa
2. Quantity in m^3/sec
3. Operating hour per year
4. Life time of the equipment in years
5. Pump Efficiency in percent decimal

Figure 3.3 shows the required data entered by user after pressing the pump properties button.

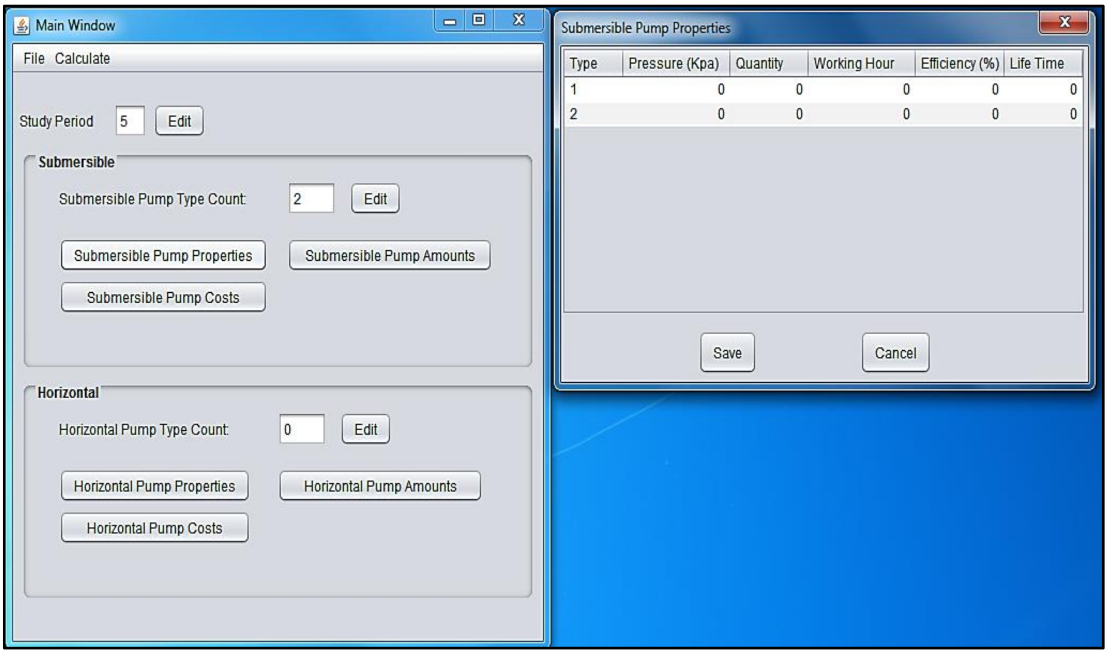
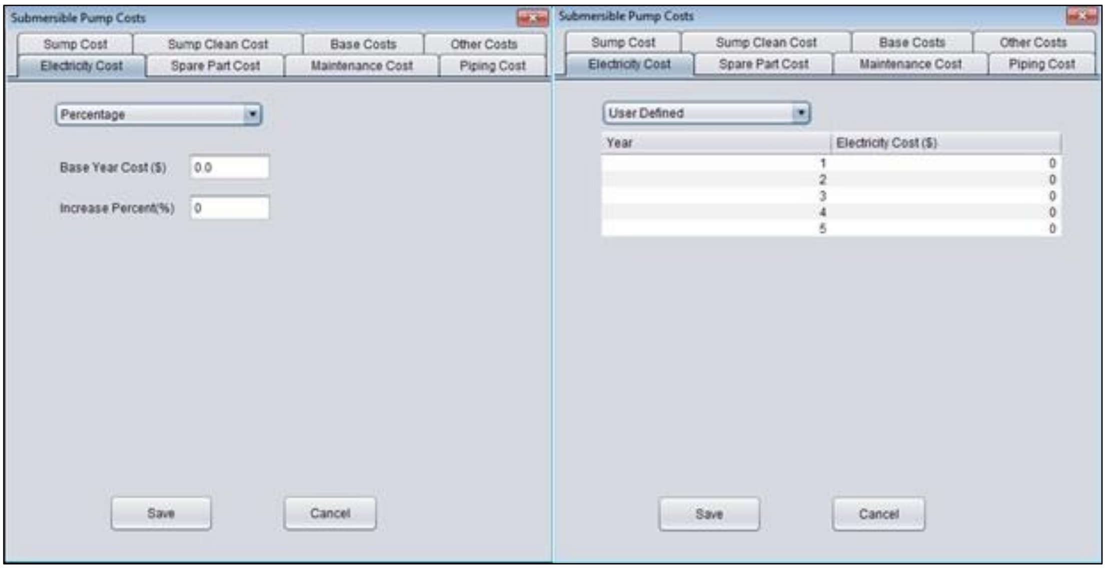


Figure 3.3 Pump Properties Segment of the Software

Pump number defines the number of all different pump types for each year. All these figures can be changed upon requirement by clicking the related years button without any problem. Pump cost button allows user to enter differential cost items. In this part of the program, end user has two options in several cost items. First one is to enter an initial year figure which can be increased by fixed percent every year while the second option is asking end user to enter all related component per year.

