Comparative Analysis and Adaptation of Appropriate Hydro-powered Water Pumping Technologies for Smallholding Agriculture under Ethiopian Context

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A DISSERTATION

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Abstract

Smallholding agriculture, the basis of Ethiopian economy, abundantly remained rain-fed. One of the main reasons for its dependency on seasonal rain is lack of appropriate water supply facilities. Though there are a number of free energy and eco friendly technologies that ease the supply of water from streams and rivers to farm lands, none of them have been sustainably introduced. This reason made the title, and central objective of the research, to focus on introduction and adaptation of such technologies.

Comparative analyses have been conducted among thirty-three hydro-powered water pumping technologies, employing Multi-criteria Decision Making (MCDM) analysis, by selecting the appropriate method out of the many available. Fourteen criteria of comparison have been identified. Pair-wise comparisons, the basis for the comparative analyses, have been made against these criteria on the equal number of technologies that have been found to prequalify for further considerations. The analysis ranked the technologies by dividing them into two main categories, based on their suitability for the two main terrain characteristics of the country, rugged (highlands) and rolling (lowlands). The results have rigorously been checked for consistency and sensitivity and found to be strongly acceptable.

Hydraulic Ram Pump, the top ranking technology from both categories, is selected for adaptation. The adaptation on a commonly used model of hydraulic ram pump, has dwelled on efficiency and flexibility. The efficiency, in the main, focused on fastening closure time of the impulse valve through replacing the *weight-only* impulse valve with *spring-loaded* one. The surge created in hydraulic ram pump is known to be highly dependent, among others, on the speed of closure. The relative comparisons of times of closure between *weight-only* and *spring-loaded* valves show that tremendous improvement is possible. Flexibility is imparted by focusing on the interfaces between: drive pipe and main body of the pump; and pressure chamber and delivery pipe, and introducing parts that make the pump fit to varying discharges.

Key terms: bulk modulus of elasticity, closure time, comparative analysis, criteria weight, delivery height, delivery pipe, drive pipe, Eigen value, Eigen vector, fast closure, hydro-powered water pumping technology, Joukowsky equation, measure of performance, Multi-criteria Decision Making, normalization, pressure chamber, random index, slow closure, *spring-loaded* valve, supply valve, surge wave, water hammer, *weight-only* valve, Young's modulus of elasticity.

Dedicated to:

the late Biset Abate and Tsegaye Getahun
who used to call me ''Doctor''
when I was a high school and college student

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CHAPTER 1

1. Introduction

1.1. General

As per the forecast made by Central Statistics Agency, the population of Ethiopia, based on medium annual growth rate scenario, was forecast to have reached 105 Million in 2022. With same medium annual growth rate scenario (of 2.84 per cent), the population is estimated to rise to 137 Million in 2037. With the high annual growth rate scenario (of 3.10 per cent), it surpasses 142.5 Million by 2037 [1].

Ethiopia, a country of huge population, with high annual growth rate, is earning the lion's share of its foreign currency by exporting agricultural produces. Agricultural produces cover 42 per cent of the Gross Domestic Product (GDP) [2].

Private Agricultural Holding and Commercial Farms are the two major agricultural sub-sectors. Private Agricultural Holding includes rural – urban small and fragmented privately owned agricultural holdings on which all types of agricultural activities such as crop production, livestock rearing are performed by the operators/holders to obtain agricultural produce for self/family consumption and sometimes for sell. However, over 95 per cent of the annual gross total agricultural outputs of the Country is said to be generated from this sub-sector [2].

An Agricultural Sample Survey made by Central Statistical Agency [3] notes that the practice of irrigation in the Ethiopia has a long way to go to bring about the desired change. The Survey shows that the total irrigated crop area in the Country, within the private peasant holdings, is estimated to be 211,047 hectare. The farmers who practice irrigation were estimated to be about 1.3 Million.

Another sample survey [4] conducted by the Agency in 2020/21 shows that the Country has 70 Million cattle, 42.9 Million sheep, 52.5 Million goats, 2.15 Million horse, 10.8 Million donkeys, 8.1 Million camel, and 57 Million poultry. In Tropical Livestock Unit, the total livestock the Country had amounts to 79,730,000 TLU (Tropical Livestock Unit).

The aforementioned statistics show that:

1. Population of Ethiopia is huge and is increasing a very high rate;
2. The Agricultural sector continues to shoulder the different demands from such a huge population for the foreseeable future;
3. Small holding agriculture takes a significant share of the role played by Agriculture; and
4. Irrigation is at its infant stage.

For agricultural development, water is one of the major inputs. Agriculture, based on the way it acquires water, is divided in to two, rain-fed and irrigation. Rain-fed farming is planned based on the annual cycle of rainy seasons. As the rainy seasons have limited durations, the production seasons of rain-fed farming are also limited.

To sustain agricultural activities with less or no dependency on rain, irrigation is a very good alternative. Irrigation is an option of transporting accumulated river, surface or ground water to the agricultural field and using it for production.

Land holdings of Ethiopian farmers are small and fragmented, with an average of less than a hectare per family, and are likely to decline further with the increase in population. The average livestock ownership is 2 TLU. In the pastoralist area the livestock ownership increases to 2.4 TLU [5].

When one considers that 95 per cent of the annual gross total agricultural outputs are expected from the small and fragmented land holdings, it is clear to see that the effort to improve productivity of the small holding agriculture will have tremendous impact on the Country's economy. To increase productivity of the livestock as well, year round animal feed cultivation and supply of adequate amount of water are critical. In both cases irrigation plays a very vital role.

Irrigation requires transportation of water from the place of availability to place of usage. If the place of availability is higher in elevation than the place of usage, transportation by gravity could be possible. If, however, the place of availability is lower than the place of usage, then pumping is required. Pumps are the main inputs for pumping.

There are a variety of pumping technologies worldwide. Most of the pumps are factory products and use, in the main, electricity or fuel for their operation. Ethiopia imports these pumps expending a significant amount of foreign currency. Most of the farmers cannot use such imported pumps due to:

1. High initial cost -The average price (of around USD 600 for a unit) is significantly high for small holding farmers to afford [6].
2. Shortage of electric power (for electric pumps) and fuel (for fuel pumps) - In addition to the unaffordable initial price, motor pumps have other challenges such as high running cost, due to dependency on fossil fuel, and low access to electricity (54.2 % by population [7]). The price of fuel is also increasing from time to time and its availability at the work place of the farmers is not reliable. Import restriction of fuel pumps (by the Government) is also expected to be the other challenge of using diesel pumps.
3. lack of technical service (maintenance) and spare parts.
4. working hour limitation (due to over-heating of the pumps);
5. short service life;
6. green house effects.

Studies [8, 9] show that of all the pump types, diesel and petrol pumps have wide use, followed, at distance, by electric pumps. Treadle Pump and Rope and Washer pumps are the two locally made pumps that are known in Ethiopia. Both use uninterrupted human labor for their operation due to which reason their use is not expanding.

More than 54,000 water pumps have been distributed for irrigation purposes with the support from development partners, which helped cultivate some 280,000 hectares. However, Ministry of Irrigation and Lowlands has decided not to import water pumps that run on diesel and gasoline from May 2023 onwards in favor of green energy solutions [10].

1.2. Research Questions

Despite the dominance of farming and its huge number of livestock, Ethiopia is struggling for food self-sufficiency. Intensifying the annual yield per area and improving productivity of the livestock are two of the ways out of the chronic challenges the Country has been confronting. One of the requirements for this is securing dependable supply of water in all seasons. To attain this, the role of affordable pumping technologies is immense.

With all their shortcomings, Hydro-powered Water Pumping Technologies (HPWPT's) are good candidates to confront the challenges Ethiopian agriculture is facing and complement other efforts. The survey made by the conductor of this research, while preparing the Book on Hydraulic Ram Pump [11], has shown that application of such technologies is almost non-existent in Ethiopia. A comprehensive, worldwide spatiotemporal review made by scholars from two institutions in the Netherlands and one from Spain confirms this fact as well [12].

Research Questions: To formulate the objectives, the following research questions are raised.

1. What is Hydro-powered Water Pumping Technology?
2. What Hydro-powered Water Pumping Technologies are available?
3. What are the characteristics of the available Technologies (hydraulic, physical, technical, operational etc.)?
4. What should be the criteria of selection of appropriate Hydro-powered Water Pumping Technologies, for the different terrain and hydrologic classifications of Ethiopia?
5. Which of the available technologies are suitable for Ethiopia?
6. What common and specific shortcomings do the Technologies have?
7. What adaptation could be worked on to overcome the shortcomings and enhance suitability of the promising Technologies?

1.3. General and Specific Objectives of the Research

1.3.1 General Objective

In line with the aforementioned research questions, the general objective of the Research is to introduce appropriate free energy pumping technologies, and adapting of the most promising one/s, that enhance productivity of small-holding Agriculture in Ethiopia. The general objective is attained through fulfilling the following specific objectives.

1.3.2 Specific Objectives

1. appraising HPWPTs, pinpointing their inherent shortcomings and shortcomings as candidates for the conditions in Ethiopia;
2. crafting the criteria of comparison and conducting comparative analysis among the HPWPT's to select the suitable ones;
3. ranking the technologies based on their suitability/appropriateness for the different terrain and hydrologic characteristics of Ethiopia;
4. proposing the technologies appropriate to Ethiopia; and
5. working on adaptation of at least one of the most versatile and promising Technologies to enhance its suitability.

By addressing the aforementioned general and specific objectives, the Research fills one of the critical gaps in the journey of improving productivity of small holding agricultural in Ethiopia, that is, free energy water pumping technologies.

1.4. Scope of the Research

The six challenges (stated under the sub-heading "General") Ethiopian smallholder farmers are confronting with respect to the use of imported diesel or electric pumps invite introduction of the concept of Appropriate Technology during the comparative analysis. Sianipar et al. [quoted in 13] stated that appropriate technology has been acknowledged as the best solution for a given community under a particular condition.

Appropriate technology is small-scale technology which is simple enough that people can manage it directly and on a local level. Appropriate technology makes use of skills and technology that are available in a local community to supply basic human needs such as gas and electricity, water, food, and waste disposal. Appropriate Technology:

1. requires only small amounts of capital;
2. emphasizes the use of locally available materials, in order to lower costs and reduce supply problems;
3. would be relatively labor-intensive but more productive than many traditional technologies;
4. would be small enough in scale to be affordable to individual families or small groups of families;
5. can be understood, controlled and maintained by villagers whenever possible, without a high level of specific training;
6. can be produced in villages or small workshops;
7. supposes that people can and will work together to bring improvements to communities;
8. offers opportunities for local people to become involved in the modification and innovation process;
9. would be flexible, can be adapted to different places and changing circumstances; and

10. can be used in productive ways without doing harm to the environment. [14]

Proceedings of the International Workshop on Appropriate Technology [15] stated *Construction of Pumps that use the Water Flow as a Driving Force* as one of the Topics in Appropriate Technology Projects.

Scope of the research is, therefore, limited to the Hydro-powered Water Pumping Technologies that:

- could be manufactured and maintained at local level by Small Enterprises, and
- have relatively low production, running, and maintenance costs,
- have reasonable adequate literature coverage.

Due to these, turbine type hydro-powered pumping technologies such as: water current turbine pumps; hybrid turbine pumps; water turbine pumps; and tabular multi-propeller turbine pumps have not been made main focus of this research. The reasons for the exclusion are the following.

1. Water Current Turbine Pumps are generally difficult for the local farmers (or Small Enterprises) to manufacture and require water bodies that are large enough to produce tidal wave which are not promisingly available. If we take Markov self-propelled pump as a show case, it is to be manufactured in such a way that its propellers adjust their direction and angle in order to be aligned with the direction of the current. It also requires floating devices to keep it in water.

2. The other turbine type pumps are manufactured at factory level. Chinese Water Turbine Pump is presented and discussed briefly for representative comparison.

3. Apart from the difficulty of manufacturing at local level, turbine type pumps are generally suitable for rivers with higher flow volume and rate.

4. Most of the aforementioned technologies have very limited (or no) literature coverage.

1.5. Context and Significance of the Study

Ethiopia, endowed with numerous rivers and streams, holds immense potential for harnessing hydropower not only for electricity but also for water pumping applications. However, deficiency of introduction and adaptation of appropriate hydro-powered pumping technologies pose serious challenges. Factors such as local socio-economic conditions (very limited capacity of the small-holding farmers to acquire electric and diesel pumps), and acute shortage electric power and diesel, necessitate careful comparative analyses and adaptation strategies to ensure optimal performance and sustainability. In these regards, the study fills the dearth and lays ground for further researches.

CHAPTER 2

2. Materials and Methods

2.1 Introduction

Hydro-powered pumping technologies offer promising solutions for the critical challenges in sustainable agricultural water supply and climate resilience, particularly in regions like Ethiopia where, despite the abundance of water, access to pumping devices and reliable source of pumping energy is challenging. Water and Energy are both key to the Climate Resilience Green Economy and Ethiopia's goals for economic growth and poverty reduction [16]. This research endeavors to conduct a comprehensive comparative analysis and adaptation study of hydro-powered pumping technologies, specifically tailored to Ethiopian contexts. The overarching goal is to assess the technical feasibility, economic viability, social acceptability, and operational sustainability of various hydro-powered pumping technologies, thereby providing insights crucial for their effectiveness and utilization in Ethiopia's diverse geographic, hydrological and agro-climatic zones.

2.2 Methodological Approach

The study adapts a comparative and descriptive analysis approach, allowing for a systematic evaluation and comparison of different hydro-powered pumping technologies, and adaptation of the most promising one/s. Comparative analysis is a systematic approach used to evaluate and compare two or more entities, variables, or options to identify similarities, differences, and patterns. It involves assessing the strengths, weaknesses, opportunities, and threats associated with each entity or option to make informed decision [17]. A Comparative Analysis is a side – by – side comparison that systematically compares two or more alternatives to pinpoint their similarities and differences. The focus of the investigation might be conceptual, - a particular problem, idea, or theory – or perhaps something more tangible, like two different data sets [18]. A comprehensive research methodology combining qualitative and quantitative approaches is employed under the following six steps. Details of the methodologies employed are elaborated under the respective titles.

2.2.1 Literature Review

Thorough review of existing literature is made on Hydro-powered Pumping Technologies, focusing on: technical (hydraulic, hydrologic, and mechanical); operational; and social characteristics.

2.2.2 Data Collection

Data has been collected through a combination of literature review, manufacturers' specifications and experimental trials. Both literature coverage and application of the technologies at local level are assessed. This approach ensures acquiring of robust pieces of information encompassing technical and performance data, and practical insights from experts in the field, through their Articles.

2.2.3 Establishing Criteria for Comparison

Criteria for comparison are developed under four categories: Technical (hydraulic, mechanical); Economical; Social; and Operational. Fourteen such criteria are established. Fourteen criteria have been developed by: incorporating the ones obtained from literature; brainstorming; collecting experts' opinion in similar fields of study.

2.2.4 Conducting Comparative and Descriptive Analysis

The study adopts a comparative and descriptive analysis approach, allowing for a systematic evaluation and comparison of different hydro-powered pumping technologies. Qualitative descriptive studies (also known as 'exploratory studies' and 'qualitative description approaches') are relatively new in the qualitative research landscape. A qualitative descriptive study is an important and appropriate design for research questions that are focused on gaining insights about a poorly understood research area, rather than on a specific phenomenon. Since qualitative descriptive research study design seeks to describe rather than explain, explanatory frameworks and theories are not required to explain or 'ground' a study and its results. The researcher may decide that a framework or theory adds value to their interpretations, and in that case, it is perfectly acceptable to use them [19]. The research conducts detailed comparisons between different hydro-powered water pumping technologies by setting full-fledged criteria of evaluation that are categorized under four heads: Technical; Economical; Social; and Operational. Some criteria may fall under more than one category. Analyzing the Technical (hydraulic, mechanical); Economical; Social; and Operational characteristics of the varying technologies against the criteria of comparison are made to prioritize same, emphasizing their suitability for varying hydrological conditions prevalent across different regions of Ethiopia. The appropriate method of comparison is selected by weighing the relevance of abundantly available techniques. Analytical Hierarchy Process has been found to be the most suitable method for the cases at hand. The Analytical Hierarchy Process involves the following:

A. ***Establishing relative weights through pair-wise comparison***: Establishing relative weights are made for both the criteria of comparison and the technologies (alternatives). For the criteria of comparison, the relative weights are established by comparing each criterion with the rest of the criteria. Similarly, each technology is compared (weighed) against the rest of the technologies to establish the relative weight of the technologies. In each cycle of comparison, for both cases, consistencies are checked to be within the allowable limits. Unnecessary influences of scales are eliminated through normalization. Linear normalization (by sum) is chosen for its transparency and simplicity.

B. ***Aggregation of the Results of Pair-wise Comparison***: Ranking of the technologies is arrived at by aggregating the relative weights of pair-wise comparisons made for both the criteria and the technologies. This is done by: i) multiplying the relative weight given to each criterion by the relative weight won by each technology for the corresponding criteria; and ii) summing the products. Rank of the technology is determined as per the magnitudes of the sums.

C. ***Conducting sensitivity analysis on criteria weight***: Sensitivity analysis on criteria weight measures how robust the ranking is against alterations made to relative points won by the criteria. Sensitivity on criteria weights is measured by the relative variation (in %) required by the criteria weights to reverse ranks of the candidate technologies. If the ranking obtained has high sensitivity, it shows that the ranking is likely to be altered with slight changes of weights of the criteria. Ranking with high sensitivity cannot be highly dependent as subjective evaluations are highly likely to show slight variations from person to person and from trial to trial.

D. ***Conducting sensitivity analysis on measure of performance***: Sensitivity analysis on measure of performance looks for the threshold value (in %) by which the measure of performance of a candidate technology (as manifested through the relative weights won by the criteria) needs to be modified such that the ranking of a candidate technology swaps with the rest of competing technology/ies. Each technology is checked against the rest of the technologies for the threshold value. The lower the threshold value is the less dependable the ranking will be. For convenience of comparison, the term *criticality degree* is introduced. The smaller the criticality degree of a technology (an alternative)is, the easier the ranking of that technology swaps with the other alternatives (technologies).

2.2.5 Categorization and Adaptation

The prioritized technologies are clustered, mainly based on: i) their flow requirement (discharge and head for their operation), and delivery head, and ii) mechanics of operation.

Of the identified, reviewed, and analyzed (prioritized) technologies, the most promising one is further examined to look for gaps (inherent and specific to application of the technology in Ethiopia) that need to be addressed in order to enhance its suitability. The cause/s for the gaps are traced following Root Cause Analysis method, a structured facilitated process to identify root causes of an event that resulted in an undesired outcome, and develop corrective actions [20]. Adaptation that improves suitability of the technology under varying hydrologic and geographic conditions is made. For the adaptation, hydraulic and mechanical properties of the selected pump are examined against the better performing one/s.

2.2.6 Validation and Recommendations

Validation of findings of the adaptation is made against selected indicators of improvement. Recommendations to implement the adaptation are also discussed. Areas for further research are included under this topic.

2.3 Ethical Considerations

Ethical considerations guide all aspects of the research, adherence to research ethics guidelines, and responsible dissemination of findings.

2.4 Conclusion

By systematically investigating and comparing hydro-powered pumping technologies under the Ethiopian context, this research aims to contribute valuable insights into sustainable energy solutions that align with local environmental, economic, and social priorities. The subsequent sections of the paper delves into each methodological step in detail, presenting analyses, findings, and recommendations essential for advancing ranking of the technologies and adaptation of the appropriate one/s.

2.5 Limitations and Considerations

Vast subject matter Experts opinion could not be obtained as all the technologies have very little or (in majority of the cases) no familiarity in Ethiopia**.**

CHAPTER 3

3. Literature Review

3.1. General

As the research is based on Comparative Analyses of Hydro-powered Water Pumping Technologies (HPWPTs), and there are thirty three such technologies to be compared, the literature review covers the hydraulic, mechanical, technical, and physical, characteristics of the thirty three pumps. As the literature review establishes the basis for the comparative analysis, it takes considerable portion of the volume.