Required data entering for below given sub components are asked in pump cost part as shown in below and can be entered using the windows in Figure 3.4 (a) and (b). All data to be entered would be USD currency.

1. Energy Cost ($ US)
2. Spare Part Costs ($ US)
3. Maintenance-Repair Cost ($ US)
4. Sump Construction and Cleaning ($ US)
5. Piping Cost ($ US)
6. Initial Investment Cost ($ US)
7. Other Cost ($ US)



(a) (b)

Figure 3.4 (a) User Defined Data Input and (b) Base Year with Fixed Increase

In energy, sump clean-construction- piping, maintenance-repair cost items, user has options of either manual data entering or base year figure with fixed percent increment for overall year of the study. On the other hand, spare part and initial investment cost enables user to enter the price and salvage value of the pumps. Salvage value is represented by buyback option and it was used as depreciation analysis in the calculation mode. Straight line depreciation method was used and was deducted from overall costs. In energy cost of part cost electricity is the variable which was entered by user.

Maintenance-repair cost codes are man hour-hourly salary and amount of man working in the pump maintenance operation. In sump construction cost size of sumps and excavation cost in the form of advance cost is entered by user to form a database for construction. Piping-sump cleaning modes, on the other hand, are just for cost entering for database formation. In spare part construction part, numbers of critical spare parts together with their unit price were asked. These spare parts were defined by detail investigation and discussion of pump suppliers and several companies in the mining industry. Below spare parts were asked for both of submersible and centrifugal part cost items. Figure 3.5 is typical cost data center formation part of the program for spare parts.

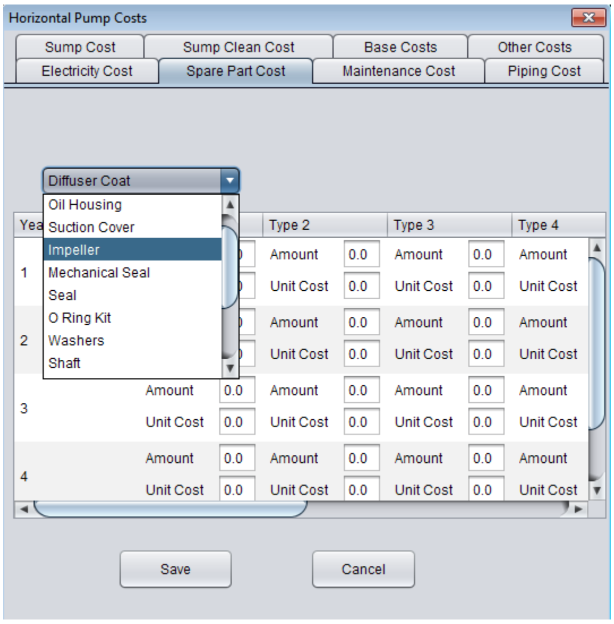


Figure 3.5 Pump Spare Part Cost Segment of the Software

Spare part items are defined after consulting with the pump suppliers. These items are either quoted with proposal sent to clients with critical spare parts per year or are the most frequently placed parts in overall spare part sale divisions. Since two pump types are different in nature of the operation. Required spare parts are different. Table 3.8 shows the spare part lists included in the program of the pump. Unit and price are entered for each part of the pump for each year. These figures can be edited later to understand the impact in cost break down structure.

Table 3.8 Centrifugal and PD Pump Type Spare Part List in Software

No	Centrifugal Pumps	Positive Displacement Pumps
1	Diffuser Coat	Suction Valve
2	Oil Housing	Discharge Valve
3	Suction Cover	Diaphragm
4	Impeller	Piston Rods
5	Sealing	Dampener
6	O Ring	Pump
7	Washers	Valve Seats
8	Shaft	2-2 way
9	Valves and Flanges	3-2 way valves
10	Bearings and Others	Others

There are several differences in positive displacement pump module similar to spare part list. Another difference is the initial investment cost analysis. Cost items are mainly different in here since investment is made from different point of view. Depreciation is done from pump price. Data of pump, screen, channels, and pump house are the component to be entered in initial investment mode of positive displacement pump. Typical section of this part of the program is given in Figure 3.6

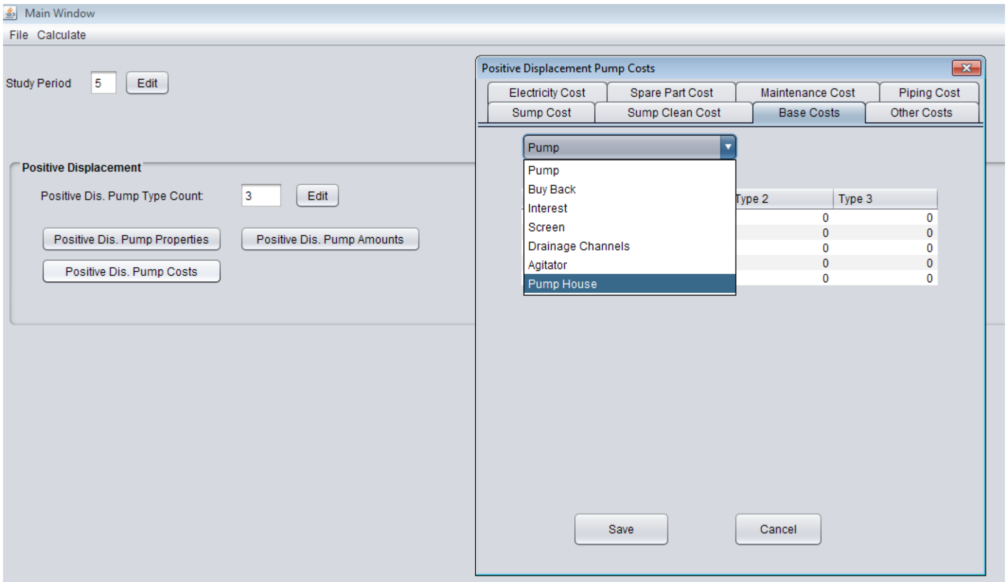


Figure 3.6 Initial Investment Segment of the Software

This window of the program shows the positive displacement pump option and it is designed according to requirements of it. In system with positive displacement pump, single stage pump is used in mine bottom. Moreover, there are additional requirements of this system as compared to system with centrifugal pumps. First difference is water channels to bring down the mine water in mine bottom. Second difference is larger pump house together with screen and agitator mounted in the pumping feeding point. Aim of this screen is to protect the larger particle to enter the pump and damage the diaphragm. These items are designed and invested at the first stage of the investment. For that reason they are given in initial investment window of the program. The program also capable of entering other cost items by end users. This module is designed for contingency purposes and if end user foresees any related cost item that is not defined in the program; this module helps end user to consider this item in the calculations. It consisted of simple table showing the year and total other cost component in this year. Typical other cost application is given in Figure 3.7. This cost item is added to total cash flow and total output of the program as LCC.

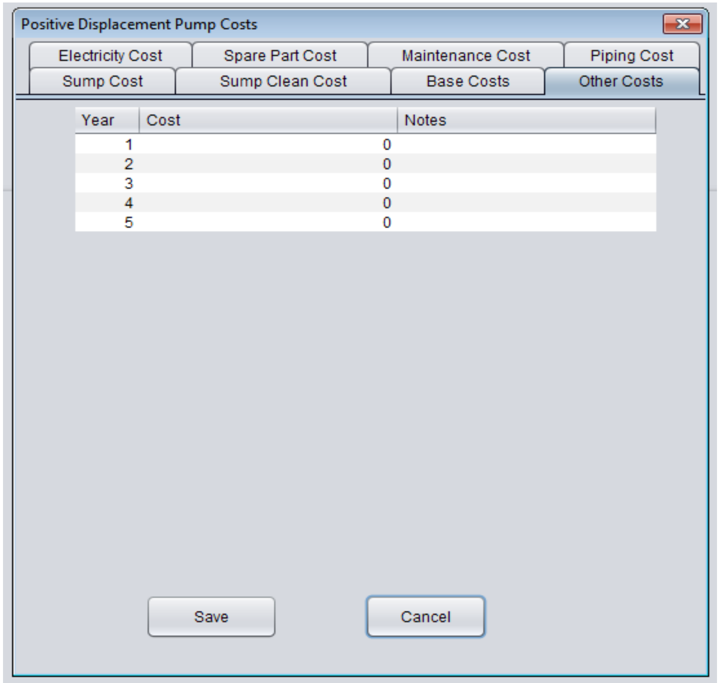


Figure 3.7 Other Costs Segment of the Software

CHAPTER 4

IMPLEMENTATION AND VERIFICATION OF THE PROGRAM

In this part of the study, data set given in previous section will be used as input to program to calculate LCC of mine dewatering system with centrifugal and positive displacement pumps respectively. In order to enter the data, pump type is selected and following input is entered by user.