3.2. Hydro-powered Water Pumping Technologies

Hydro-powered Water Pumping Technologies (HPWPTs), are those technologies which pump water by using the energy contained in the water to be pumped. They do not need any other source of energy, such as fossil fuel, electricity, solar, wind … etc. They use only energy of the water to be pumped. As the technologies use energy of the water itself, they do not pump all the volume that imparts the possibility of rising water well above elevation of the source. This is due to conservation of energy. Based on specifics of the technology, the source of pumping could be kinetic, potential, tidal … etc. energy.

The In the following section, the available HPWPTs are reviewed with emphasis on their: prime movers; pumping principles; head requirement; and flow of energy conversion. Based on similarities of their pumping principles, the reviewed technologies are classified into groups.

3.2.1 Manometric Pumps

Positive displacement pumps consisting of pipes winding around a fixed central point partly submerged in water that rotate and alternatively take in both water and air pockets through open ends (inlets) in each rotation are known as manometric pumps. The other ends (outlets), which pass through the central (longitudinal) axes, are connected by water tight rotary fittings to a fixed pipe. Manometric pumps (one group of HPWPT) are so named as they operate on the principle where the series of loops of the pipe, separated from one another by the trapped air columns, act as manometers. The total lifting head at the outlet results from the addition of the manometric head differences in each loop. The shape of the winding pipe can be either planar, convolved in a three dimensional cylindrical surface, or in a conical one. Besides, regarding the water stream, the axes of the pipes can be cross flow or axial flow [12].

Throughout this research the cross-flow non-planar, cross-flow planar, axial flow non-planar are referred as:

- Hydro-powered Coil Pump
- Hydro-powered Spiral pump; and
- Hydro-powered Helix Pump respectively

1) Hydro-powered Coil Pump (Wirtz Pump)

Coil Pump, also known by its other name - Wirtz pump, (after Zürich Pewterer Andreas Wirtz who invented the pump in 1749 [21] - is one of the hydro-powered water lifting technologies. Coil Pump is a coil of pipe, wound to form a cylindrical coil rotating about a central, longitudinal axis of the cylinder (Figure 3-1 [22]). Portion of the wheel is immersed in a flowing water in such a way that the flow provides the energy necessary for the rotation of the wheel. One end of the coil lies on the outer area and the other end passes through the longitudinal axis. The scooping tip (the outer end) of the coil dips below the surface of a running water once per revolution and the other end of the coil leads to the center of the wheel where it joins a rotary coupling that leads to delivery line. Coil Pump is cross-flow non-planar as the coil is arranged in three dimensions and it is positioned in a stream in such a way that the flow of the stream is perpendicular to the axis of the drum. It is easily adapted to be driven by the running water and can be used to pump water to a height of 20 meters and a maximum flow rate of at least, 43.6 m^3/day [23]. The flow of energy conversion in Hydro-powered Coil Pump is shown in Figure 3-2.

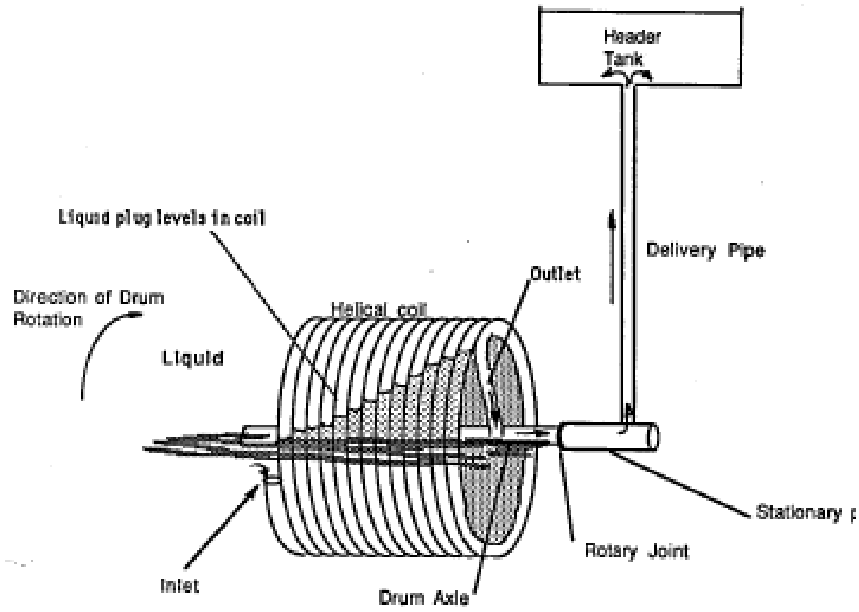


Figure 3.1: Schematic representation of Coil Pump

With each rotation of the pump, the scoop collects and fills portion of the volume of outer coil. Several water columns are generated inside the Coil, separated from each other by columns of compressed air trapped between the water columns. As water is driven into the inner coils, each column of water transmits the pressure through the air to the preceding column of water. In this manner, the water in each coil is displaced to provide a pressure head. A cumulative pressure head which is the summation of the pressures developed in each trap is built up at the outer coil and water is conveyed through the rotary fitting to an elevated delivery point. In Coil Pumps, therefore, the number of coils (number of water columns) determines the net pumping head.

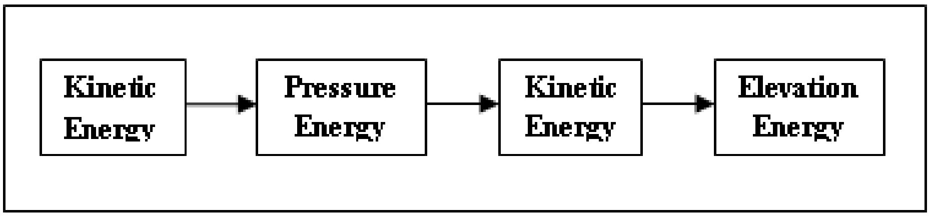


Figure 3.2: Flow of energy conversion in Hydro-powered Coil Pump

Figure 3.3 shows a single loop taken from Figure 3.1. Its simplified representation is the one shown in Figure 3.4. Figure 3.1 has same configuration as Figure 3.5, but arranged as "n" -turn Archimedean spiral, a Coil. For the given arrangement, the Coil rotates in counterclockwise direction (as seen from left side) and its open end (inlet / scooper) is submerged for some time in water at each rotation.

Figure 3.4 models a simple manometer which shows that the pressure difference between p_1 and p_0 is Δh. The actual pressure difference depends on the density of the fluid in the manometer. In Figure 3.5, "n" such manometers are connected in series. Assuming that the fluids in the "n" columns are similar, the pressure difference between H_T and H_A is $\Delta h_1 + \Delta h_2 + \Delta h3 + \ldots + \Delta hn$. Its standard form is given as Equation 3.1 [24].

$H_P = H_T - H_A = \sum_i^N h_i$	*Eqn. 3.1*
Where:	
$H_P =$	the supply head
$H_T =$	the absolute pressure head at the outlet,
$H_A =$	the atmospheric pressure and
$h_i =$	the pressure differential produced for each water plug for the N produced plug inside the Coil where N is the number of coils or manometric loops

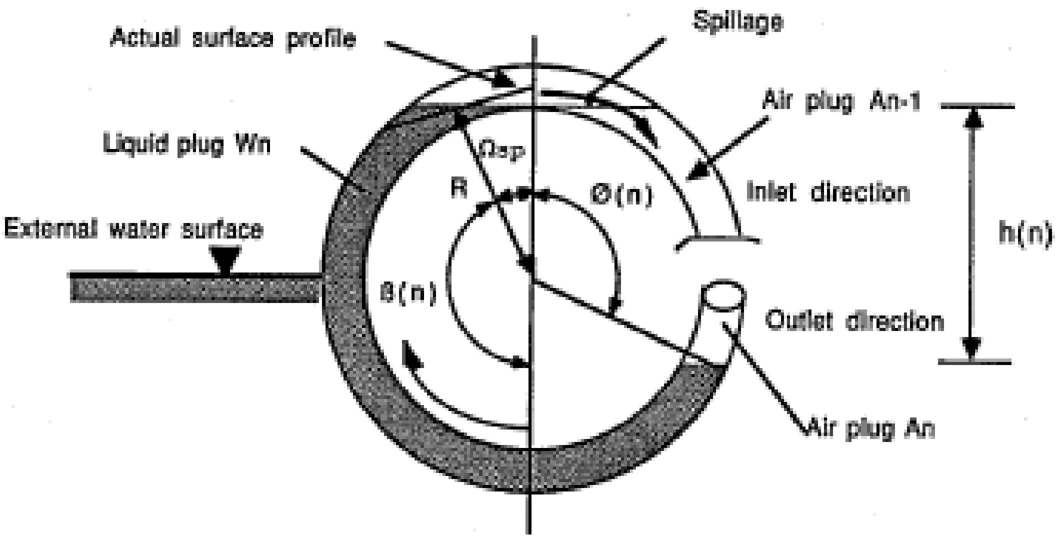


Figure 3.3: A single loop from the Coil Pump

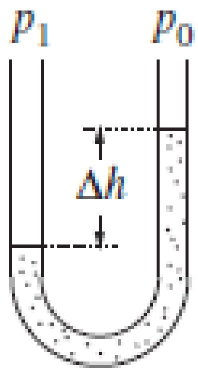


Figure 3.4: Simple manometer (Source: [21])

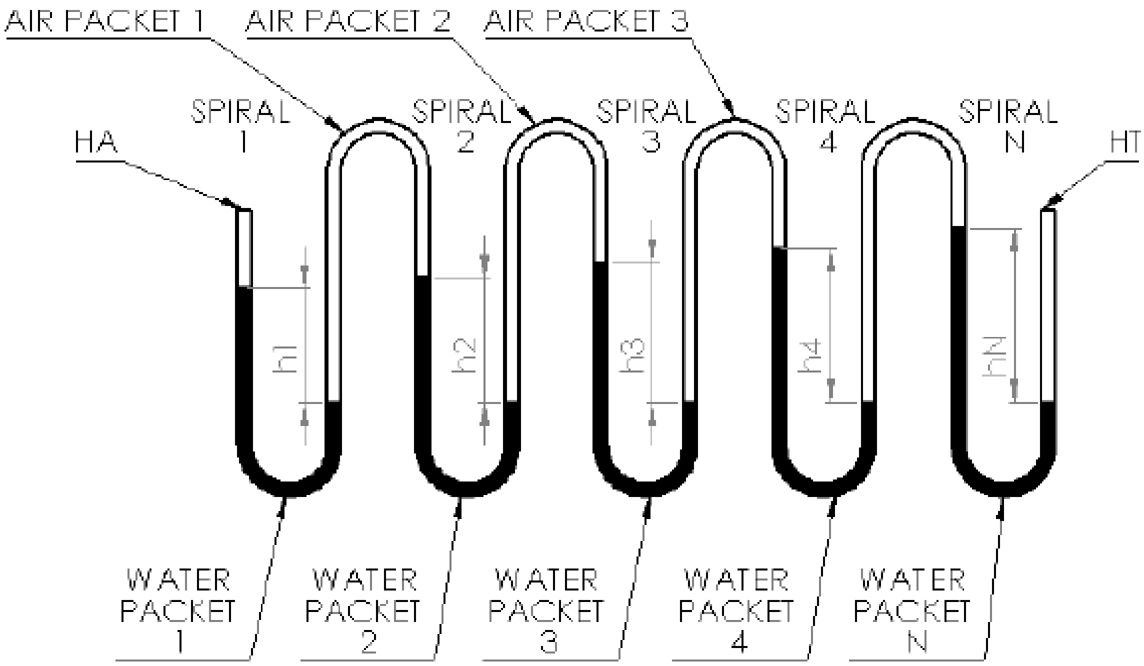


Figure 3.5: Manometric representation of the Coil Pump [21]

The Coil Pump analytical model to determine the flow rate and the pumping head was proposed by Mortimer and Annable as presented by Equation 3.2 [24].

$Q_P = N_S * \pi R^2 L_{W1}$	*Eqn. 3.2*
Where:	
Q_P =	flow rate through the pump
R =	distance from the center of the wheel to the middle line of the external loop of the pump.
Ns =	the rotational velocity of the Pump (cycles per minute)
L_{W1}=	length of the first packet (slug) at the pump inlet

Air plugs length are the result of the path of the Pump inlet rotating above the water surface. The presence of consecutive water and air plugs produce an intermittent delivery.

The initial volume of air plugs, specifically for the first coil depends on the drum geometry, the hose internal diameter and the pump submerged percentage. Because the air plug is limited by the water plug next to it, different air pressures are developed. The air pressure can be studied using a polytrophic relation (Equation 3.3) [24]

$PV^{1.15} = constant$	*Eqn. 3.3*
Where:	
P=	absolute pressure in the air plug
V =	the packet volume

As the air plugs are moving from the inlet to the outlet of the pump, the developed high pressure reduces the air plug volume increasing the water plug volume. This volume change can be calculated using the polytrophic relation shown by Equation 3.4. When the water plug reaches the crown (center) of the coil, a spill back of the water plug can occur eliminating he air plug between them. Disappeared air plugs involve loss of produced pressure differentials in the coil causing an outlet pressure reduction.

$H_A L_A^{1.15} = H_n L_{A.n}^{1.15}$	*Eqn. 3.4*
Where:	
H_n=	The absolute pressure head in coil *n*
$L_{A,n}$=	The air plug length in coil *n*
H_A and L_A=	The head and length of the occupied space by the air in the pump inlet

Therefore, the air plug length change between different coils can be determined by Equation 3.5 [24].

$L_A - L_{A.n} = L_A(1 - {}^{H_A}/_{H_n})^{0.87}$	*Eqn. 3-5*

The established flow pattern in this type of pump is characterized by a sequence of air and water plugs produced during operation of the Pump. This discontinuation of flow will not be a concern if the pumped volume is stored which is the situation in most cases. In order to properly design a Coil pump, a sequence of calculations are essential to meet the given requirements. The most important analytical relations are the following.

Equation 3.6 [13] provides the coil radius in terms of L_{AA} and L_{BB}, that are related to the length between the pockets in the hose per rotation.

$L_{BB} - L_{AA} = 2\pi R$	*Eqn. 3.6*

The pump discharge is a function of the drum angular velocity, the hose cross-sectional area and the submergence ratio as shown in Equation 3.7 [13].

$Q_D = L_{W1} * A_T * \omega$		*Eqn. 3.7*
Where:		
Q_D=	Pump discharge	
L_{W1}=	Submerged ratio of the Pump	
A_T=	Cross sectional area of the hose	
ω =	Angular velocity of the Pump (in revolution per minute)	

Finally the required torque M under the established pressure conditions is computed employing Equation 3.8 [13].

$M = (H_D - H_A) * A_T * R$		*Eqn. 3.8*
Where:		
H_A=	Atmospheric pressure	
H_D=	The total pump outlet pressure	
R =	The drum radius	

The main characteristics of Wirtz Pump are depicted in Table 3-1

Table 3.1: **Summary of main characteristics (Wirtz Pump)**

Principal mover	Water wheel
Pumping principle	Positive displacement
Integration	Direct attachment
Required head	No head requirement
Position in water	Partly submerged

2) Hydro-powered Spiral Pump

A Spiral Pump is a rotating coil of pipe, mounted in a vertical plane about a horizontal axel generating a spiral that is fastened to a water wheel. The Spiral tube could be single where the wheel is only one, and it could also be double where the wheels are two. Where the tubes are spiraled at both ends of a drum, it is also named as Bashra Pump. Portion of the water wheel is immersed in a flowing water in such a way that the flow provides the energy necessary for the rotation of the wheel. The scooping outer pipe coil dips below the surface of running water once per rotation and the inner coil leads to the center of the wheel where it joins a rotary coupling that leads to delivery line (Figure 3.6 [21]). It is easily adapted to be driven by the running water and can be used to pump water to a height of quite a few meters. The flow of energy conversion in Hydro-powered Spiral Pump is shown in Figure 3.7.

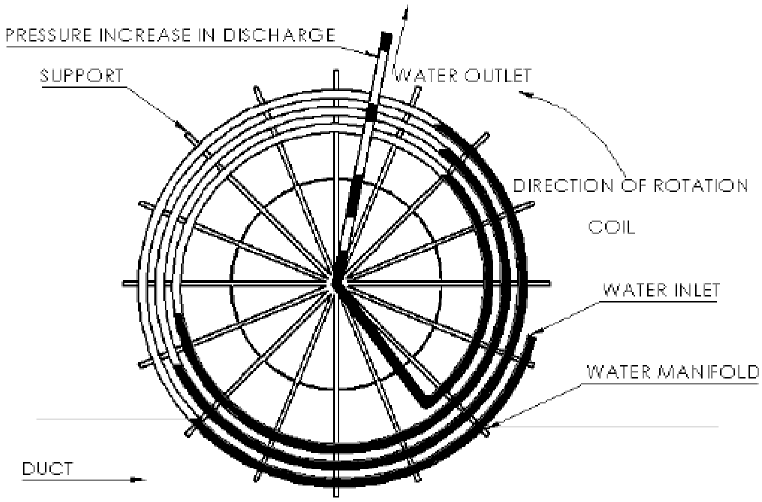


Figure 3.6: Schematic representation of Hydro-powered Spiral Pump

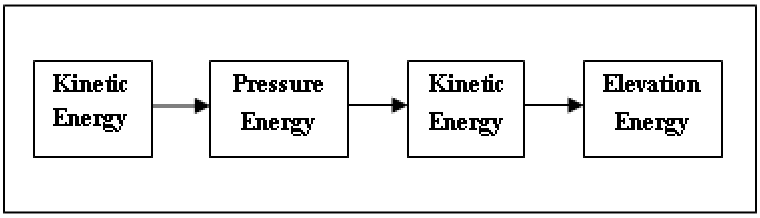


Figure 3.7: Flow of energy conversion in Spiral Pump

Coils Pump and Spiral Pump are basically similar. The difference between them is that in Coil Pumps as the pipe is wound around a drum, each coil assumes similar diameter while in Spiral Pump the diameter increases while moving from center to the outer, as each coil is wound on a single plane. Due to their similarities the models developed for Coil Pump could also be used for Spiral Pumps as well. Manometric representation of Hydro-powered Coil Pump could be used to Hydro-powered Spiral Pump as well. Spiral Pump is cross-flow planar as the spiral is arranged in a plane and its is positioned in a stream in such a way that the flow of the stream is perpendicular to the axis of the spiral. The main characteristics of Spiral Pump are depicted in Table 3-2.

Table 3.2: Summary of main characteristics (Spiral Pump)

Principal mover	Water wheel
Pumping principle	Positive displacement
Integration	Direct attachment, Coaxial shaft
Required head	No head requirement
Position in water	Partly submerged

3) Hydro-powered Helix Pump (same as Rife River Pump)

Hydro-powered Helix Pump is a modified version of Hydro-powered Coil Pump (Figure 3.8). The difference is that:

1. Hydro-powered Helix Pump is put in a case and has a propeller; and

2. The energy of the flowing water that rotates the Pump is transmitted through rotation of the propeller (which is the prime mover), fixed along the longitudinal axis of the Coil. The rotary coupling passes through the center of the propeller and is connected to the delivery pipe. Using right-hand-rule, the rotational direction of the propeller is same as that of the flowing water.

The flow of energy conversion in Hydro-powered Helix Pump is shown in Figure 3.9.

Figure 3.8: Photographic view of Hydro-powered Helix Pump (Source [12])

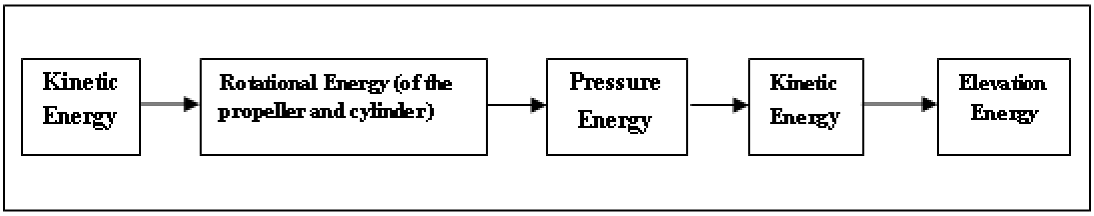


Figure 3.9: Flow of energy conversion in Hydro-powered Helix Pump

Helix Pump is axial flow non-planar as the spiral is arranged in three dimensions and it is positioned in a stream in such a way that the flow of the stream is parallel to the axis of the drum. Manometric representation of Hydro-powered Coil Pump could be used to Hydro-powered Helix Pump. The main characteristics of Helix Pump are depicted in Table 3-3

Table 3.3: Summary of main characteristics (Helix Pump)

Principal mover	Water wheel
Pumping principle	Positive displacement
Integration	Direct attachment
Required head	Zero head
Position in water	Partly submerged

3.2.2 Lambach Pump

Lambach Pump pushes water using the pressure head contained in a river. The process of pumping is as follows.