1. Study period,
2. Pump types and pump numbers, and
3. Pump specifications.

Based on these databases, additional information for electricity cost, spare part amounts and unit costs, maintenance man hour cost, sump construction advance rates and sump amounts, sump cleaning costs, piping cost, capital investment of pumps and number of pumps are entered. In several areas, like piping, maintenance, electricity, and sump cleaning, cost can be incremented starting from a reference year. In this case, increment percentage need to be entered.

After all required data is entered computations are performed based on discounted cash flow analysis integrated in the program. In the program, calculate tool box can be used to see the below cost components according to various years. These cost components are:

1. Energy Cost,
2. Spare Part Cost,
3. Maintenance and Repair Cost,
4. Piping Cost,

5. Sump Cost,
6. Initial Investment, and
7. Cash Flow.

In all units, submersible and horizontal ones are shown in different tables to see and compare the total costs in both types. Under the cash flow button, cash flow analysis and net present value can be monitored. By having total net present cost value for all pump type, determining the one with the lowest cost can be selected. Typical example of cash flow and NPV result can be seen in Figure 4.1 and Figure 4.3

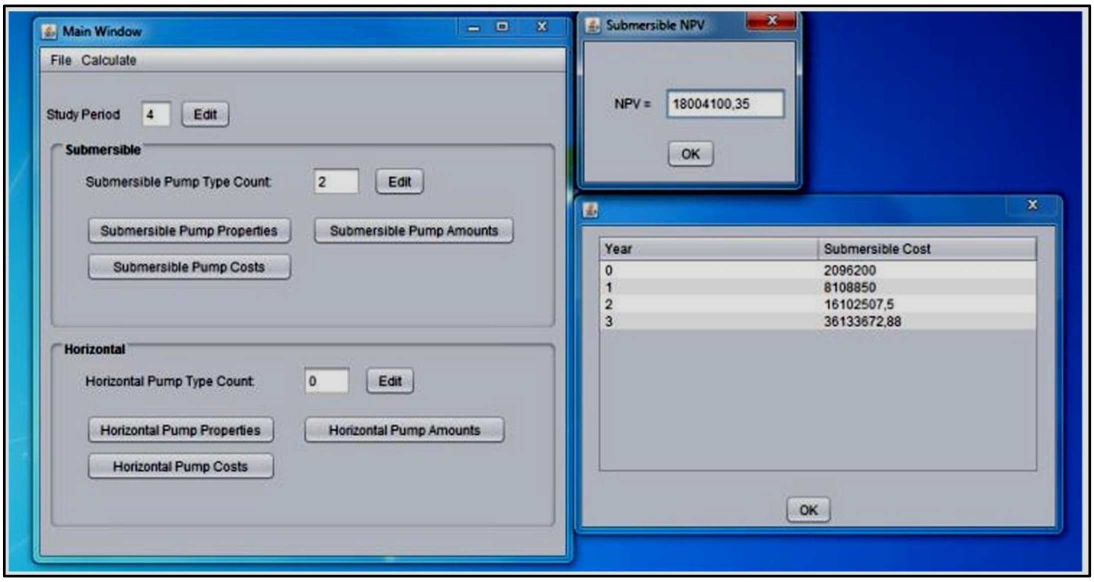


Figure 4.1 NPV and Cash Flow Windows of Program

File tool box can be used in order to save any draft study and visualize the previously saved draft. In order to open the saved drafts, first pump type needs to be selected under file tool box, then open menu needs to be clicked. Location of the saved draft is opened and file type in window is selected as all files than draft studies can be seen. After opening the required files any desired modification or view can be conducted.

When the same data set used in the previous section is entered as input to program, several assumption and combinations are made. For instance, while entering the data, piping cost is allocated in the horizontal pump cost center and sump cleaning cost is associated with submersible pump only. Since specific spare parts are not given with data set, spare part and maintenance cost is included in the maintenance cost center in the application.

When program is run with available data, following net present values are gathered. In the centrifugal pump option, total net present value is determined as 2.07 Million $ USD and 0.77 Million $ USD for submersible and horizontal pumps, respectively, as shown in Figure 4.2 and 4.4. On the other hand positive displacement pumps results in total figure of 2.01 Million $ USD as shown in Figure 4.5

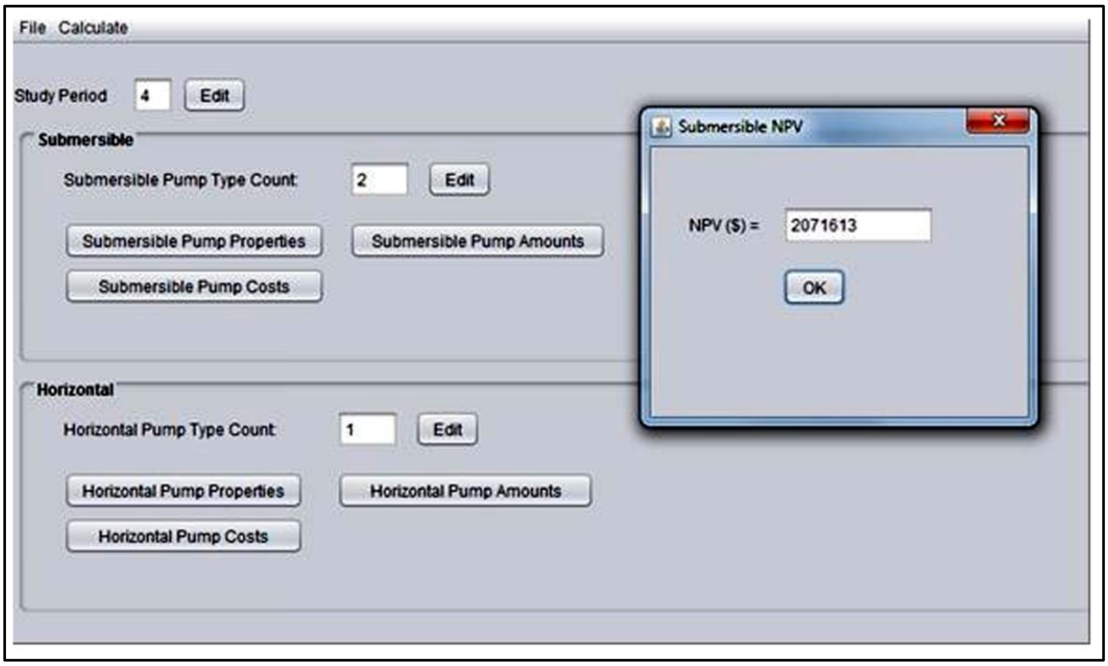


Figure 4.2 NPV of Typical Submersible Pump LCC

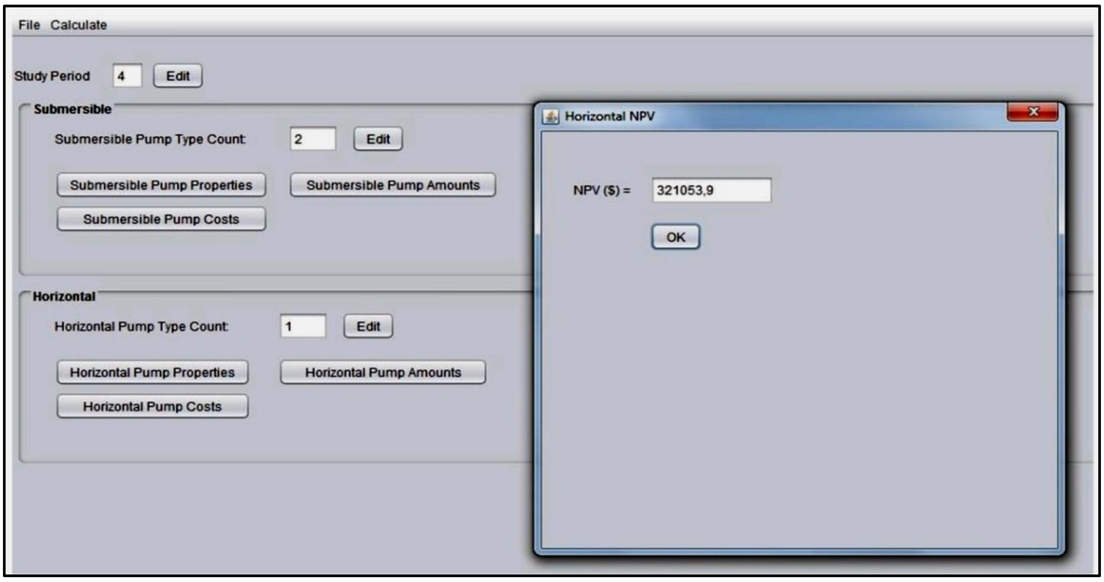


Figure 4.3 NPV of Submersible Pump LCC

Total LCC of submersible and horizontal option is 2.84 Million $ USD while positive displacement system yields total net present value of 2.01 Million $ USD LCC as net present cost value. Both of these figures are consisted with the manual calculation made with available data.