1. The river flow from an elevated position enters into the pump via the inlet of the blue section from the right hand side. For the position where the Pump is at, the left green valve is closed and the right green valve is open and this allows water to flow to the right (blue) chamber. The pressure head of the water entering into the right chamber pushes the right twin pistons to the right, thereby pushing water in the right cyan chamber (right cyan pipe) up. The pressure in the blue chamber (that is equal to the pressure head of the incoming flow) is amplified by the ratio of the area of the larger piston to that of the smaller piston. The pumping height depends on this area ratio. Neglecting the friction and other losses, the pumping height would be calculated using Equation 3.9.

Pumping Height =Pressure head of the flow to the chamber * $\frac{Areaoflargerpiston}{Areaofsmallerpiston}$	*Eqn. 3.9*

   Upward flow of water to take place, the lower valve of the right (cyan color) chamber allows flow only in the upward direction.

2. The right twin pistons, the left twin pistons, and the rail of the upper smaller gear are joined as one frame. At the position where the pump is at, both the left and right twin pistons are moving to the right. Due to the rightward movement of the frame, the weight that is attached to the upper gear is rotating counter clockwise. The right ward movement of the right twin pistons pushes water in the right cyan chamber up, and same movement of the left twin pistons pulls in water from light cyan left chamber.

3. By the time the right twins reach their limit, the rotating weight tips over and comes down to hit the lower rail of the larger gear. The hit displaces position of the lower gear to the right and the rail takes position E-A. This position opens the right yellow valve, opens the left green valve, closes the right green valve, and closes the left yellow valve. This condition allows water to flow to the left chamber and push the twin pistons to the left (with the total frame). The leftward movement of the twin pistons pushes water up via the left cyan pipe and pulls water via right light cyan pipe.

4. During the leftward movement of the twin pistons, the weight that is attached to the upper gear rotates clockwise. Such cycle repeats and in each cycle water is alternatively sucked and pumped. The water through the right and left cyan pipes are joined at the top left corner and moves up. The discharge that is used to alternatively pressurize the right and left chambers flows out to join the stream. Under these circumstances, water is sucked and pumped from the immediate downstream of the river.

The flow of energy conversion is shown in Figure 3.10.

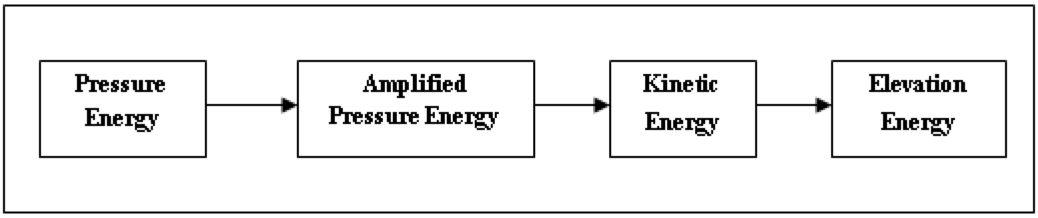


Figure 3.10: Flow of energy conversion in Lambach Pump

Lambach Pump has two types (vertical pistons and horizontal pistons). The one shown in Figure 3.11 of horizontal pistons type. Figure 3.12 shows sectional view of Lambach Pump with horizontal piston. The main characteristics of Lambach Pump are depicted in Table 3-4.

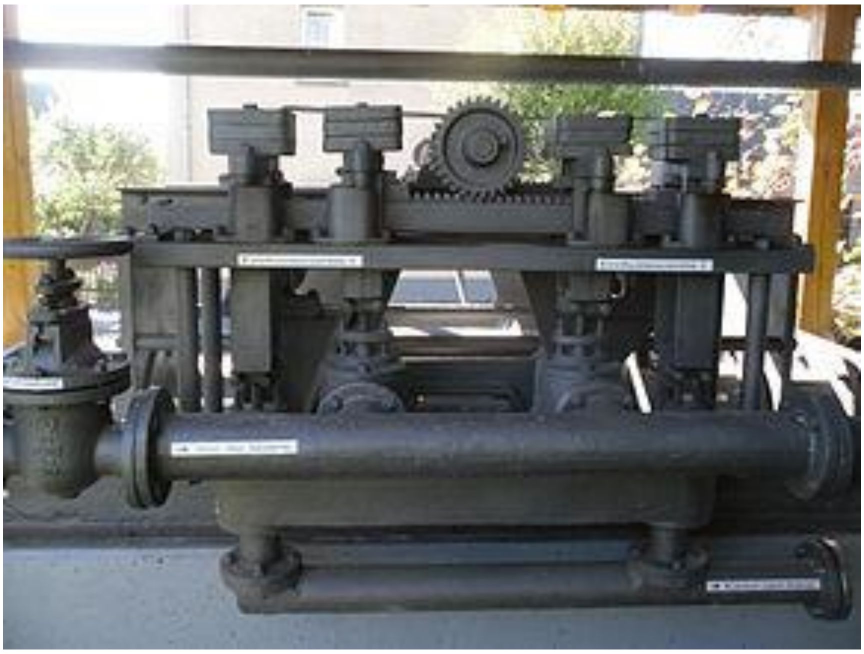


Figure 3.11: Photographic View of Lambach Pump (horizontal piston). Source [25]

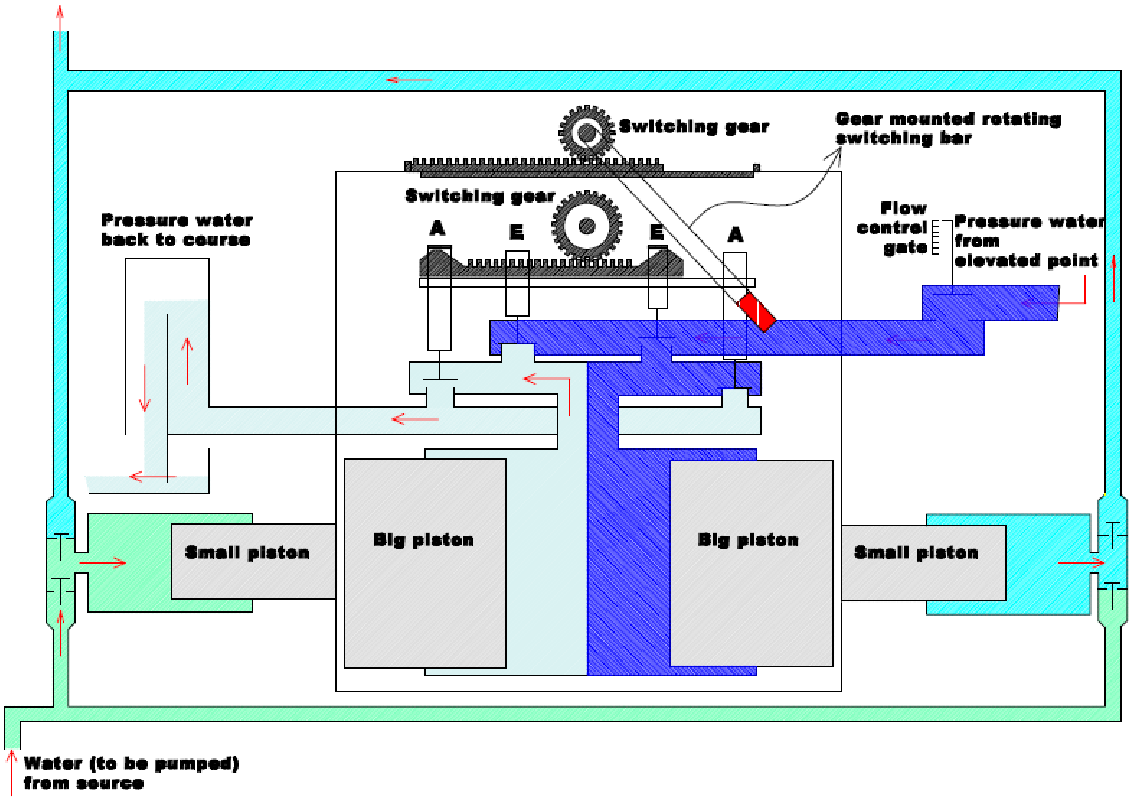


Figure 3.12: Sectional view of Lambach Pump - horizontal piston. (Source: redrawn from [26])

Table 3.4*:* Summary of main characteristics (Lambach Pump)

Principal mover	Pressure head
Pumping principle	Positive displacement
Integration	Piston
Required head	Low head
Position in water	Over surface

3.2.3 Hydrautomat Pump

Hydrautomat Pump is composed of water tanks arranged vertically. The pump shown in Figure 3.13 is composed of four tanks (A, B, C, D). Tank A (open reservoir), tank B (sealed tank with valve that allows flow only in the upward direction), Tank C (feeder tank, open tank with valve that allows flow only in the upward direction), and tank D (pumping tank, sealed, with an automatic valve that allows downward flow direction during suction phase and closes during the pumping phase). The Pump works in two phases, Suction Phase and Supply Phase.

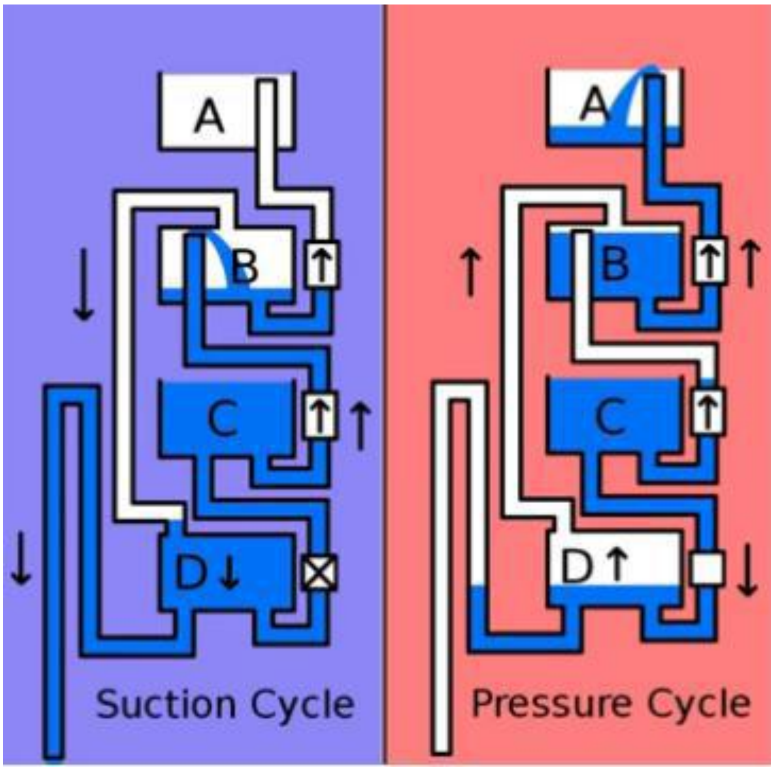


Figure 3.13: Schematic representation of Hydrautomat Pump (Source: [27])

In Suction Phase, water from the source enters into tank C in which case the valve of tank D is closed. Water is then allowed to flow to tank D by opening its valve. The water level rises up through the siphon till it reaches the water level of tank C. Here it is good to note that the upper tip of the siphon assumes same level as the full water level of Tank C. Filling of the siphon triggers downward flow. The process till this stage is known as Suction Phase. When the siphon flow starts, the valve to tank D will be closed. Flow of water through the siphon, develops sub-atmospheric pressure in tank D which is transmitted to the sealed tank B through the connecting line. As valve of tank D is closed, the sub-atmospheric pressure created in tank B sucks water up to tank B. This ends the Suction Phase. The strength of suction depends on the outlet level of the siphon. The lower the outlet is the higher will be the suction strength. Tank B and tank C has valve that allow flow only in the upper direction.

When is now allowed to flow to tank D by opening its valve. Raise the level of water in tank D will create high pressure in the line that connects tank B and Tank D. As both tanks are sealed, this pressure pushes up the water in tank B to tank A (reservoir). The pressure created in the line that connects tanks B and D mainly depends upon the volume of tank D. The suction (negative) pressure depends on the length of siphon pipe below the bottom of tank D. The flow of energy conversion is shown in Figure 3.14. The main characteristics of Hydrautomat Pump are depicted in Table 3-5.

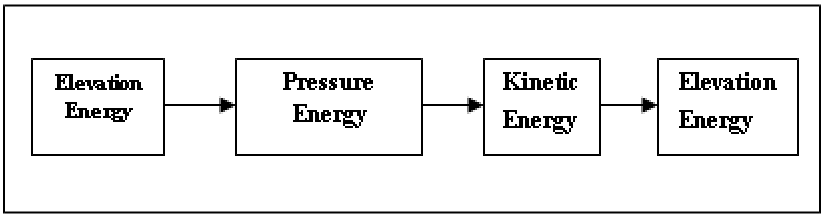


Figure 3.14: Flow of energy conversion in Hydrautomat Pump

Table 3.5: Summary of main characteristics (HydrautomatPump)

Principal mover	Compressed air
Pumping principle	Positive displacement
Integration	Piston and Valve
Required head	Low head
Position in water	On surface

3.2.4 Cherepnov Pump

Cherepnov Pump consists of three interconnected tanks. The two tanks (tank 1 and 2) are placed at a higher elevation than the third tank (tank 3). Tank 1 is an open tank while tank 2 and 3 are compressor tanks. A siphon is connected to tank 3. The energy flow of the Pump is given in Figure 3.15.

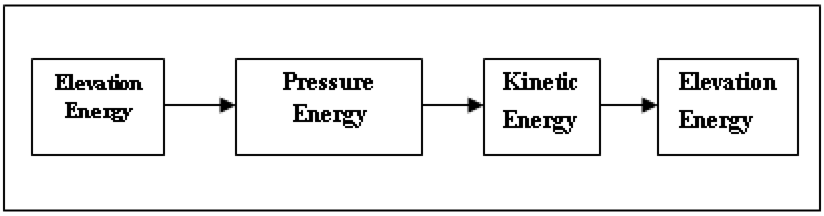


Figure 3.15: Flow of energy conversion in Cherepnov Pump

Referring to Figure 3.16, water from a source enters tank 1 by gravity. Portion of the flow goes to tank 2 through a line (with one way valve that prevents back flow) that connects the two tanks. When the level of water reaches the opening of the stand pipe, it starts flowing to the third tank. The rising water level in tank 3 compresses the air in the tank and increases its pressure. This pressure is transmitted to tank 2 and pushes water up through the delivery line above the elevation of the source. As water is forced out of tank 2, the water levels in tank 3 and the siphon rise. When tank 2 is drained, the water level in tank 3 reaches its top, and the water in the siphon reaches to its crest. The siphone is thus automaticallu activated, causing the water in tank 3 to drain through the siphon. The siphon continuous to drain water till the water level in tank 3 has fallen to the elevation of the siphon inlet. This breaks the siphon action and tank 3 is vented. The lifter has now completed a cycle and will immediately start a new cycle. This cycle repeats at a frecuency that depends on the design of the lifter. Some similarities are observed between Cherepnov and Hydrautomat pumps. Both use compression of air by flowing water into sealed tanks [28]. The main characteristics of Cherepnov Pump are depicted in Table 3-6.

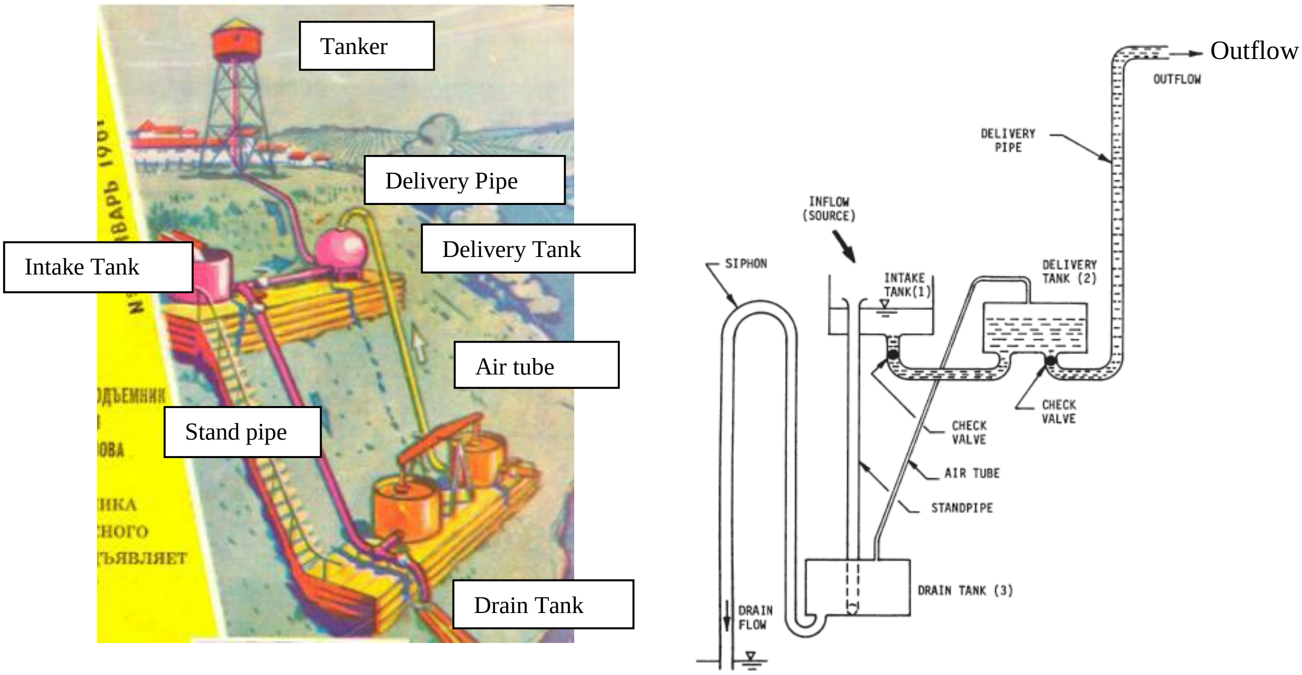


Figure 3.16 : Schematic representation of Cherepnov Pump (left) and its sectional view (right). (Source: [12, 23])

Table 3.6: Summary of main characteristics (Cherepnov Pump)

Principal mover	Compressed air
Pumping principle	Positive displacement
Integration	Valve
Required head	Low head
Position in water	On surface

3.2.5 High Lifter Pump

The High Lifter (Figure 3.17) is a double-acting, reciprocating differential piston, fluid-powered pressure intensifier. It transfers the energy from a larger volume of low-pressure liquid to a smaller volume of liquid, imparting to it higher pressure. This pumps the smaller volume under high pressure. The degree of pressure intensification that the High Lifter provides depends on the volumetric ratio of the pump: the ratio of the area of its large piston to the area of its small piston. [29]

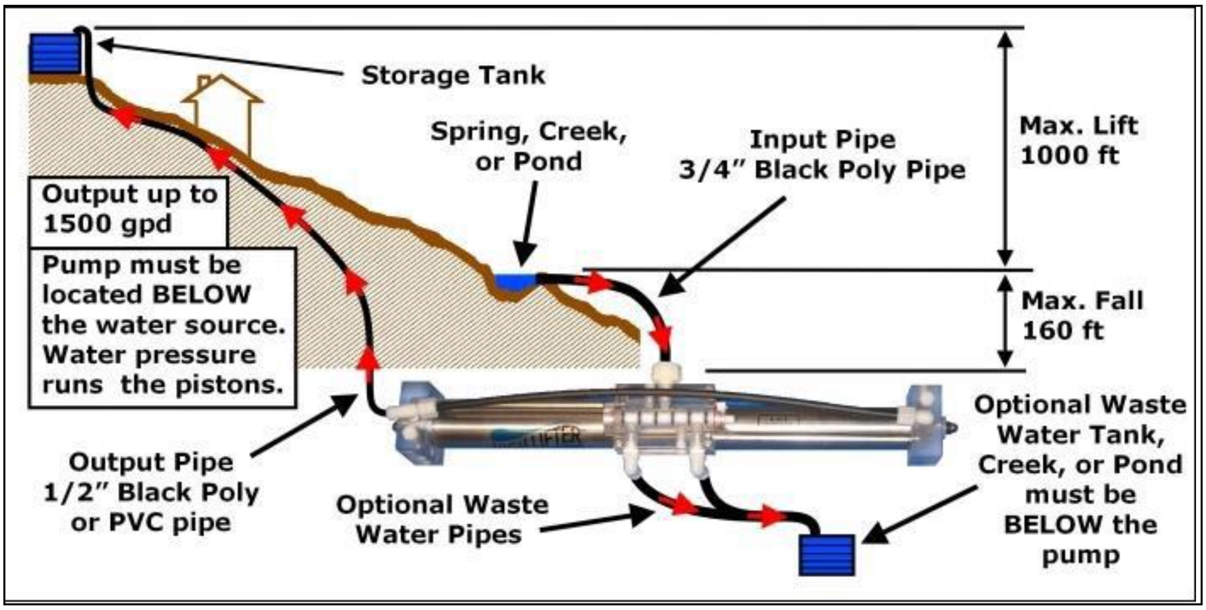


Figure 3.17: Schematic Representation of High Lifter Pump. (Source: [30])

Specific needs will determine the pump ratio selected. This ratio will in turn determine the percentage of inlet flow being pumped. High Lifter model H74 is available in volumetric ratios from 2:1 to 22:1. The smaller models H44 or H49 are 4.5:1 and 9:1, respectively. Because of their design, High Lifter pumps can be readily converted from one ratio to another [24 no page]. The energy conversion is shown in Figure 3.18. The main characteristics of High Lifter Pump are depicted in Table 3-7.

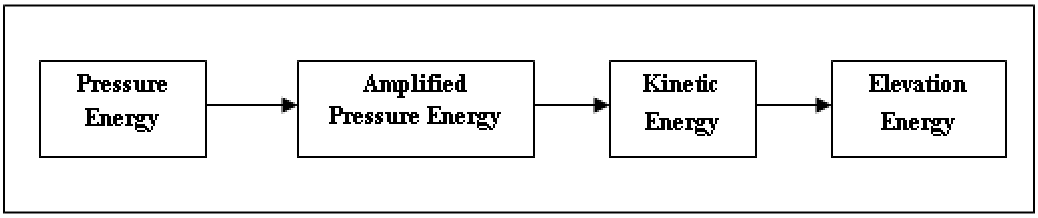


Figure 3.18: Flow of energy conversion in Hydro-powered High Lift Pump

Table 3.7*: Summary of main characteristics (High LifterPump)*

Principal mover	Compressed air
Pumping principle	Positive displacement
Integration	Piston
Required head	Low head
Position in water	On surface

3.2.6 Hydrobine Pump

A number of propellers are fixed on a rod that runs along the central axis of a cylinder. The Pump is set parallel to the flow of a stream and the propellers rotate due to the axial flow of water. At the exit of the cylinder, a gadget that converts the rotational motion to oscillatory motion is installed. The oscillatory (up and down) motion runs a piston that responsible for pumping water up hill (Figure 3.19). The flow of energy conversion is given in Figure 3.20. The main characteristics of Hydrobine Pump are depicted in Table 3-18.

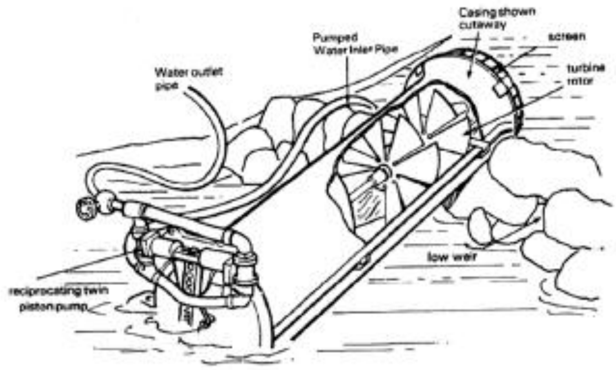


Figure 3.19: Photographic view of Hydrobine Pump (left) and its sectional view (right) Source: [26, 12]

Kinetic Energy → **Rotational Energy (of the propeller)** → **Mechanical Energy** → **Kinetic Energy** → **Elevation Energy**

Figure 3.20: Flow of energy conversion in Hydrobine Pump

Table 3.8: Summary of main characteristics (Hydrobine Pump)

Principal mover	Multi-propeller turbine
Pumping principle	Positive displacement
Integration	Transmission system
Required head	Ultra low head
Position in water	Partly submerged

3.2.7 Bunyip Pump

Bunyip Pump is a perpetual piston pump. The bottom portion of the Pump consists, in the main, of large steel cylinder, a steel ring, a car tire, inlet pipe, and springs. The upper portion consists of: a small piston; suction pipe; delivery pipe; and an inverted T casing for the piston, suction pipe and delivery pipe. The upper and lower portions are connected with a steel piston rod that runs from (center) bottom of the cylinder up to the piston (Figure 3.21).

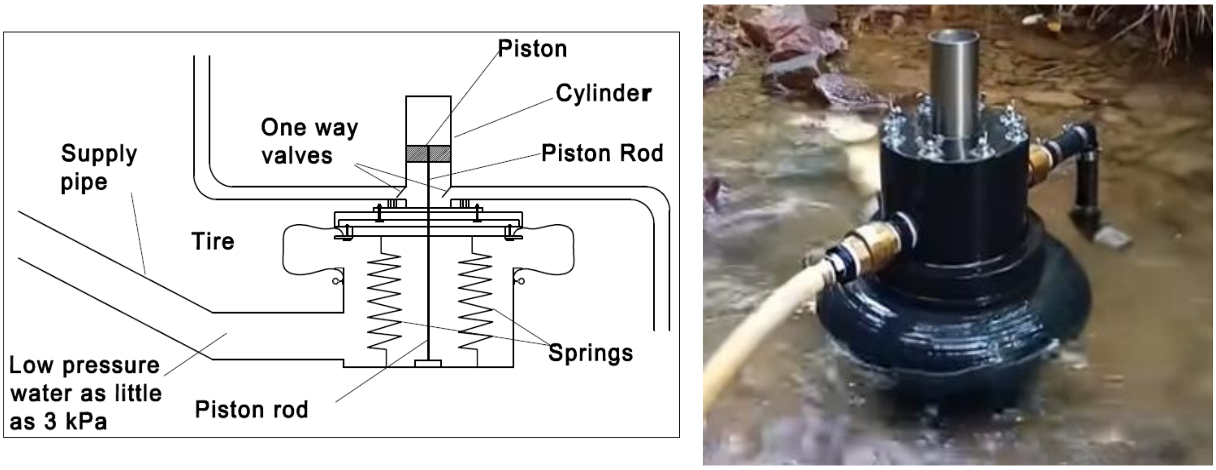


Figure 3.21: Sectional view of Bunyip Pump (left) and its photographic view (right). (Source: left, redrawn from [32], right [33]

Water from an elevated upstream enters into the lower cylinder of the Pump. The pressure head of the water inflates the tire, and, due to the inflation, the upper portion of the Pump moves up. This upward movement creates a relative downward movement of the piston with respect to the (smaller) piston cylinder. This movement enables the pump to push water up via the left (red) delivery pipe. Inflation of the tire stretches the springs. This stretch of the spring develops a pulling force on the tire. As the inflation increases, stretch of the spring also increases and at some point it balances the force of inflation, and starts to pull back the tire, thereby resulting in dropping back. When the tire drops back, the piston takes a relative upward movement and this enables the pump to suck water via the (blue) right pipe.

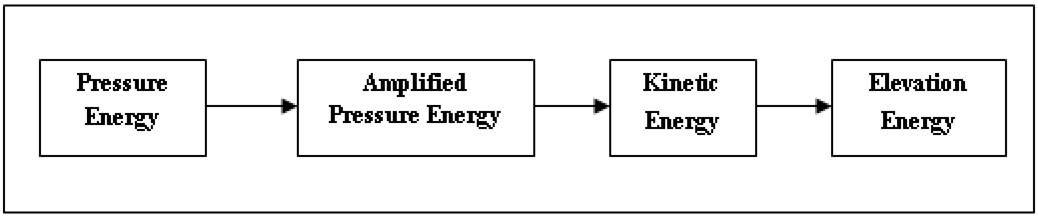


Figure 3.22: Flow of energy conversion in Bunyip Pump

The tire is serving as a big piston pushing the smaller piston. The pressure difference depends on the ratio of (horizontal sectional) areas of the tire and the smaller piston. Two one way valves are installed at the left and right sides of the cylinder. In terrain conditions where there is a pressure head high enough to inflate the tire, Bunyip Pump works well. For conditions where the head increases, cycle of pumping fastens.

The water that runs the Pump could be different from the water that is being pumped. Using this opportunity, it is possible to use flowing water with relatively reduced quality to pump stagnated water (such as ground or pond water) of the required quality. The flow of energy conversion is shown in Figure 3.22. The main characteristics of Bunyip Pump are depicted in Table 3-9.

Table 3.9: Summary of main characteristics (Bunyip Pump)

Principal mover	Rubber tire
Pumping principle	Positive displacement
Integration	Direct attachment
Required head	Low head
Position in water	On surface

3.2.8 Hydraulic Ram Pump

Hydraulic Ram Pump is a hydro-powered water lifting device that uses the energy contained in a flowing (or falling) water. Conversion of the energy contained in a flowing (or falling) water in to a pumping head is governed by the principles of Water Hammer. Hydraulic Ram Pump has eight distinct components (Figure 3.23):

1. drive pipe, that feed water to the pump from an elevated source;
2. main body, where the water hammer effect takes place;
3. impulse valve (self-regulating outlet gate);
4. supply valve;
5. air chamber, where pressure responsible for the pumping is developed;
6. delivery line;
7. snifter, a pinhole that replaces the air dissolved by water from the chamber (optional); and
8. pressure gauge, that is used to measure the pressure developed in the chamber (optional).

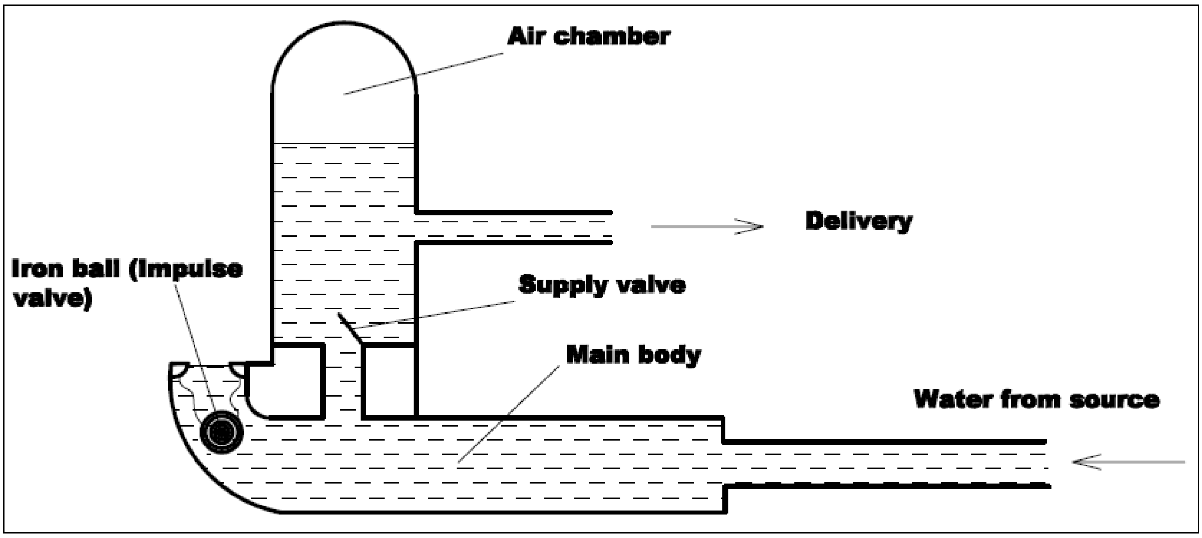


Figure 3.23: Hydraulic Ram Pump, as designed by Montgolfier (Source: [redrawn from 34])

Water that comes from the source passes through the impulse valve. The flowing water pushes the iron ball and slam shuts the valve. Due to this fast closure of the valve the kinetic energy contained in the running water will be converted into pressure head. Such a phenomenon is known as water hammer. The pressure developed travels back and instantaneously reaches the supply valve, opens it and enables water to flow to the air chamber. Flow of water into the Air Chamber creates pressure increase in the Chamber. The pressure continues traveling and reaches the source from which the water is trapped. The backward movement of the pressure wave, after reaching the source tends to drive water away from the main body of the pump body and this creates sub-atmospheric pressure which causes reopening of the impulse valve. Water in the Air chamber tends to flow back, but it cannot do that as the supply valve allows flow only in to the air chamber. The pressure increase in the air chamber pushes water via the Delivery line. Reopening of the Impulse Valve releases the pressure in the main body of the pump. This brings back the situation before closure of the Impulse Valve and water starts to flow through the Impulse Valve again. This cycle continues and in each cycle water is pumped uphill.

As water flows out of the pump till the Impulse Valve closes with the drag force of the flowing water, and this repeats every cycle, it is not all the volume of water that is pumped. This cannot happen as it would be against conservation of energy principle. Based on efficiency of the pump, the amount of water pumped ranges from 15 to 25 percent of the amount that gets in to the pump. The flow of energy conversion is shown in Figure 3.24.

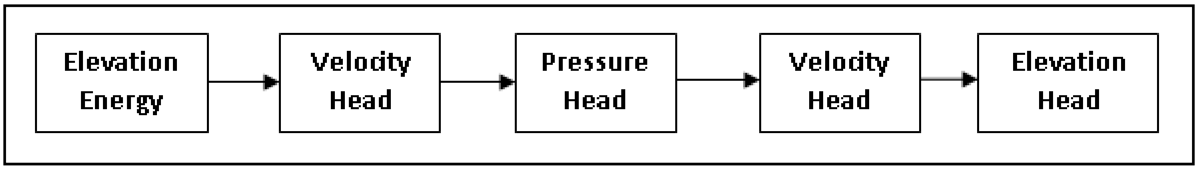


Figure 3.24: Flow of energy conversion in Hydraulic Ram Pump

The basic principle with which the pump operates could be explained with Figure 3.25.

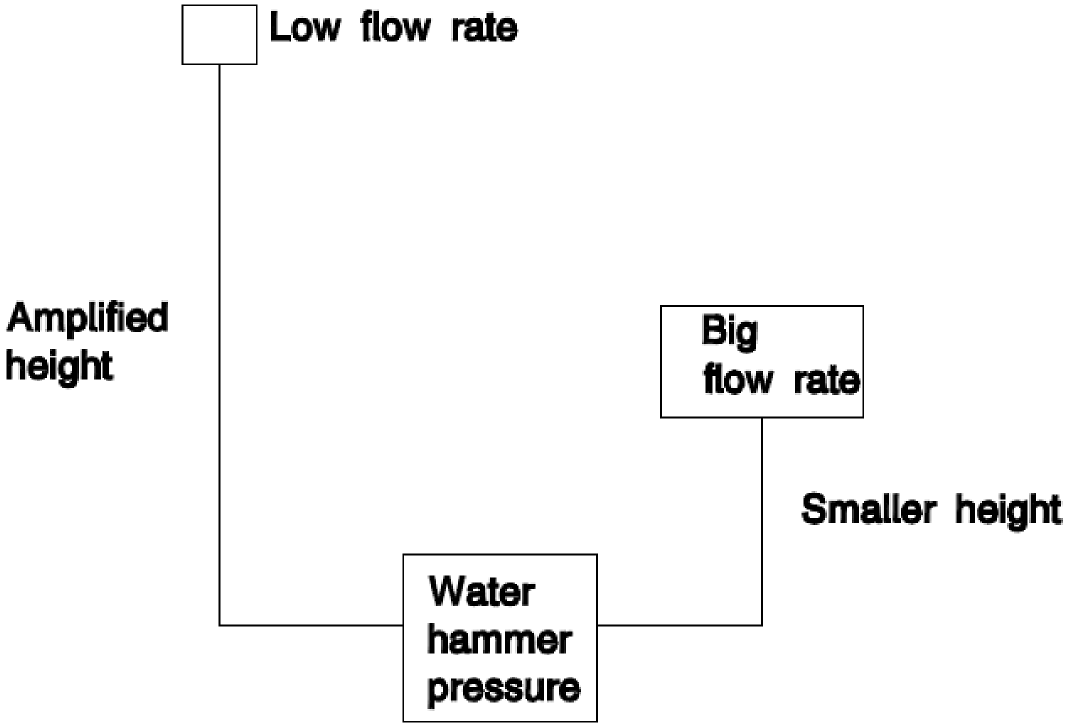


Figure 3.25: Working principle of Hydraulic Ram Pump

Hydraulic Ram Pump has to distinct zones – Pressure Zone and Supply Zone (Figure 3.26). When water flowing through a pipe, the rise in pressure due to the sudden closure of a valve is computed by assuming that water is incompressible employing Equation 3.10. The pressure developed at the point of closure moves back with a speed at which sound wave travels in water. Development of pressure due to closure depends on the speed at which the valve is closed. Generally, there are two types of closure: slow closure and fast closure. When the time taken to close the valve is longer than the time required for pressure wave (that travels at the speed of sound in water medium) to travel from the point of closure to a point where the pipe line is exposed to atmospheric pressure and arrive back to the point of closure, the closure is named as slow closure. If the time is shorter than this time, the closure is fast closure.