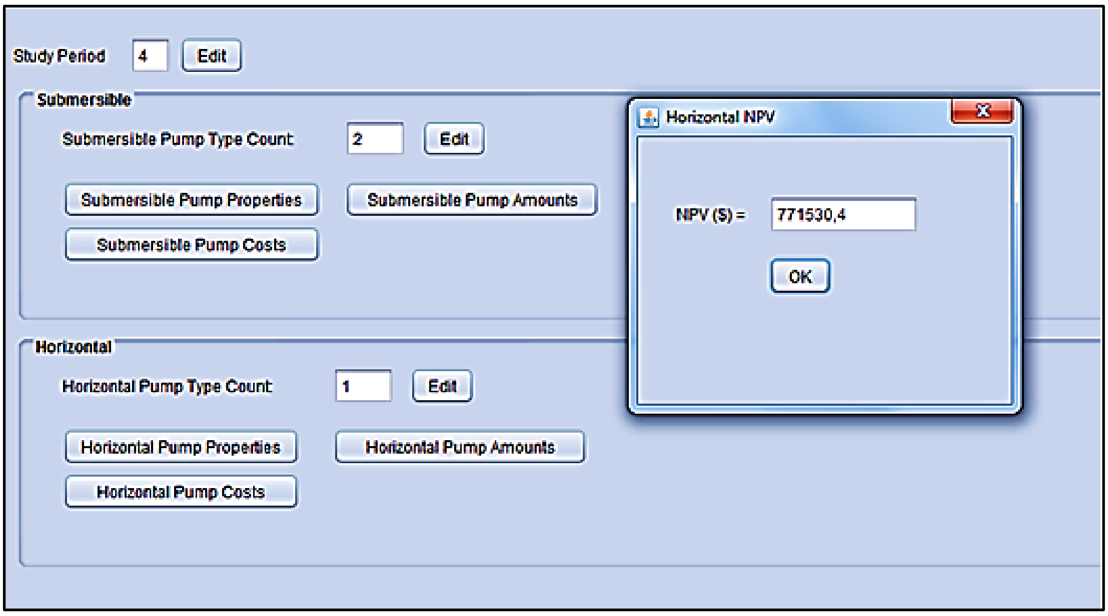


Figure 4.4 NPV of Horizontal Pump LCC

As a preliminary result it may be said that, decision making process can be supported and provided that two alternatives are compared. The lowest cost profile option can be selected at the beginning of the investment. This case calculation favors the option with positive displacement pump.