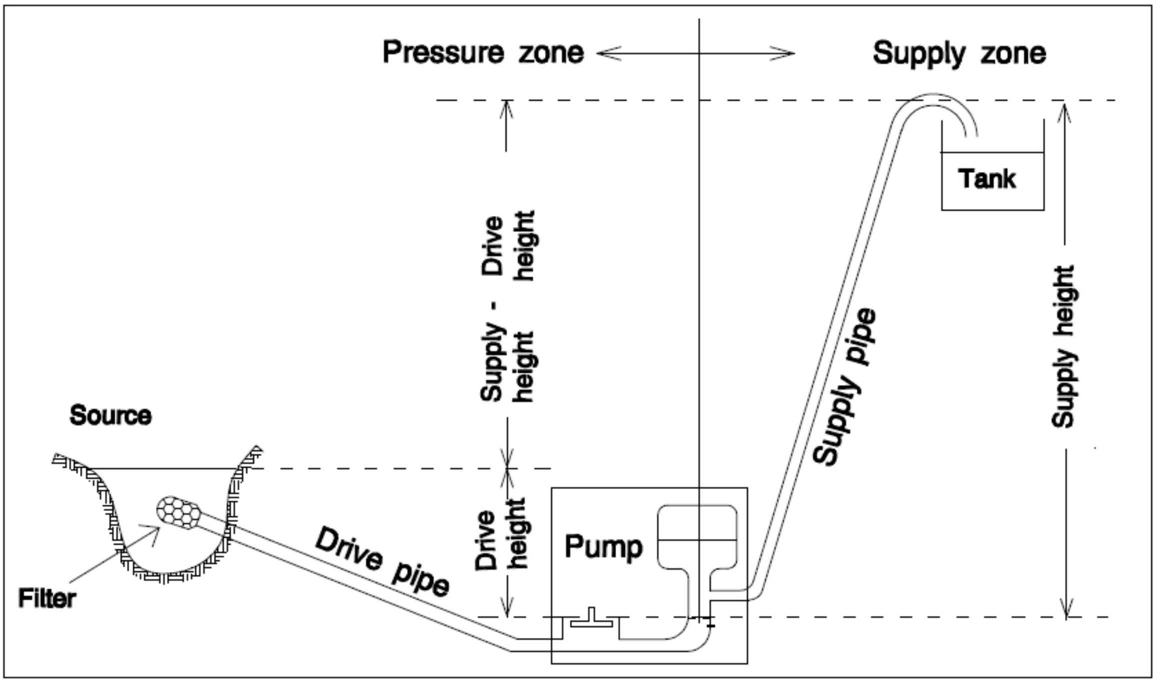


Figure 3.26: Schematic representation of Hydraulic Ram Pump

$$\Delta P = \frac{\rho L \Delta V}{T}$$	*Eqn. 3.10*
Where:	
P=	Pressure
ρ=	Density of water
L =	Length of the pipe (from the point of closure to a point where the pipe is open to atmospheric pressure
ΔV=	Velocity of flow
T =	Time of closure

In an ideal (absolutely rigid) pipe line that conveys water of bulk modulus of elasticity, the speed of sound wave is computed by Korteweg's formula (Equation 3.11)

$$C = \sqrt{\frac{K}{\rho}}$$	*Eqn. 3.11*
Where:	
C=	Speed of sound in water (m/sec)
K=	Bulk modulus of elasticity of water (N/m^2)
ρ=	Density of water (kg/m^3)

In the real world, however, no water is incompressible and no pipe is absolutely rigid. Velocity of sound in water, of bulk modulus of elasticity *K*, flowing in a pipe line of diameter *D*, elasticity *E* and wall thickness ***e*** is computed by the Korteweg formula (Equation 3.12) .

$$C = \sqrt{\frac{1}{\rho\left[\frac{1}{K} + \frac{D}{Ee}\right]}}$$	*Eqn. 3.12*

Where:

C=	Speed of sound in water (m/sec)
ρ=	Density of water
K=	Bulk modulus of elasticity of water (N/m^2)
D=	Diameter of the pipe (m)
E=	Modulus of elasticity of the pipe material (N/m^2)
e=	Wall thickness of the pipe (m)

Equation 3.11 is a special case of Equation 3.12. This could be seen by inserting a huge number in place of E and simplifying Equation 3.12

When the velocity water, of bulk modulus of elasticity K, that flows in an ideally rigid pipe line of area A, and length L comes to halt, the kinetic energy contained in the water will be converted into strain energy of water. This equivalence can be expressed by Equation 3.13.

$$\frac{1}{2}\rho V^2 AL = \frac{1}{2}\frac{P^2}{K}AL$$	*Eqn. 3.13*

Where:

ρ=	Density of water (kg/m^3)
V=	Velocity of water (m/sec)
A=	Cross sectional area of the pipe (m^2)
L=	Length of the pipe (m)
P=	The pressure developed (N/m^2)
K=	Bulk modulus of elasticity of water (N/m^2)

The left hand side of Equation 3.13 is the kinetic energy of the flowing water while the right hand side is the pressure energy. Simplifying and rearranging Equation 3.13 yields Equation 3.14 which is known as Joukowsky's Equation.

$$P = C\rho V$$	*Eqn. 3.14*

Where:

C=	Speed of sound in water (m/sec)
ρ=	Density of water (kg/m^3)
V=	Velocity of water in the pipe (m/sec)

From the aforementioned formulae, it can be seen that the pressure developed when water flowing in a pipe comes to a halt is:

1. directly proportional to the velocity of water in the pipe;
2. the speed of closure; and

3. directly proportional to the speed of sound in water, which in turn is directly proportional to the wall thickness of the pipe material and it modulus of elasticity.

The pressure developed when water of bulk modulus of elasticity, K, and density, ρ, travels with velocity V, in a pipe of material with elasticity E, diameter D, and wall thickness "e" encounters fast closure, the pressure that develops could be computed with a formula obtained by combing Korteweg's general formula (Equation 3.12) and Joukowsky formula (Equation 3.14). The combination yields Equation 3.15.

$$P = V\sqrt{\frac{\rho}{\left[\frac{1}{K}+\frac{D}{Ee}\right]}} \qquad \textit{Eqn. 3.15}$$

Where:

P=	The pressure developed (N/m^2)
V=	Velocity of water in the pipe (m/sec)
ρ=	Density of water
K=	Bulk modulus of elasticity of water (N/m^2)
D=	Diameter of the pipe (m)
E=	Modulus of elasticity of the pipe material (N/m^2)
e=	Wall thickness of the pipe (m)

From Equation 3.15 it is seen that if water that travels with a velocity of 1 m/sec in a pipe of material with absolute rigidity stops in no time, the pressure that is developed can push water as high as 150 meters. The actual pressure, however, is much less than this as there is absolute rigid pipe material and zero time closure of valve are not practical. This figure, however, tells us that working on the speed of closure and using pipelines with high rigidity helps to improve the pressure created in a pipeline.

The tremendous pressure caused by water hammer could damages pipelines in water supply network and penstocks in hydroelectric power generation. In the design of water supply network and penstock, water hammer is a phenomenon that is not needed. In Hydraulic Ram Pump, however, water hammer is intentionally created and the result is used to pump up water. The main characteristics of Hydraulic Ram Pump are depicted in Table 3.10.

Table 3.10: Summary of main characteristics (Hydraulic Ram Pump)

Principal mover	Compressed air
Pumping principle	Positive displacement
Integration	Valve
Required head	Low head
Location in water	On surface, partly submerged, submerged,

3.2.9 Glockmann Pump

Glockmann Pump is an improved version of Hydraulic Ram Pump. Its working principles depend on water hammer. Referring to Figure 3.27 and 3.28, Glockmann has two chambers (left and right). Water that comes through the Drive Tube (left chamber) goes out via the Exit Pipe. While flowing out through the Exit Pipe, it slum shuts the Exhaust Valve (that is hinge supported at the body of the pump). Exhaust valve is equivalent to Impulse Valve in Hydraulic Ram Pump. The process up to this stage is named as Charging Stage (Figure 3.27). Stretching of the spring at the right chamber pulls the piston in the right chamber to the left and this action sucks water from the source to the chamber. Fast closure of the Exhaust Valve creates a water hammer pressure spike in the left chamber of the Pump. This pressure pushes: the diaphragm; the plate, to which a spring is mounted; the spring and the piston to the right. This action pushes up water to an elevated point. This stage of the pump action is called Push/Stroke Stage. At the right end of the right chamber are two pipe lines with nun-return valves that allow flow in opposing directions, right and left. In this case, the upper valve allows outflow and the lower valve allows incoming flow. The rightward push of the piston pumps up water through the upper line.

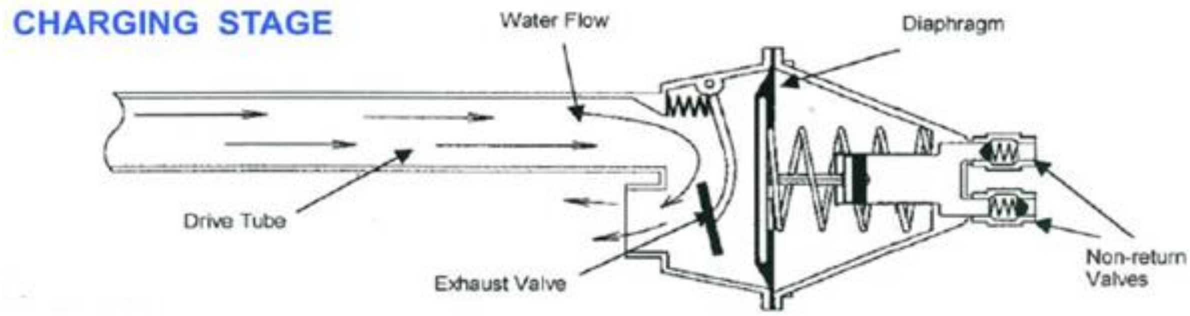


Figure 3.27: Glockemann Pump (Driving Phase) [Source 30]

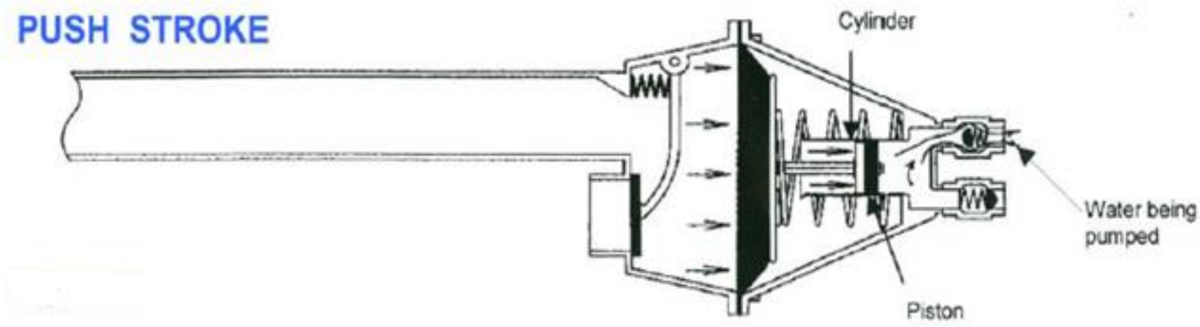


Figure 3.28: Glockmann Pump - Pumping Phase. (Source: [35])

When the pressure wave moves backward and triggers left ward movement of the water, sub atmospheric pressure is created in the left chamber of the diaphragm and this opens the Exhaust Valve. Opening of the Exhaust Valve releases the pressure developed in left chamber and the spring attached to the piston pulls the diaphragm back to its position that was prior to pressure spike in the left chamber. This leftward movement of the piston sucks water via the lower pipe line, thereby availing water in the right chamber for the next round of pumping. The energy conversion process is shown in Figure 3.29

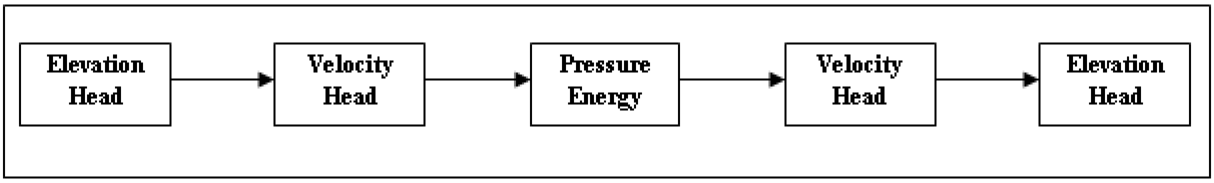


Figure 3.29: Flow of energy conversion in Glockmann Pump

The following points differentiates Glockmann Pump from Hydraulic Ram Pump.

1. The Glockmann Pump has two chambers separated by a diaphragm. The left chamber creates pressure spike and the right one pumps water
2. Piston Action is responsible for pumping up of water
3. In Glockmann Pump, the water that flows through the Drive Tube is not directly pumped. It is only used to create pressure spike in the left chamber of the Pump and push the piston in the right chamber. It is the left and right movement of the piston that is responsible for pumping. The water that is to pumped could be the water that flows out of the Exhaust Valve or any other source of water that is connected to the suction pipe. Figures 3.27 and 3.28 shows the pumping phases.

The following similarities are observed between Glockmann Pump and Bunyip Pump. In both pumps:

1. the pressure spike created is used to move pistons;
2. The water used to create pressure spike could be different from the water to be pumped.

Note: The spring needs to have a stiffness high enough to push back the diaphragm and suck water in. When the diaphragm is pushed against the spring, the work done against it is a lost energy for the pumping phase. Of course the work done against the spring will be used to suck in water when it stretches and push back the diaphragm. The lost energy is particularly is absolutely lost if the stiffness of the spring is more than what is required to suck water in. The main characteristics of Glockmann Pump are depicted in Table 3-11.

Table 3.11: Summary of main characteristics (Glockmann Pump)

Principal mover	Compressed water
Pumping principle	Positive displacement
Integration	Diaphragm, valve, piston
Required head	Low head
Position in water	On surface, partly submerged

3.2.10 Venturi Pump (Papa Pump)

Venturi Pump (Papa Pump) is the other improved version of Hydraulic Ram Pump. The sectional photographic view of the pump is shown in Figure 3.30. The main feature that differentiates Venturi (Papa) Pump from Hydraulic Ram Pump is that closure of the Main Venturi Valve (equivalent of Impulse Valve in Hydraulic Ram Pump) is caused by the venturi action at the throat of the passage to the Exhaust Port.

Water flows in through the Supply Port and reflects back circumferentially to the Main Venturi Valve. As the flow passes through to the Exhaust Port, the opening gets narrower and this increases the flow velocity. The increase in velocity creates a pressure gradient around the Valve. The pressure to the left of the valve will become higher than the pressure to the right of it. This pressure gradation pushes the Valve to the right and closes it. The closure creates a pressure spike and opens the Non Return Valve thereby pumping water up via the Delivery Port . The energy conversion process is shown in Figure 3.31.

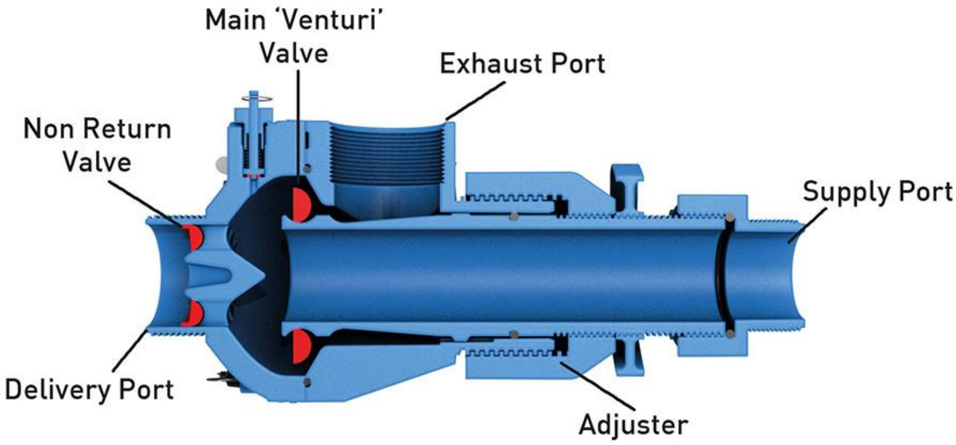


Figure 3.30: Sectional, photographic view of Venturi (Papa) Pump. (Source-[36])

Like the previously discussed two pumps of Hydraulic Ram Pump family, when the backward travel of the pressure wave triggers flow of water in opposite direction, the Main Venturi Valve opens and releases the pressure developed in the body of the Pump. This brings the end of a cycle of pumping and the following cycle begins.

One unique feature of the Venturi (Papa) Pump is its adjuster. By turning the Adjuster, it is possible to control opening of throat of the Pump. When the incoming flow gets higher, the width of the throat is increased by loosening the Adjuster. As the net is fixed the bolt (the Supply Port pipe) is pushed to the left while loosening the Adjuster. On the contrary, when the flow decreases, tightening the adjuster moves the Supply Port to the right thereby decreasing area of the throat. Venturi (Papa) Pump has a variety of sizes reaching as high as

500 millimeter of Supply Port. The main characteristics of Venturi Pump are depicted in Table 3-12.

Elevation Energy → Velocity Head → Pressure Energy → Velocity Head → Elevation Energy

Figure 3.31: Flow of energy conversion in Venturi (Papa) Pump

Table 3.12: Summary of main characteristics (Venturi/Papa Pump)

Principal mover	Compressed air
Pumping principle	Positive displacement
Integration	Valve
Required head	Low head
Position in water	On surface, semi-submerged, submerged,

3.2.11 Full Belly's Gravity Pump

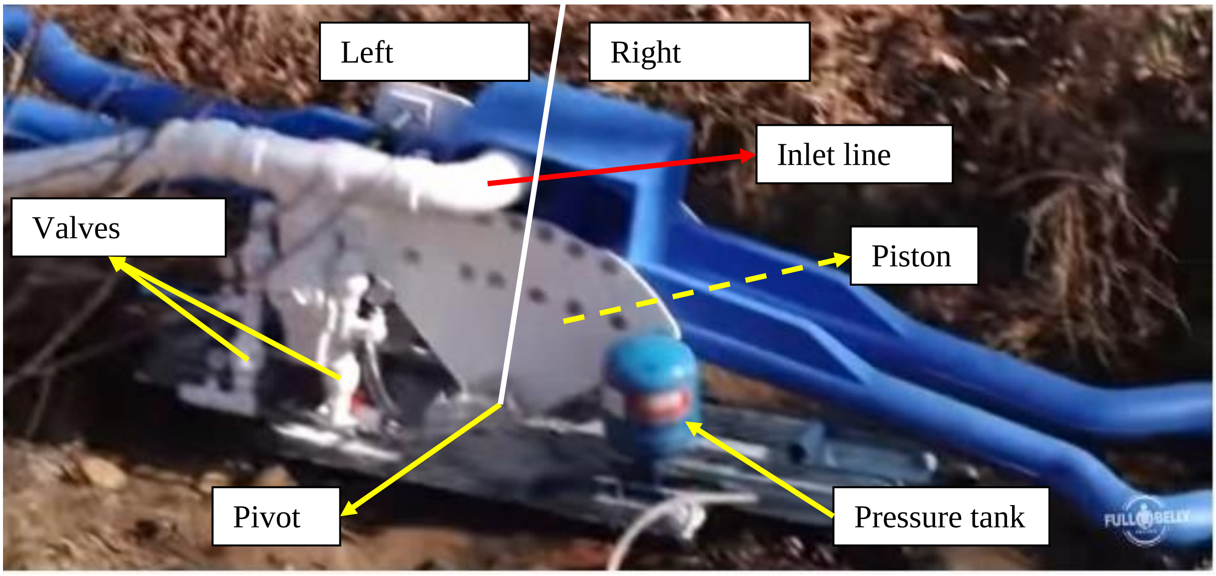


Figure 3.32: Photographic view of Full Belly's Gravity Pump. (Source [37])

Not much is written on Full Belly's Gravity Pump. The working process of Full Belly's Gravity Pump studied to be as follows.

1. Water from the source flows through the inlet line to the blue chambers and to the valves connected to the inlet line with a T. The left and right blue chambers are separated by a wall aligned with the pivot point. For the position shown in the Figure (3.32), the inflow is filling the left chamber. Underneath of the right chamber, close to the pivot point, is a vertical piston. For the position given in the Figure, the piston is in compression (pumping) state and the chamber is expelling water via the outlet at the right tip. The piston has two nozzles (top and bottom) to receive two hoses. The hoses from the two nozzles are connected to the valves tower (to which pressure gauges are

installed). The whole sets of gadget rest on a precast concrete pad with readily positioned anchorage points for the different components.

2. When the left blue chamber is filled with water, weight of the water swings the chamber to the left, about the pivot, and this: i) stretches the piston; ii) aligns the inlet of the right chamber with flow from the source. After swinging, the left chamber also self-empties via its out let it the left tip.

3. Water starts to flow from the inlet to the right chamber. When the right chamber gets filled, the chamber again swings to the right, pressing the piston and aligning inlet of the left chamber with the flow. These alternative pressing and releasing of the piston, due to seesaw of the chambers, sucks water through one of the valves and pumps via the other. To fill the space between the valves and the piston priming is required.

4. Oscillation of the piston following the swinging of the right and left chambers sucks and pumps water to an elevated position. The moment created due to filling of the chambers and distance of the piston, as measured from the pivot, are the two main factors that determine the pumping height. To smoothen the pulses and boost the pumping pressure, a pre-pressurized tank with diaphragm is installed on the pumping line.

The energy conversion flow of Full Belly's Gravity Pump is shown in Figure 3.33. The main characteristics of Full Belly's Gravity Pump are depicted in Table 3.13.

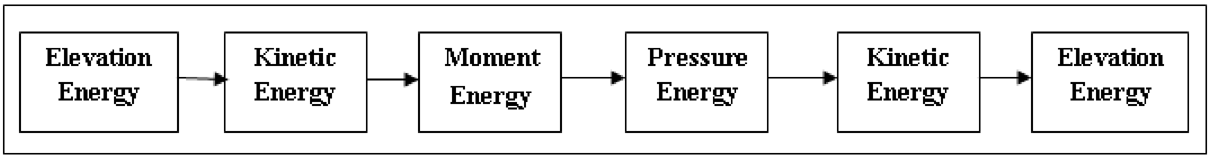


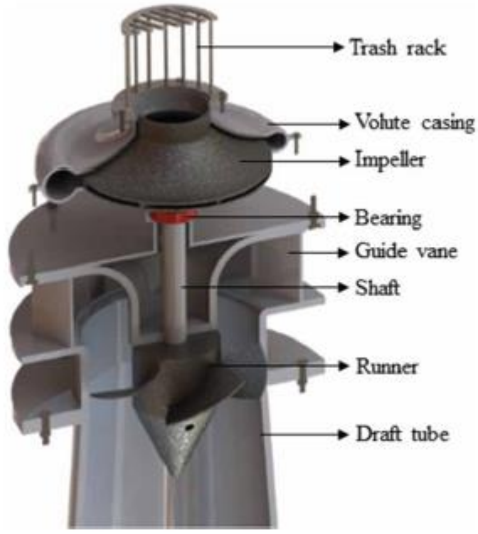
Figure 3.33: Flow of energy conversion in Full Belly's Gravity Pump

Table 3.13: Summary of main characteristics (Full Belly's Gravity Pump)

Principal mover	Moment about a pivot
Pumping principle	Positive displacement
Integration	Piston, valve
Required head	Low head
Position in water	On surface

3.2.12 Chinese Water Turbine Pump

The impeller is submerged in the flowing water. When the impeller rotates, the water in the impeller also rotates. As the water rotates, it is pushed outwards in all direction to the edge of the impeller. As the water moves out of the impeller, it creates a region of low pressure which causes more water through the suction inlet. The rotation of the impeller imparts kinetic energy to the water. When water reaches at the edge of the impeller, it attains high velocity.



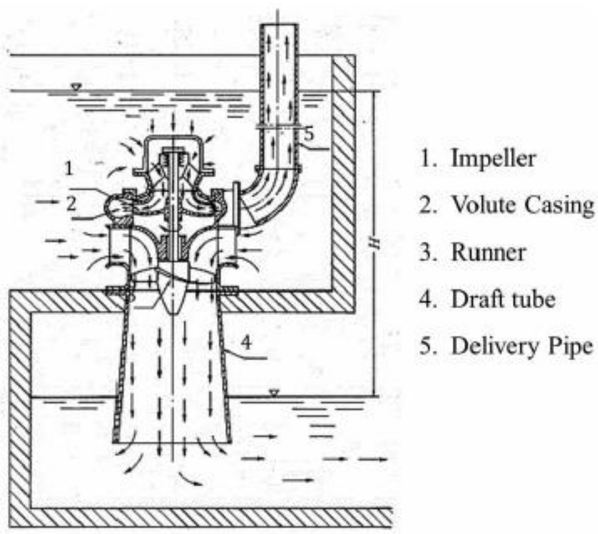


Figure 3.34: Chinese Water Turbine Pump photographic section (top) submerged section (bottom). Source: [38]

The incoming flow rotates the runner. A shaft connects the rotary and impeller of the pump. Rotation of the shaft rotates the impeller which is responsible for pumping. As rotation of the rotary depends on the incoming flow to the pump and is velocity (that in turn depends on the falling head), the design of the pump depends on the incoming discharge (Figure 3.34). As the pumping discharge and head depends on the width and radius of impeller, design of Chinese Water Turbine Pump is very site specific. The Flow of energy conversion for Chinese Water Turbine Pump is given in Figure 3.35. The main characteristics of Chinese Water Turbine Pump are depicted in Table 3-14.

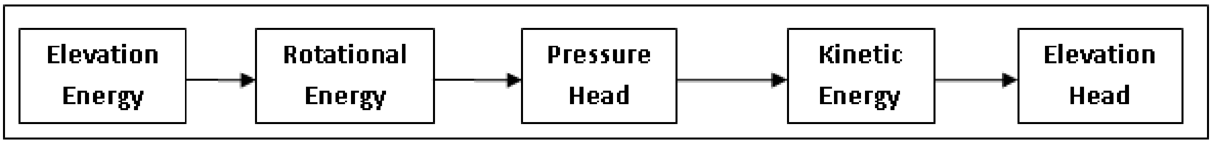


Figure 3.35: Flow of energy conversion in Chinese Water Turbine Pump

Table 3.14: Summary of main characteristics (Chinese Water Turbine Pump)

Principal mover	Kaplan turbine
Pumping principle	Velocity head
Integration	Coaxial shaft, transmission system
Required head	Low head, medium head
Position in water	Submerged

CHAPTER 4

4. Contents and Results

4.1 Comparative and Descriptive Analysis, and Ranking of Hydro-powered Pumping Technologies

Fourteen hydro-powered pumping technologies have been identified as candidate technologies in Chapter 3. This chapter deals with making a comparative and descriptive analysis and ranking of the technologies. The ranking employs the following steps [17]:

1. Step I: Identification
    a. Setting objective/s
    b. Identifying long list of alternatives
    c. Setting criteria of comparison
2. Step II: Ranking
    a. Selecting appropriate comparison method
    b. Calculating relative weights for the of criteria
    c. Evaluating consistency
    d. Aggregating the results
3. Step III: Evaluating
    a. Conducting sensitivity analysis
        i. Sensitivity to criteria weight
        ii. Sensitivity to Measure of Performance

4.2 Step I: Identification

4.2.1 Setting Objective

In line with the aforementioned steps, the objective is to identify and rank the candidate Hydro-powered Pumping Technologies employing the criteria of comparison.

4.2.2 Identifying Long List of Alternatives (Technologies)

The total number of Hydro-powered Pumping Technologies, identified through literature review, is more than 30. However, in line with the scope of the research, fourteen have been found to be appropriate for further analysis (Table 4.1). The rest have not been considered by their own for the following reasons:

1. The potential application is very rare;
2. It was possible to see, from the outset, that the technologies are too complex or difficult to be manufactured at local levels by Small Enterprises.
3. Adequate literature have not been found;
4. They do have very high similarity with the other technologies, included in the comparison;

One of the selected fourteen (Chinese Water Turbine Pump) represents other types of pump that belong to similar group of technology (turbine type). For comparison purpose, some technologies with high complexity (for local level manufacturing), difficulty of production and very limited literature are included among the fourteen technologies.

Table 4.1: Selected candidate technologies and reasons for their selection

Se. No.	Technology	Reason for being considered as candidate
1	Hydro-powered Coil Pump (Wirtz Pump)	Relative simplicity of manufacturing, suits to relatively higher flow in a mild slope channels
2	Hydro-powered Spiral Pump	Relative simplicity of manufacturing, suits to relatively higher flow in a mild slope canals
3	Hydro-powered Helix Pump	Suits to varying types of flow conditions
4	Lambach Pump	Difficult to manufacture, but included for comparison.
5	Hydrautomat Pump	It is not difficult to manufacture, difficult to operate, included for comparison
6	Cherepnov Pump	It is not very difficult to manufacture, difficult to operate, included for comparison
7	High Lifter Pump	Easy to use
8	Hydrobine Pump	Suits to varying types of flow conditions
9	Bunyip Pump	Has very high pumping height
10	Hydraulic Ram Pump	Relative simplicity of manufacturing, suits to varying types of flow conditions
11	Glockmann Pump	A modified and improved version of Hydraulic Ram Pump
12	Venturi Pump (Papa Pump)	A modified and improved version of Hydraulic Ram Pump
13	Full Belly’s Gravity Pump	Suits to varying types of flow conditions
14	Chinese Water Turbine Pump	Difficult to manufacture, but included for comparison. It represents turbine type pumps.

Table 4.2 shows the technologies that are not selected as candidate, and the associated reasons for not being included for further analysis.

Table 4.2: Technologies that are not considered as candidates and the associated reasons

Se. No.	Technology	Reason for not considering as a candidate
1	Aero-hydraulic water lifter	Inadequate literature coverage
2	Hydro-pulsor	Complexity of production for Small Enterprises, Inadequate literature coverage. Its family, Chinese Water Turbine, is included.
3	Hydraulic Transformer	Complexity of production for Small Enterprises, Inadequate literature coverage. Its family, Chinese Water Turbine, is included.
4	Hydraulic converter	Complexity of production for Small Enterprises, Inadequate literature coverage. Its family, Chinese Water Turbine, is included.
5	Globe case coaxial water turbine pump	Complexity of production for Small Enterprises, Inadequate literature coverage. Its family, Chinese Water Turbine, is included.
6	Vietnamese hydraulic pump	Inadequate literature coverage. Its family, Chinese Water Turbine, is included.
7	Turbo pump	Inadequate literature coverage
8	Garman turbine	Limited applicability as it uses water current for its operation, Complexity of production for Small Enterprises, inadequate literature coverage.
9	Tyson turbine	
10	Hydrokinetic linear turbine	
11	Markovic self-propelled pump	
12	Waterwheel-driven pump	Difficulty of production for Small Enterprises, inadequate literature coverage
13	Axial-flow turbine-driven pump	Complexity of production for Small Enterprises, inadequate literature coverage
14	Mixed-flow turbine-driven pump	Complexity of production for Small Enterprises, inadequate literature coverage
15	Tangential-flow turbine-driven pump	
16	Pump-as-Turbine pump	
17	Cross-flow turbine-driven pump	Complexity of production for Small Enterprises, inadequate literature coverage
18	Filardo pump	Inadequate literature coverage
19	Plata	Very high similarity with Hydrobine pump, inadequate literature coverage

4.2.3 Setting Criteria of Comparison

To make comparisons among the Technologies, criteria of comparison need be developed. Fourteen Criteria of Comparison are arrived at under four Heads (Technical, Economic, Social, and Operational). Some of the Criteria fall under more than one Head (Table 4.3). Descriptions of the Criteria of comparison are rendered in Table 4.4.

Table 4.3: Criteria of comparison of the technologies

Se. No.	Criteria of Comparison	Heads of Comparison			
		Technical	Economical	Social	Operational
1	Ease of manufacturing at local (Small Enterprises) level. Local and imported, materials requirement	▪	▪		
2	Ease of operation	▪		▪	▪
3	Maintenance requirement (frequency and ease of maintenance, availability of spare parts)	▪	▪		▪
4	Frequency of supervision	▪		▪	▪
5	Security (against theft)	▪		▪	▪
6	Service year	▪	▪		
7	Mobility (ease of mobilization)				▪
8	Operational head requirement	▪			▪
9	Pumping height (Delivery Head)	▪			▪
10	Flow required for operational	▪			▪
11	Pumping volume (delivery volume)	▪			▪
12	Literature coverage	▪			
13	Commercial manufacturing (Is the technology being manufacture for commerce?)	▪			
14	Patent right (Is the technology protected by Patent Right?)			▪	

Table 4.4: Description of criteria of comparison

Se. No.	Criteria of Comparison	Explanation
1	Ease of manufacturing	Technical: Possibility of manufacturing at local (Small and Medium Enterprises) level, The required level of precision Material: Requirement for, local and imported, material Availability of the required materials
2	Ease of operation	Starting up, Stopping, Priming, troubleshooting (association between theoretical background and starting, stopping, priming and troubleshooting)
3	Maintenance requirement	Frequency and ease of maintenance Availability of spare parts for maintenance
4	Frequency of supervision	As Hydro-powered pumps lift only portion of the water that is required to operate them, they generally need to work for extended number of hours, even days, continuously. Full time attendance may not be possible. Number of cases that causes malfunction of the technology determines the frequency of supervision (monitoring) required.
5	Mobility	Course of a river varies slightly each season following high floods. Shifting of the pumps could be required in need of a suitable spot for the pump. The lighter in weight are mobile while fencing may be required to protect them against theft. The heavier ones are not easily mobile, but their weight protects them against theft.
6	Pumping Height	The head to which the pumps push water
7	Security (against theft)	As Hydro-powered pumps lift only portion of the water that is required to operate them, they generally need to work for extended number of hours, even days, continuously. Full time attendance may not be possible, and different technologies have different suitability for protection against theft.
8	Service year	Material wear and tear
9	Operational head requirement	The head required to activate and/or run the pumps
10	Operational flow volume requirement	The flow (discharge) of water required to run the pump. Some pumps need to be submerged (partly) to operate. This requires high body/volume of water/flow.
11	Pumping volume	Generally, as the pumping height increases, the flow rate decreases. Notwithstanding this interchangeability of pumping head and pumping volume, pumps capacity varies in both Pumping Height and Pumping Volume.
12	Literature coverage	Literature coverage could be an indirect measurement of consolidation of the technologies
13	Patent right	Patent right may restrict the application of the technologies
14	Commercial manufacturing	Commercial manufacturing of the technologies show their current application.

4.2.4 Step II: Ranking

Ranking involves the following steps.

a. Selecting appropriate comparison method
b. Calculating relative weights for the of criteria
c. Evaluating consistency
d. Aggregating the results

4.2.5 Selection of Comparison Method

When there are more than one criterion to compare alternatives, Multi-Criteria Analysis techniques are used. Multi-Criteria Analysis establishes preferences between options with reference to an explicit set of objectives (criteria) that the decision maker has identified, and for which it has established measurable criteria to assess the extent to which the objectives have been achieved [39]. The important considerations while choosing Multi-Criteria Analysis method is the number of alternatives (Technologies for this case under consideration) to be evaluated and the number of criteria used for the evaluation.

Criteria for selecting Multi-Criteria Analysis method mainly depends on the following conditions.

1. **Problem type**: Choosing (where the decision maker needs to select one or a few alternatives from a set of alternatives), ranking (where the evaluator order the options from “best” to “worst” or vice versa), sorting (where the evaluator needs to cluster the alternative to predefined categories).
2. **Criteria structure**: Are the evaluation criteria independent? Are the evaluation criteria qualitative or quantitative? For the case at hand, all possible cautions have been considered to make sure that the criteria are independent. In addition, tolerance to dependence has been considered while choosing the Multi-criteria Decision Making method. The evaluation criteria are dominantly qualitative.
3. **Decision maker involvement**: Is the process being conducted by a single decision maker or by a group of people? A wide range of assessment has been made to find professionals with the exposure to the spectrum of Technologies (both theoretical and practical application), but could not be found. Due to this reason, therefore, the evaluation is limited to the researcher. A few professionals have been consulted on the criteria of comparison. To verify consistency and robustness of the evaluation, rigorous examinations have been conducted.
4. **Data availability and quality**: Is there enough data to cover all the alternatives and criteria? For the case at hand, the nature of most criteria requires qualitative data. Where quantitative data are appropriate, they have been used to group the technologies into categories such as high medium and low.
5. **Method complexity and performance**: How simple or difficult to understand, apply and interpret the method? How robust and sensitive is the method to changes in the data? Capacity to measure consistency of comparisons. Transparency and Traceability.

Strength, weakness, and suitability of the widely used Multi-Criteria Analysis Methods are given in Table 4.5. The full names of the methods are given in Table 4.6 [40].

Table 4.5: Strengths, weaknesses, and suitability of the frequently used Multi-Criteria Decision-Making Methods

Method	Strengths	Weakness	Suitability
TOPSIS	• Simple and easy to apply. • Provides a clear ranking of alternatives based on proximity to the ideal solution. • Handles both qualitative and quantitative criteria.	• Assumes that the weights of criteria are independent. • Sensitive to the choice of normalization method.	• Suitable when you need a quick and intuitive ranking of alternatives. • Best for problems with a clear ideal solution and when alternatives are not too diverse in terms of criteria.
AHP	• Provides a structured framework for decision-making. • Helps to decompose complex problems into a hierarchy of sub-problems. • Allows for subjective judgments through pair-wise comparisons.	• Can be computationally intensive as the number of criteria increases. • Sensitivity to inconsistencies in pair-wise comparisons (though consistency ratios can be used). • Can become difficult to manage for very large problem sets or many criteria.	• Suitable for problems where subjective judgment plays a significant role, such as when expert opinions are involved. • Works well for problems with a relatively manageable number of criteria and alternatives.
ELECTRE	• Deals well with both qualitative and quantitative data. • Useful for handling problems with complex and conflicting criteria. • Helps in dealing with situations where decision-makers are uncertain about the performance of alternatives.	• Difficult to understand and implement for non-experts. • Requires a lot of pair-wise comparison and preference information, which can be subjective. • Not ideal for situations where the decision-makers cannot clearly define thresholds or preferences.	• Suitable for complex, multi-dimensional problems where criteria are conflicting. • Appropriate when decision-makers need to eliminate infeasible alternatives rather than ranking them.
PROMETHEE	• Easy to apply and interpret. • Can handle both quantitative and qualitative criteria. • Can be used with both discrete and continuous alternatives.	• May not be very effective if there are strong interdependencies among criteria. • The results may be highly sensitive to the choice of preference functions and weight assignments. • Can be computationally intensive for large problems with many alternatives.	• Suitable when there is a need to rank alternatives and the decision-makers are comfortable with providing preference functions. • Ideal when dealing with multiple conflicting criteria and when alternatives need to be ordered based on preference.
DAE	• Measures the efficiency of decision-making units (DMUs) in terms of inputs	• Assumes that the data used are accurate, and performance is solely based on input-output	• Suitable for performance evaluation or benchmarking where efficiency (input-

Method	Strengths	Weakness	Suitability
	and outputs. • Does not require a predetermined weight for criteria. • Useful for benchmarking and performance evaluation.	efficiency. • Sensitive to outliers and data quality issues. • Requires a large amount of data to perform effectively.	output ratio) is key. • Particularly useful in environments like manufacturing or service industries where units are compared based on operational efficiency.
ANP	• Can model complex interdependencies between criteria and alternatives. • Handles both qualitative and quantitative factors. • Accounts for the influence of criteria on each other, which is not captured in AHP.	• More complex than AHP and requires a lot of expert input for pair-wise comparisons. • Computationally intensive. • Requires careful interpretation due to the interdependencies among criteria and alternatives.	• Suitable for decision problems where criteria are interdependent or influence each other. • Best for complex, hierarchical problems where interactions between factors need to be captured.
VIKOR	• Focuses on finding a compromise solution, balancing the trade-offs between conflicting criteria. • Useful when a decision-maker needs to select a solution that is closest to the ideal compromise. • Provides ranking of alternatives based on a set of aggregated values.	• Requires the specification of a weight for each criterion. • Sensitive to the choice of aggregation functions. • May struggle to differentiate alternatives when there are close ties.	• Suitable when a compromise solution is needed and there is a clear ranking of alternatives. • Ideal for problems where the decision-maker cannot opt for the ideal solution but wants a satisfactory one.
DELPHI	• Relies on expert judgment, which is valuable for complex or uncertain decisions. • Iterative process helps to refine opinions and converge towards consensus. • Useful for forecasting and opinion-based decisions.	• Can be time-consuming, as it requires multiple rounds of surveys or feedback. • Subjective and dependent on the expertise of the participants. • May lead to groupthink or bias if expert opinions are not well diversified.	• Suitable for qualitative decision-making when expert opinions are needed. • Ideal for forecasting, policy-making, and decisions with a high degree of uncertainty.
QFD	• Focuses on aligning customer needs with engineering characteristics,	• Complex to implement without proper training and knowledge.	• Suitable for product development and improvement, especially in manufacturing

Method	Strengths	Weakness	Suitability
	improving product development. • Useful for translating customer requirements into specific technical specifications. • Encourages cross-functional teamwork and collaboration.	• Can be time-consuming and resource-intensive for large projects. • May not be effective if customer needs are unclear or difficult to quantify.	and engineering. • Ideal for situations where customer satisfaction and technical performance need to be aligned.
DEMATEL	• Useful for understanding and visualizing the relationships between various factors in a system. • Can identify cause-and-effect relationships between criteria. Helps in simplifying complex systems by showing direct and indirect influences.	• Requires expert judgment for establishing causal relationships, which may be subjective. • Can be complex to analyze and interpret, especially in large systems. Requires significant data and expert input to model the system accurately.	• Suitable for complex decision-making problems where causal relationships need to be understood and visualized. Ideal for systems thinking and when interdependencies between various factors or criteria are significant.