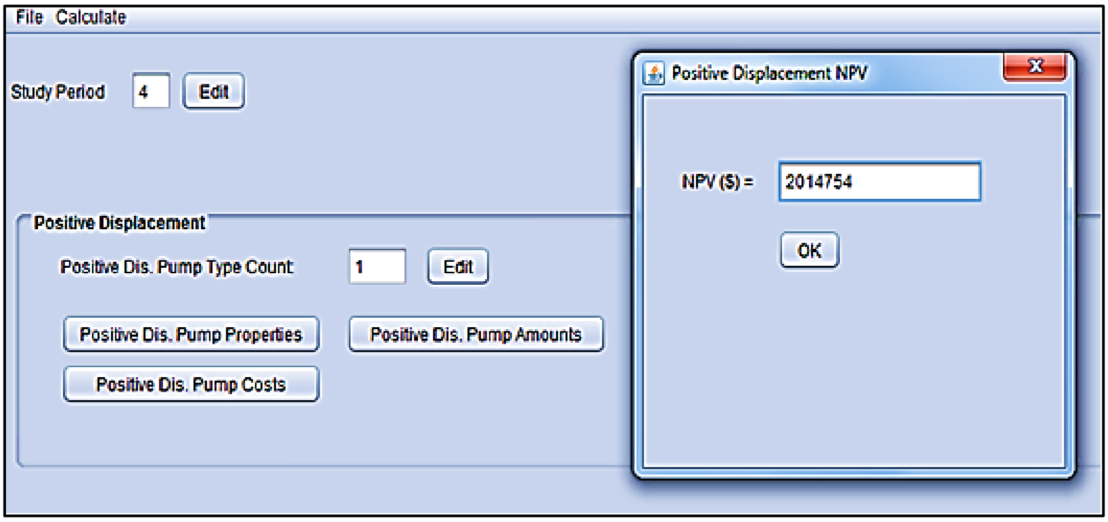


Figure 4.5 NPV of Positive Displacement Pump LCC

In this example, it may be suggested that net present cost positive displacement pumps is 828,389 $ USD is less than the system with centrifugal pumps. Based on the obtained result, it is also seen that initial investment of the positive displacement system is higher than the centrifugal pump system. By the help of this program, and these figures decision maker is supported in a basic level to select the most economic option. Moreover, decision maker has also option of visualizing all different cost components and associated portions of these items. Cost flow can also be seen in the program. As shortly, this program can be used to make preliminary evaluation of the two different pump system in mine dewatering operations. Based on the given data in one particular project, it turns out to be 29.13% of the total centrifugal pumps cost in positive displacement pumps which means decision maker can select option with positive displacement pump and start evaluation of this system in more detail.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study is conducted in order to compare the centrifugal and positive displacement pumps in mine dewatering activities by using LCC analysis and to develop a program as a decision support tool. Sample case data has been gathered from a mine used both of the system. Data from 2004 and 2007 represents the mine dewatering operation system with centrifugal pumps as a combination of submersible and centrifugal pumps while 2007-2010 data covers the mine dewatering system operation with positive displacement pump. Data, covering the years 2004 and 2007, is used to make manual LCC analysis to find the option with lowest net present cost as feasible option. Moreover, program was also developed to calculate the net present cost of the both system. This program based on LCC analysis can be used as decision support tool at basic level for selecting the pump types.

The major conclusions that can be made from this study are listed as:

i. LCC can be used as a decision support tool since it focuses on overall cost rather than initial capital investment cost of the systems. This can be used effectively in pump type selection of mine dewatering operations between centrifugal and positive displacement pumps since there is huge difference in initial investment of both systems.
ii. The program was developed with LCC concept that can be used in the selection process in mine dewatering system.
iii. When future value of the total investment is taken into account for the year of 2007 for both of the system, it is found that total investment made to positive displacement system is 711,960 $ USD more than total investment future value

of the centrifugal system. Ratio of the difference over total centrifugal pump investment is 1.98.

iv. Total energy cost in centrifugal pumps are 52.65% more (265,693 $ USD) than that of positive displacement pump. Since centrifugal pumps require more pumps due to the nature of operations. Centrifugal pumps are less efficient and as mine goes deeper total energy requirement of smaller pumps goes beyond the requirement of positive displacement pumps.

v. Total spare part and maintenance cost in common year 4.63 times more in the centrifugal pumps yielding a difference of 958,426 $ USD in grand total. This substantial difference is mainly for two reasons. First one is the fact that total number of pump requirement in the centrifugal system increases the spare part consumption. Second reason is mechanical and electrical problems encountered in these pumps. Hence; external maintenance supervisors and services are charged more.

vi. Total cost in the year of 2007 is determined 1.88 times more in centrifugal pumps in manual LCC. Same calculation also shows that there is 1,769,471 $ USD net cost saving in positive displacement pumps. When these figures are run in the software which can be thought as usage stage LCC comparison of these two systems at the same time, positive displacement pump option gives net present cost 29.14 % less than the centrifugal pump option with total cost difference of 828,389 $ USD. Hence, it is concluded in manual calculations that replacing the system from centrifugal pumps to positive displacement pump is right decision to save money from LCC perspective. On the other hand; given that both systems are compared by using the developed program, positive displacement pump option is determined as feasible since it gives the lowest total cost for the four years of operation.