Table 4.6: Full Names of the abbreviated multi-criteria analysis methods (mentioned in Table 4.5)

TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
AHP	Analytical Hierarchy Process
ELECTRE	Elimination and Choice Expressing Reality
PROMETHEE	The Preference Ranking Organization Method for Enrichment of Evaluation
DAE	Linear Programming Data Envelopment Analysis
ANP	Analytical Network Process
VIKOR	VIšekriterijumsko KOmpromisno Rangiranje (A Serbian term for “multi-criteria optimization and compromise solution”
DELPHI	A questionnaire technique that can be used in MCDM to help determine the most relevant criteria for a process or to make group decision
QFD	Quality Function Deployment
DEMATEL	Decision MAking Trial and Evaluation Laboratory

4.2.6 Analytical Hierarchy Process (AHP)

A very extensive and deep review of the literature (108 scientific papers, published since 1999) revealed that many MCDM methods and their combination have been used. The most frequently used method was the Analytical Hierarchy Process (AHP), followed by TOPSIS, ANP, DEA, VIKOR, DELPHI, QFD, DEMATEL, PROMETHEE, ELECTRE, and ISM [41]

Analytical Hierarchy Process(AHP) has been found to be the most appropriate for the case at hand as well. As the case under consideration has fourteen alternatives with similar number (14) of evaluation criteria, there are 196 pair-wise comparisons for the criteria; and similar number of pair-wise comparisons for the Technologies under each criterion. This makes the number of pair-wise comparisons 2940. The sensitivity analysis involves a total of 3822 pairs (for criteria weight and measure of performance). These make the analysis to be classified as complex and hence Analytical Hierarchy Process (AHP) is the most appropriate.

Analytical Hierarchy Process does also fulfill the other suitability criteria used to select Multi-Criteria Analysis method in relation to: problem type; criteria structure; decision maker involvement; data availability and quality; and method complexity and performance. The provisions to measure consistency (in undergoing the pair-wise comparisons) and sensitivity (of the ranking to the criteria weights, and measures of performance)are the other significant advantages.

For the case under consideration, the type of task is ranking where the evaluator orders the options from “best” to “worst”. Analytical Hierarchy Process yields the prioritized alternatives in their order of importance based on the relative weight allocated to each criterion and the relative importance of the criteria. As to the criteria structure, for the case at hand, the evaluation criteria are dominantly qualitative. The necessary care has been taken to minimize dependence among the criteria. Analytical Hierarchy Process entertains qualitative data both at the stage of evaluation of the relative importance of the criteria and weight allocation for each alternative. Fulfilling the consistency criteria may require quite a number of trials, but not unachievable.

With respect to complexity of the method and performance, Analytical Hierarchy Process is not difficult to understand, apply and interpret. Allocation of relative weights to criteria, by comparing each criterion with the rest, is rather clear and understandable. The Process also has a consistency barometer which helps the evaluator be consistent by obliging its Consistency Index to fall below a maximum set value. Analytical Hierarchy Process is fairly transparent and traceable as the final result is build upon detail and clear multi-steps. It has also a sensitivity analysis tools which indicate robustness of the evaluation.

Analytical Hierarchy Process (AHP), developed by Satty in 1971-1975, is a general theory of measurement. It is used to derive ratio scales from both discrete and continuous paired comparisons. In its general form, the Analytical Hierarchy Process is a nonlinear framework for carrying out both deductive and inductive thinking without using syllogism by taking several factors into consideration simultaneously and allowing for dependence and for feedback, and making numerical tradeoffs to arrive at a synthesis or conclusion[42].

The Analytical Hierarchy Process is decomposed into the following steps [43]

1. Defining the problem and determining the kind of knowledge sought.
2. Structuring the decision hierarchy from the top level with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of alternative).
3. Constructing a set of pair-wise comparison matrices. Each element in the upper level is used to compare the elements in the level immediately below with respect to it.
4. Using the properties obtained from the comparisons to weigh the priorities in the level immediately below. This is done for every element. Then for each element in the level below its weighted values are add and to obtain its overall or global priority. This process of weighing and adding continues till the final priorities of the alternatives in the bottom most level are obtained. The fundamental scales to be used for the pair-wise comparison are as shown in Table 4.7.

Table 4.7: The fundamental scale of absolute numbers

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over the other
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over the other
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance is demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1 – 1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

4.2.6.1 Establishing relative weights for the of criteria

Establishing relative weights for criteria involves: Development of Pair-Wise Comparison Matrices, for the different scenarios; Normalization of the Pair-Wise Comparison Matrices; Evaluating consistency of the Pair-Wise Comparison Matrices; and, if consistency is within the acceptable limit, aggregation of the Evaluation.

4.2.6.2 Developing Pair-wise Comparison Matrices

Requirements of the first two steps of the Analytical Hierarchy Process have been accomplished in the previous chapters. The Problem is defined under Introduction (Chapter

1); the knowledge sought is addressed under Materials and Methods (Chapter 2); and the Alternatives are availed through Literature Review (Chapter 3). The third step, of conducting Pair-wise Comparison, among the fourteen criteria depicted in Table 4.4 is processed as below.

Pair-wise Comparison Matrix among the Criteria: Tables 4.8 to 4.20 show the comparison of each criterion with the rest of the criteria. The relative weights are placed to the side of the criteria to which more weight is given. By summarizing these comparisons in a single table, a Pair-wise Comparison Matrix is created. As the criteria of comparison are fourteen a fourteen-by-fourteen matrix is formed. Table 4.21 is summary of the pair wise comparisons for the criteria of comparison. The matrix uses different colors for ease of matching of the corresponding cells. The columns and rows are named by the Criteria of Comparison. Each Criterion in the column of the matrix is weighed, pair wise, against each criterion in the rows. Intensity of Importance values (recommended by Satty, Table 4.7) are used. A criterion picked from a column is compared with all the criteria in the respective row. The matrix compares a pair of criteria twice. The second pair is a reversed order of the first. The value given to such a pair is the reciprocal of the value given for the reverse order[43]. While comparing two criteria (say, ‘A’ and ‘B’), the Intensity of Importance point is given in the cell where the two criteria meet. If ‘A’ is more important than ‘B’, then the point is given in the cell where row ‘A’ and Column ‘B’ meet. If ‘B’ is more important than ‘A’, the point given is written in a cell where row ‘B’ and Column ‘A’ meet. As a criterion of comparison cannot be more important than itself, the values for diagonal of the matrix are always 1 (one).

Pair-wise Comparison Matrix among the Technologies against Each Criterion: Similarly, pair-wise comparisons have been made among the Technologies against each criterion. The results are depicted in Table 4.26through Table 4.51.

Table 4.8: Pair-wise comparison (Ease of Manufacturing with the rest of criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Ease of Manufacturing									■									Ease of Operation
Ease of Manufacturing									■									Maintenance Requirement
Ease of Manufacturing								■										Frequency of Supervision
Ease of Manufacturing					■													Security (theft)
Ease of Manufacturing									■									Service Year
Ease of Manufacturing					■													Mobility
Ease of Manufacturing								■										Pumping Height
Ease of Manufacturing								■										Pumping Volume
Ease of Manufacturing								■										Literature Coverage
Ease of Manufacturing							■											Operational Flow Volume
Ease of Manufacturing							■											Operational Head Requirement
Ease of Manufacturing					■													Patent Right
Ease of Manufacturing	■																	Manufactured for Commerce

Table 4.9: Pair-wise comparison (Ease of Operation with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Ease of Operation									■									Maintenance Requirement
Ease of Operation									■									Frequency of Supervision
Ease of Operation						■												Security (theft)
Ease of Operation									■									Service Year
Ease of Operation						■												Mobility
Ease of Operation								■										Pumping Height
Ease of Operation								■										Pumping Volume
Ease of Operation								■										Literature Coverage
Ease of Operation								■										Operational Flow Volume
Ease of Operation								■										Operational Head Requirement
Ease of Operation						■												Patent Right
Ease of Operation				■														Manufactured for Commerce

Table 4.10: Pair-wise comparison (Maintenance Requirement with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Maintenance Requirement									■									Frequency of Supervision
Maintenance Requirement						■												Security (theft)
Maintenance Requirement									■									Service Year
Maintenance Requirement						■												Mobility
Maintenance Requirement								■										Pumping Height
Maintenance Requirement								■										Pumping Volume
Maintenance Requirement								■										Literature Coverage
Maintenance Requirement								■										Operational Flow Volume
Maintenance Requirement								■										Operational Head Requirement
Maintenance Requirement						■												Patent Right
Maintenance Requirement			■															Manufactured for Commerce

Table 4.11: Pair-wise comparison (Frequency of Supervision with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Frequency of Supervision					■													Security (theft)
Frequency of Supervision									■									Service Year
Frequency of Supervision							■											Mobility
Frequency of Supervision									■									Pumping Height
Frequency of Supervision									■									Pumping Volume
Frequency of Supervision								■										Literature Coverage
Frequency of Supervision								■										Operational Flow Volume
Frequency of Supervision								■										Operational Head Requirement
Frequency of Supervision							■											Patent Right
Frequency of Supervision				■														Manufactured for Commerce

Table 4.12: Pair-wise comparison (Security / Theft with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Security (theft)													■					Service Year
Security (theft)									■									Mobility
Security (theft)											■							Pumping Height
Security (theft)											■							Pumping Volume
Security (theft)										■								Literature Coverage
Security (theft)										■								Operational Flow Volume Requirement
Security (theft)										■								Operational Head Requirement
Security (theft)									■									Patent Right
Security (theft)								■										Manufactured for Commerce

Table 4.13: Pair-wise comparison (Service Year with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Service Year					■													Mobility
Service Year								■										Pumping Height
Service Year								■										Pumping Volume
Service Year							■											Literature Coverage
Service Year								■										Operational Flow Volume Requirement
Service Year								■										Operational Head Requirement
Service Year						■												Patent Right
Service Year		■																Manufactured for Commerce

Table 4.14: Pair-wise comparison (Mobility with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Mobility											■							Pumping Height
Mobility											■							Pumping Volume
Mobility										■								Literature Coverage
Mobility										■								Operational Flow Volume
Mobility										■								Operational Head Requirement
Mobility									■									Patent Right
Mobility									■									Manufactured for Commerce

Table 4.15: Pair-wise comparison (Pumping Height with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Pumping Height									■									Pumping Volume
Pumping Height								■										Literature Coverage
Pumping Height									■									Operational Flow Volume
Pumping Height									■									Operational Head Requirement
Pumping Height							■											Patent Right
Pumping Height					■													Manufactured for Commerce

Table 4.16: Pair-wise comparison (Pumping Volume with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Pumping Volume								■										Literature Coverage
Pumping Volume									■									Operational Flow Volume
Pumping Volume									■									Operational Head Requirement
Pumping Volume							■											Patent Right
Pumping Volume					■													Manufactured for Commerce

Table 4.17: Pair-wise comparison (Literature Coverage with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Literature Coverage								■										Operational Flow Volume Requirement
Literature Coverage									■									Operational Head Requirement
Literature Coverage								■										Patent Right
Literature Coverage							■											Manufactured for Commerce

Table 4.18: Pair-wise comparison (Operational Flow Volume Requirement with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Operational Flow Volume Requirement									■									Operational Head Requirement
Operational Flow Volume Requirement								■										Patent Right
Operational Flow Volume Requirement						■												Manufactured for Commerce

Table 4.19: Pair-wise comparison (Operational Head Requirement with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Operational Head Requirement								■										Patent Right
Operational Head Requirement								■										Manufactured for Commerce

Table 4.20: Pair-wise comparison (Patent Right Protection with the remaining criteria)

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria II
Patent Right								■										Manufactured for Commerce

Table 4.21: Pair-wise Comparison Matrix of criteria (n – number of criteria of comparison equals 14)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	1.00	1.00	1.00	2.00	5.00	1.00	5.00	2.00	2.00	2.00	3.00	3.00	5.00	9.00
B	1.00	1.00	1.00	1.00	4.00	1.00	4.00	2.00	2.00	2.00	2.00	2.00	4.00	7.00
C	1.00	1.00	1.00	1.00	4.00	1.00	4.00	2.00	2.00	2.00	2.00	2.00	4.00	7.00
D	0.50	1.00	1.00	1.00	5.00	1.00	3.00	1.00	1.00	2.00	2.00	2.00	3.00	6.00
E	0.20	1.00	0.25	0.20	1.00	0.20	1.00	0.33	0.33	0.50	0.50	0.50	1.00	2.00
F	1.00	1.00	1.00	1.00	5.00	1.00	5.00	2.00	2.00	3.00	2.00	2.00	4.00	8.00
G	0.20	0.25	0.25	0.33	1.00	0.20	1.00	0.33	0.33	0.50	0.50	0.50	1.00	1.00
H	0.50	0.50	0.50	1.00	3.00	0.50	3.00	1.00	1.00	2.00	1.00	1.00	3.00	5.00
I	0.50	0.50	0.50	1.00	3.00	0.50	3.00	1.00	1.00	2.00	1.00	1.00	3.00	5.00
J	0.50	0.50	0.50	0.50	2.00	0.33	2.00	0.50	0.50	1.00	2.00	1.00	2.00	3.00
K	0.33	0.50	0.50	0.50	2.00	0.50	2.00	1.00	1.00	0.50	1.00	1.00	2.00	4.00
L	0.33	0.50	0.50	0.50	2.00	0.50	2.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00
M	0.20	0.25	0.25	0.33	1.00	0.25	1.00	0.33	0.33	0.50	0.50	0.60	1.00	2.00
N	0.11	0.14	0.14	0.17	0.50	0.13	1.00	0.20	0.20	0.33	0.25	0.50	0.50	1.00
SUM	7.38	9.14	8.39	10.53	38.50	8.11	37.00	14.7	14.7	19.33	18.75	18.10	35.50	62.00

A	**Ease of Manufacturing**		H	**Pumping Height**
B	**Ease of Operation**		I	**Pumping Volume**
C	**Maintenance Requirement**		J	**Literature Coverage**
D	**Frequency of Supervision**		K	**Operational Flow Volume Requirement**
E	**Security (theft)**		L	**Operational Head Requirement**
F	**Service Year**		M	**Patent Right**
G	**Mobility**		N	**Manufactured for Commerce**

4.2.6.3 Normalization

To nullify the influence of variation in magnitudes (scales) of variables, or to obtain comparable unit, each column of the pair-wise comparison matrix is normalized. There are different methods of Normalization. The normalization is made by classifying the values as Beneficial and Non-beneficial. Beneficial value is a value that benefits the objective. If one, for instance, chooses fuel consumption as one evaluation criteria to choose the best vehicle and this criteria is measured by knowing the fuel consumption of a vehicle per kilometer, then the measuring variable (fuel per kilometer) is Non-beneficial as the bigger this value is to the disadvantage of the evaluator/buyer. On the contrary, if the fuel-efficiency is measured by the kilometers covered by a liter of fuel, then the measuring variable is Beneficial as the bigger this value is to the advantage of the evaluator/buyer. While conducting the evaluation, beneficial grading has been employed. The study used Linear Normalization (by Sum) among the available three (Linear Normalization by Sum, by Max. minus Min., and by Max.)[44].

Linear Normalization by Sum

Beneficial: The value of each cell is divided by the sum of values in that column.

Non-beneficial: The reciprocal of the value of each cell is divided by the sum of reciprocals of the values in that column.

Linear Normalization by Max – Min.

Beneficial: The value of each cell is calculated by dividing the difference between each cell and the minimum value in the column (value in each cell minus the minimum in the column) by the difference between the maximum and minimum values in the column.

Non-beneficial: The difference between the maximum value in the column and the value of the cell under consideration is divided by the difference of the maximum and minimum values of the column

Linear Normalization by Max.

Beneficial: The value in each cell is divided by the maximum value in the respective Column

Non-beneficial: The value in each cell is divided by the maximum value in the Column and the result is subtracted from 1.

There are also other techniques (such as vector normalization) for both Beneficial and Non-beneficial Criteria. Linear Normalization is used for the case at hand as it is more intuitive and yields more or less similar result. All the comparisons are made by considering the Beneficial aspect of each criteria. For instance if Operational Flow Volume Requirement is considered, then higher point is given for a technology with less Operational Flow Volume Requirement and vice versa.

The normalized matrix is depicted in Table 4.22. Here, it is worth noting that sum of the cells of a column of a normalized matrix is 1 (one). Mean of each row (of Matrix / Table 4.22) gives the relative weight (Criteria Weight) of the corresponding criteria of comparison. The Criteria are ranked based on their relative weight.

Table 4.22: Normalized matrix, criteria weight, and rank of criteria

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Criteria Weight	Rank
A	0.14	0.11	0.12	0.19	0.13	0.12	0.14	0.14	0.14	0.10	0.16	0.17	0.14	0.15	0.138	1
B	0.14	0.11	0.12	0.09	0.10	0.12	0.11	0.14	0.14	0.10	0.11	0.11	0.11	0.11	0.115	3
C	0.14	0.11	0.12	0.09	0.10	0.12	0.11	0.14	0.14	0.10	0.11	0.11	0.11	0.11	0.115	3
D	0.07	0.11	0.12	0.09	0.13	0.12	0.08	0.07	0.07	0.10	0.11	0.11	0.08	0.10	0.097	5
E	0.03	0.11	0.03	0.02	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.032	11
F	0.14	0.11	0.12	0.09	0.13	0.12	0.14	0.14	0.14	0.16	0.11	0.11	0.11	0.13	0.124	2
G	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.026	13
H	0.07	0.05	0.06	0.09	0.08	0.06	0.08	0.07	0.07	0.10	0.05	0.06	0.08	0.08	0.072	6
I	0.07	0.05	0.06	0.09	0.08	0.06	0.08	0.07	0.07	0.10	0.05	0.06	0.08	0.08	0.072	6
J	0.07	0.05	0.06	0.05	0.05	0.04	0.05	0.03	0.03	0.05	0.11	0.06	0.06	0.05	0.055	9
K	0.05	0.05	0.06	0.05	0.05	0.06	0.05	0.07	0.07	0.03	0.05	0.06	0.06	0.06	0.055	8
L	0.05	0.05	0.06	0.05	0.05	0.06	0.05	0.07	0.07	0.05	0.05	0.06	0.06	0.03	0.054	10
M	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.028	12
N	0.02	0.02	0.02	0.02	0.01	0.02	0.03	0.01	0.01	0.02	0.01	0.03	0.01	0.02	0.017	14
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

A	**Ease of Manufacturing**		H	**Pumping Height**
B	**Ease of Operation**		I	**Pumping Volume**
C	**Maintenance Requirement**		J	**Literature Coverage**
D	**Frequency of Supervision**		K	**Operational Flow Volume Requirement**
E	**Security (theft)**		L	**Operational Head Requirement**
F	**Service Year**		M	**Patent Right**
G	**Mobility**		N	**Manufactured for Commerce**

Table 4.23: Multiplication of pair-wise comparison matrix by the criteria weight (for criteria of comparison)

I														II	III	IV
Pair-wise Comparison Matrix														Criteria Weight	Multipli-cation	Eigen Value
1.00	1.00	1.00	2.00	5.00	1.00	5.00	2.00	2.00	2.00	3.00	3.00	5.00	9.00	0.14	1.99	14.45
1.00	1.00	1.00	1.00	4.00	1.00	4.00	2.00	2.00	2.00	2.00	2.00	4.00	7.00	0.12	1.67	14.47
1.00	1.00	1.00	1.00	4.00	1.00	4.00	2.00	2.00	2.00	2.00	2.00	4.00	7.00	0.12	1.67	14.47
0.50	1.00	1.00	1.00	5.00	1.00	3.00	1.00	1.00	2.00	2.00	2.00	3.00	6.00	0.10	1.41	14.52
0.20	1.00	0.25	0.20	1.00	0.20	1.00	0.33	0.33	0.50	0.50	0.50	1.00	2.00	0.03	0.47	14.51
1.00	1.00	1.00	1.00	5.00	1.00	5.00	2.00	2.00	3.00	2.00	2.00	4.00	8.00	0.12	1.80	14.50
0.20	0.25	0.25	0.33	1.00	0.20	1.00	0.33	0.33	0.50	0.50	0.50	1.00	1.00	0.03	0.37	14.45
0.50	0.50	0.50	1.00	3.00	0.50	3.00	1.00	1.00	2.00	1.00	1.00	3.00	5.00	0.07	1.05	14.51
0.50	0.50	0.50	1.00	3.00	0.50	3.00	1.00	1.00	2.00	1.00	1.00	3.00	5.00	0.07	1.05	14.51
0.50	0.50	0.50	0.50	2.00	0.33	2.00	0.50	0.50	1.00	2.00	1.00	2.00	3.00	0.05	0.79	14.43
0.33	0.50	0.50	0.50	2.00	0.50	2.00	1.00	1.00	0.50	1.00	1.00	2.00	4.00	0.05	0.79	14.46
0.33	0.50	0.50	0.50	2.00	0.50	2.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	0.05	0.79	14.47
0.20	0.25	0.25	0.33	1.00	0.25	1.00	0.33	0.33	0.50	0.50	0.60	1.00	2.00	0.03	0.40	14.44
0.11	0.14	0.14	0.17	0.50	0.13	1.00	0.20	0.20	0.33	0.25	0.50	0.50	1.00	0.02	0.24	14.35
															Average	14.47