The lists of recommendations for future studies in this research domain are listed as follows:

i. Efficient mine dewatering system is important for any mine since inefficient mine dewatering systems can cause mine flooding. Overflowing of sumps and lack of efficiencies may lead accumulation of excess amount of water in production places leading production lose or even casualties and injuries. In order to overcome this, technical comparison between two pumps systems should be the subject matter of other studies as LCC analysis shows that even a higher investment can yield better and more reliable results.

ii. Better design with centrifugal pumps such that optimization in maintenance-spare part inventory and sump amounts should be made since major operational cost item is in these areas. By improving dewatering system with centrifugal pumps will yield cost effective and safer design since there will be less spare part consumption and sumps will be on the operation.

iii. In the future studies, software can also be developed such that pump selection module can be added in the program. In order to do that, several pump curves will be defined in the system and depending on the head and capacity, pump suggestion will be made so that end user can only enter the expected water flow to mining environment. Sump sizes according to pump sizes can also be defined in the system so that alternative and optimum selections can be suggested to the end user after mine water amount is entered to system.

iv. Future value calculation and graphical visuals of the cost components can also be added as future topics of future studies as well as sensitivity analysis depending on the results are interpreted.

v. Treatment of the material depending on the constituents of the mine water can also be integrated in the cash flow. Given that there is a valuable ore in the mine water, this amount can be treated in mineral processing plant. In centrifugal option sump cleaning option can easily compensated while if it is possible initial investment can be paid back very shortly in positive displacement pumps especially in metal mines.

vi. Total amount of water being pumped by both of the pump types in operation years can also be gathered and used in order to compute the unit cost. This unit cost can be used in comparison of pump performances in total service life of the pump types. Unit cost together with total service life of the pumps can also be integrated to program calculation module for future studies.

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APPENDIX A

A.1 Source Code of Submersible Pump Section of Software

```
package javaapplication;
import java.util.ArrayList;
import java.util.Vector;
/**
 *
 * @author
 */
public class Study {
    private int yearCount;
    //submersible
    private int submersibleTypeCount;
    private Vector<PumpProperties> submersiblePumpProperties;
    private Vector< Vector <Integer> > submersiblePumpAmounts;
    private Cost submersibleElectricityCost;
    private PumpSparePartCosts submersibleSparePartCost;
    private Cost submersibleMaintenanceCost;
    private Cost submersiblePipingCost;
    private Cost submersibleSumpCost;
    private Cost submersibleSumpCleanCost;
    private BaseCosts submersibleBaseCosts;
    public Study() {
        yearCount = 0;
        submersibleTypeCount = 0;
        submersiblePumpProperties = new Vector<PumpProperties>();
        submersiblePumpAmounts = new Vector< Vector <Integer> >();
        submersibleElectricityCost = new PercentageCost();
        submersibleSparePartCost = new PumpSparePartCosts();
        submersibleMaintenanceCost = new MaintenancePercentageCost();
        submersiblePipingCost = new PercentageCost();
```

```
        submersibleSumpCost = new SumpUserDefinedCost();
        submersibleSumpCleanCost = new PercentageCost();
        submersibleBaseCosts = new BaseCosts();
    public int getYearCount() {
        return yearCount;
    }
    public void setYearCount(int yearCount) {
        this.yearCount = yearCount;
    }
    public int getSubmersibleTypeCount() {
        return submersibleTypeCount;
    }
    public void setSubmersibleTypeCount(int submersibleTypeCount) {
        this.submersibleTypeCount = submersibleTypeCount;
}
    public Vector<PumpProperties> getSubmersiblePumpProperties() {
        return submersiblePumpProperties;
    }
    public void setSubmersiblePumpProperties(Vector<PumpProperties>
submersiblePumpProperties) {
        this.submersiblePumpProperties = submersiblePumpProperties;
    }
    public Vector<Vector<Integer>> getSubmersiblePumpAmounts() {
        return submersiblePumpAmounts;
    }
    public void setSubmersiblePumpAmounts(Vector<Vector<Integer>>
submersiblePumpAmounts) {
        this.submersiblePumpAmounts = submersiblePumpAmounts;
    }
    public Cost getSubmersibleElectricityCost() {
        return submersibleElectricityCost;
    }
```

```
public void setSubmersibleElectricityCost(Cost submersibleElectricityCost) {
   this.submersibleElectricityCost = submersibleElectricityCost;
}
public PumpSparePartCosts getSubmersibleSparePartCost() {
   return submersibleSparePartCost;
}
public void setSubmersibleSparePartCost(PumpSparePartCosts pSparePartCost) {
   this.submersibleSparePartCost = pSparePartCost;
}
public Cost getSubmersibleMaintenanceCost() {
   return submersibleMaintenanceCost;
}
public void setSubmersibleMaintenanceCost(Cost submersibleMaintenanceCost) {
   this.submersibleMaintenanceCost = submersibleMaintenanceCost;
}
public Cost getSubmersiblePipingCost() {
   return submersiblePipingCost;
}
public void setSubmersiblePipingCost(Cost submersiblePipingCost) {
   this.submersiblePipingCost = submersiblePipingCost;
}
```