Consistency Index, CI=3.58 %

Consistency Ratio CR = 2.2 % CR<10 % shows that the evaluation has acceptable consistency

RANDOM INDICES [48]															
n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.58

Table 4.24: Pair-wise comparison matrix of the technologies (with respect to Ease of Manufacturing)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	5.00	9.00	1.00	9.00	7.00	6.00	4.00	0.25	7.00	5.00	4.00	9.00
2	1.00	1.00	5.00	9.00	1.00	9.00	7.00	6.00	4.00	0.25	7.00	6.00	6.00	9.00
3	0.20	0.20	1.00	9.00	0.50	6.00	4.00	2.00	1.00	0.33	1.00	4.00	2.00	6.00
4	0.11	0.11	0.11	1.00	0.11	0.20	0.20	0.17	0.13	0.11	0.13	0.17	0.17	0.33
5	1.00	1.00	2.00	9.00	1.00	8.00	6.00	3.00	2.00	1.00	2.00	5.00	3.00	9.00
6	0.11	0.11	0.17	5.00	0.13	1.00	0.50	0.33	0.25	0.11	0.17	0.20	0.20	2.00
7	0.14	0.14	0.25	5.00	0.17	2.00	1.00	0.25	0.33	0.14	0.20	1.00	0.17	4.00
8	0.17	0.17	0.50	6.00	0.33	3.00	4.00	1.00	1.00	0.20	0.33	2.00	2.00	4.00
9	0.25	0.25	1.00	8.00	0.50	4.00	3.00	1.00	1.00	0.25	2.00	4.00	2.00	6.00
10	4.00	4.00	3.00	9.00	1.00	9.00	7.00	5.00	4.00	1.00	8.00	6.00	4.00	9.00
11	0.14	0.14	1.00	8.00	0.50	6.00	5.00	3.00	0.50	0.13	1.00	4.00	3.00	7.00
12	0.20	0.17	0.25	6.00	0.20	5.00	1.00	0.50	0.25	0.17	0.25	1.00	1.00	5.00
13	0.25	0.17	0.50	6.00	0.33	5.00	6.00	0.50	0.50	0.25	0.33	1.00	1.00	5.00
14	0.11	0.11	0.17	3.00	0.11	0.50	0.25	0.25	0.17	0.11	0.14	0.20	0.20	1.00
SUM	8.69	8.57	19.94	93.00	6.88	67.7	52	29	19.1	4.3	29.6	39.6	28.733	76.3

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.25: Multiplication of pair-wise comparison matrix by the criteria weight (for Ease of Manufacturing)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.115	0.117	0.251	0.097	0.145	0.133	0.135	0.207	0.209	0.058	0.237	0.126	0.139	0.118	0.149	2.59	17.38
2	0.115	0.117	0.251	0.097	0.145	0.133	0.135	0.207	0.209	0.058	0.237	0.152	0.209	0.118	0.156	2.71	17.39
3	0.023	0.023	0.050	0.097	0.073	0.089	0.077	0.069	0.052	0.077	0.034	0.101	0.070	0.079	0.065	1.02	15.65
4	0.013	0.013	0.006	0.011	0.016	0.003	0.004	0.006	0.007	0.026	0.004	0.004	0.006	0.004	0.009	0.13	15.33
5	0.115	0.117	0.100	0.097	0.145	0.118	0.115	0.103	0.105	0.232	0.068	0.126	0.104	0.118	0.119	1.89	15.87
6	0.013	0.013	0.008	0.054	0.018	0.015	0.010	0.011	0.013	0.026	0.006	0.005	0.007	0.026	0.016	0.23	14.53
7	0.016	0.017	0.013	0.054	0.024	0.030	0.019	0.009	0.017	0.033	0.007	0.025	0.006	0.052	0.023	0.34	14.74
8	0.019	0.019	0.025	0.065	0.048	0.044	0.077	0.034	0.052	0.046	0.011	0.051	0.070	0.052	0.044	0.68	15.52
9	0.029	0.029	0.050	0.086	0.073	0.059	0.058	0.034	0.052	0.058	0.068	0.101	0.070	0.079	0.060	0.98	16.18
10	0.461	0.467	0.150	0.097	0.145	0.133	0.135	0.172	0.209	0.232	0.271	0.152	0.139	0.118	0.206	3.58	17.41
11	0.016	0.017	0.050	0.086	0.073	0.089	0.096	0.103	0.026	0.029	0.034	0.101	0.104	0.092	0.065	1.04	15.96
12	0.023	0.019	0.013	0.065	0.029	0.074	0.019	0.017	0.013	0.039	0.008	0.025	0.035	0.066	0.032	0.47	14.94
13	0.029	0.019	0.025	0.065	0.048	0.074	0.115	0.017	0.026	0.058	0.011	0.025	0.035	0.066	0.044	0.67	15.21
14	0.013	0.013	0.008	0.032	0.016	0.007	0.005	0.009	0.009	0.026	0.005	0.005	0.007	0.013	0.012	0.18	14.87
SUM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Average	15.78

CI = 13.72

CR = 8.74 %CR<10 % shows that the evaluation has acceptable consistency

Table 4.26: Pair-wise comparison matrix of the technologies (with respect to Ease of Operation)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.000	1.000	0.500	7.000	2.000	7.000	2.000	1.000	2.000	1.000	2.000	2.000	2.000	4.000
2	1.000	1.000	0.500	7.000	2.000	7.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000	4.000
3	2.000	2.000	1.000	8.000	3.000	8.000	3.000	1.000	4.000	2.000	3.000	2.000	4.000	4.000
4	0.143	0.143	0.125	1.000	0.333	1.000	0.333	0.167	0.333	0.200	0.333	0.250	0.500	0.500
5	0.500	0.500	0.333	3.000	1.000	3.000	1.000	0.250	0.333	0.200	0.250	0.333	0.333	0.500
6	0.143	0.143	0.125	1.000	0.333	1.000	0.333	0.200	0.250	0.143	0.167	0.200	0.250	1.000
7	0.500	0.500	0.333	3.000	1.000	3.000	1.000	0.500	2.000	0.333	0.500	0.500	3.000	4.000
8	1.000	1.000	2.000	6.000	4.000	5.000	2.000	1.000	3.000	2.000	2.000	3.000	2.000	4.000
9	0.500	0.500	0.250	3.000	3.000	4.000	0.500	0.333	1.000	1.000	3.000	0.500	1.000	3.000
10	1.000	1.000	0.500	5.000	5.000	7.000	3.000	0.500	1.000	1.000	2.000	1.000	3.000	3.000
11	0.500	0.500	0.333	3.000	4.000	6.000	2.000	0.500	0.333	0.500	1.000	0.500	2.000	3.000
12	0.500	1.000	0.500	4.000	3.000	5.000	2.000	0.333	2.000	1.000	2.000	1.000	0.500	2.000
13	0.500	0.500	0.250	2.000	3.000	4.000	0.333	0.500	1.000	0.333	0.500	2.000	1.000	2.000
14	0.250	0.250	0.250	2.000	2.000	1.000	0.250	0.250	0.333	0.333	0.333	0.500	0.500	1.000
SUM	9.54	10.036	7	55	33.7	62	19.8	7.53	19.6	11	19.1	14.8	22.083	36

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.27: Multiplication of pair-wise comparison matrix by the criteria weight (for Ease of Operation)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.1	0.0996	0.0714	0.13	0.06	0.11	0.1	0.13	0.1	0.09	0.1	0.14	0.0906	0.11	0.10314	1.553	15.059
2	0.1	0.0996	0.0714	0.13	0.06	0.11	0.1	0.13	0.1	0.09	0.1	0.07	0.0906	0.11	0.09831	1.478	15.033
3	0.21	0.1993	0.1429	0.15	0.09	0.13	0.15	0.13	0.2	0.18	0.16	0.14	0.1811	0.11	0.15502	2.355	15.191
4	0.01	0.0142	0.0179	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.0226	0.01	0.01688	0.256	15.189
5	0.05	0.0498	0.0476	0.05	0.03	0.05	0.05	0.03	0.02	0.02	0.01	0.02	0.0151	0.01	0.03329	0.491	14.756
6	0.01	0.0142	0.0179	0.02	0.01	0.02	0.02	0.03	0.01	0.01	0.01	0.01	0.0113	0.03	0.01584	0.236	14.897
7	0.05	0.0498	0.0476	0.05	0.03	0.05	0.05	0.07	0.1	0.03	0.03	0.03	0.1358	0.11	0.05992	0.913	15.243
8	0.1	0.0996	0.2857	0.11	0.12	0.08	0.1	0.13	0.15	0.18	0.1	0.2	0.0906	0.11	0.13404	2.040	15.222
9	0.05	0.0498	0.0357	0.05	0.09	0.06	0.03	0.04	0.05	0.09	0.16	0.03	0.0453	0.08	0.06264	0.960	15.327
10	0.1	0.0996	0.0714	0.09	0.15	0.11	0.15	0.07	0.05	0.09	0.1	0.07	0.1358	0.08	0.09856	1.500	15.221
11	0.05	0.0498	0.0476	0.05	0.12	0.1	0.1	0.07	0.02	0.05	0.05	0.03	0.0906	0.08	0.065	0.983	15.123
12	0.05	0.0996	0.0714	0.07	0.09	0.08	0.1	0.04	0.1	0.09	0.1	0.07	0.0226	0.06	0.07535	1.151	15.275
13	0.05	0.0498	0.0357	0.04	0.09	0.06	0.02	0.07	0.05	0.03	0.03	0.14	0.0453	0.06	0.05391	0.812	15.067
14	0.03	0.0249	0.0357	0.04	0.06	0.02	0.01	0.03	0.02	0.03	0.02	0.03	0.0226	0.03	0.02811	0.422	15.011
SUM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Average	15.115

CI = 8.58

CR = 5.46 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.28: Pair-wise comparison matrix of the technologies (with respect to Maintenance Requirement)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	1.00	8.00	3.00	1.00	2.00	3.00	4.00	0.25	3.00	1.00	3.00	0.33
2	1.00	1.00	2.00	8.00	2.00	2.00	1.00	2.00	4.00	0.25	3.00	2.00	3.00	0.33
3	1.00	0.50	1.00	8.00	0.33	0.33	1.00	1.00	3.00	0.20	2.00	0.50	4.00	0.33
4	0.13	0.13	0.13	1.00	0.33	1.00	0.50	0.33	0.33	0.17	0.33	0.25	0.33	0.25
5	0.33	0.50	3.00	3.00	1.00	2.00	2.00	3.00	2.00	0.50	3.00	1.00	2.00	0.50
6	1.00	0.50	3.00	1.00	0.50	1.00	0.50	0.50	3.00	0.33	3.00	1.00	2.00	0.33
7	0.50	1.00	1.00	2.00	0.50	2.00	1.00	0.50	2.00	0.20	2.00	2.00	1.00	0.33
8	0.33	0.50	2.00	3.00	0.33	2.00	2.00	1.00	2.00	0.20	2.00	0.50	1.00	0.33
9	0.25	0.25	0.33	3.00	0.50	0.33	0.50	0.50	1.00	0.25	2.00	0.33	1.00	0.33
10	4.00	4.00	5.00	6.00	2.00	3.00	5.00	5.00	4.00	1.00	4.00	3.00	3.00	2.00
11	0.33	0.33	0.50	3.00	0.33	0.33	0.50	0.50	0.50	0.25	1.00	0.50	2.00	0.50
12	1.00	0.50	2.00	4.00	1.00	1.00	0.50	2.00	3.00	0.33	2.00	1.00	2.00	0.50
13	0.33	0.33	0.25	3.00	0.50	0.50	1.00	1.00	1.00	0.33	0.50	0.50	1.00	0.33
14	3.00	3.00	3.00	4.00	2.00	3.00	3.00	3.00	3.00	0.50	2.00	2.00	3.00	1.00
	14.2	13.54	24.21	57	14.3	19.5	20.5	23.3	32.8	4.77	29.8	15.6	28.33	7.42

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.29: Multiplication of pair-wise comparison matrix by the criteria weight (for Maintenance Requirement)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.07	0.07	0.04	0.14	0.21	0.05	0.10	0.13	0.12	0.05	0.10	0.06	0.11	0.04	0.09	1.46	15.70
2	0.07	0.07	0.08	0.14	0.14	0.10	0.05	0.09	0.12	0.05	0.10	0.13	0.11	0.04	0.09	1.46	15.73
3	0.07	0.04	0.04	0.14	0.02	0.02	0.05	0.04	0.09	0.04	0.07	0.03	0.14	0.04	0.06	0.93	15.50
4	0.01	0.01	0.01	0.02	0.02	0.05	0.02	0.01	0.01	0.03	0.01	0.02	0.01	0.03	0.02	0.30	15.21
5	0.02	0.04	0.12	0.05	0.07	0.10	0.10	0.13	0.06	0.10	0.10	0.06	0.07	0.07	0.08	1.25	15.80
6	0.07	0.04	0.12	0.02	0.03	0.05	0.02	0.02	0.09	0.07	0.10	0.06	0.07	0.04	0.06	0.93	15.90
7	0.04	0.07	0.04	0.04	0.03	0.10	0.05	0.02	0.06	0.04	0.07	0.13	0.04	0.04	0.06	0.86	15.57
8	0.02	0.04	0.08	0.05	0.02	0.10	0.10	0.04	0.06	0.04	0.07	0.03	0.04	0.04	0.05	0.85	15.91
9	0.02	0.02	0.01	0.05	0.03	0.02	0.02	0.02	0.03	0.05	0.07	0.02	0.04	0.04	0.03	0.49	15.09
10	0.28	0.30	0.21	0.11	0.14	0.15	0.24	0.21	0.12	0.21	0.13	0.19	0.11	0.27	0.19	3.06	16.00
11	0.02	0.02	0.02	0.05	0.02	0.02	0.02	0.02	0.02	0.05	0.03	0.03	0.07	0.07	0.03	0.52	15.11
12	0.07	0.04	0.08	0.07	0.07	0.05	0.02	0.09	0.09	0.07	0.07	0.06	0.07	0.07	0.07	1.04	15.78
13	0.02	0.02	0.01	0.05	0.03	0.03	0.05	0.04	0.03	0.07	0.02	0.03	0.04	0.04	0.04	0.54	15.26
14	0.21	0.22	0.12	0.07	0.14	0.15	0.15	0.13	0.09	0.10	0.07	0.13	0.11	0.13	0.13	2.10	16.10
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	15.62

CI = 12.43

CR = 7.92 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.30: Pair-wise comparison matrix of the technologies (with respect to Frequency of Supervision)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	1.00	2.00	3.00	3.00	2.00	1.00	0.50	0.20	0.33	0.50	2.00	2.00
2	1.00	1.00	1.00	2.00	3.00	3.00	2.00	1.00	0.50	0.25	0.33	0.50	2.00	2.00
3	1.00	1.00	1.00	1.00	2.00	2.00	3.00	2.00	1.00	0.33	0.50	0.50	2.00	1.00
4	0.50	0.50	1.00	1.00	2.00	1.00	2.00	0.50	0.33	0.20	0.33	0.33	0.50	0.50
5	0.33	0.33	0.50	0.50	1.00	1.00	1.00	0.33	0.33	0.25	0.33	0.50	0.50	0.50
6	0.33	0.33	0.50	1.00	1.00	1.00	1.00	0.33	0.33	0.25	0.33	0.33	0.50	0.33
7	0.50	0.50	0.33	0.50	2.00	1.00	1.00	0.25	0.50	0.20	0.50	0.50	2.00	4.00
8	1.00	1.00	0.50	2.00	3.00	3.00	4.00	1.00	2.00	0.20	2.00	0.50	2.00	1.00
9	2.00	2.00	1.00	3.00	3.00	3.00	2.00	0.50	1.00	0.50	1.00	0.50	2.00	2.00
10	5.00	4.00	3.00	5.00	4.00	4.00	5.00	5.00	2.00	1.00	3.00	3.00	3.00	2.00
11	3.00	3.00	2.00	3.00	3.00	3.00	2.00	2.00	1.00	0.33	1.00	1.00	2.00	0.50
12	2.00	2.00	2.00	3.00	2.00	3.00	2.00	2.00	2.00	0.33	1.00	1.00	3.00	2.00
13	0.50	0.50	0.50	2.00	2.00	2.00	0.50	0.50	0.50	0.33	0.50	0.33	1.00	0.50
14	0.50	0.50	1.00	2.00	2.00	3.00	0.25	1.00	0.50	0.50	2.00	0.50	2.00	1.00
SUM	18.67	17.67	15.33	28.00	33.00	33.00	27.75	17.42	12.50	4.88	13.17	10.00	24.50	19.33

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.31: Multiplication of pair-wise comparison matrix by the criteria weight (for Frequency of Supervision)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.05	0.06	0.07	0.07	0.09	0.09	0.07	0.06	0.04	0.04	0.03	0.05	0.08	0.10	0.06	0.99	15.46
2	0.05	0.06	0.07	0.07	0.09	0.09	0.07	0.06	0.04	0.05	0.03	0.05	0.08	0.10	0.06	1.00	15.43
3	0.05	0.06	0.07	0.04	0.06	0.06	0.11	0.11	0.08	0.07	0.04	0.05	0.08	0.05	0.07	1.05	15.89
4	0.03	0.03	0.07	0.04	0.06	0.03	0.07	0.03	0.03	0.04	0.03	0.03	0.02	0.03	0.04	0.58	15.56
5	0.02	0.02	0.03	0.02	0.03	0.03	0.04	0.02	0.03	0.05	0.03	0.05	0.02	0.03	0.03	0.44	15.30
6	0.02	0.02	0.03	0.04	0.03	0.03	0.04	0.02	0.03	0.05	0.03	0.03	0.02	0.02	0.03	0.43	15.27
7	0.03	0.03	0.02	0.02	0.06	0.03	0.04	0.01	0.04	0.04	0.04	0.05	0.08	0.21	0.05	0.78	15.67
8	0.05	0.06	0.03	0.07	0.09	0.09	0.14	0.06	0.16	0.04	0.15	0.05	0.08	0.05	0.08	1.28	15.85
9	0.11	0.11	0.07	0.11	0.09	0.09	0.07	0.03	0.08	0.10	0.08	0.05	0.08	0.10	0.08	1.28	15.38
10	0.27	0.23	0.20	0.18	0.12	0.12	0.18	0.29	0.16	0.20	0.23	0.30	0.12	0.10	0.19	3.05	15.85
11	0.16	0.17	0.13	0.11	0.09	0.09	0.07	0.11	0.08	0.07	0.08	0.10	0.08	0.03	0.10	1.52	15.59
12	0.11	0.11	0.13	0.11	0.06	0.09	0.07	0.11	0.16	0.07	0.08	0.10	0.12	0.10	0.10	1.59	15.56
13	0.03	0.03	0.03	0.07	0.06	0.06	0.02	0.03	0.04	0.07	0.04	0.03	0.04	0.03	0.04	0.61	14.96
14	0.03	0.03	0.07	0.07	0.06	0.09	0.01	0.06	0.04	0.10	0.15	0.05	0.08	0.05	0.06	0.97	15.31
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Average	15.51

CI = 11.58

CR = 7.38 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.32: Pair-wise comparison matrix of the technologies (with respect to Security)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	1.00	0.33	1.00	0.33	2.00	1.00	1.00	0.33	0.33	2.00	0.50	0.50
2	1.00	1.00	2.00	0.33	0.50	0.33	3.00	2.00	1.00	0.25	2.00	2.00	1.00	0.50
3	1.00	0.50	1.00	0.33	0.50	0.33	2.00	1.00	1.00	0.25	2.00	2.00	1.00	0.33
4	3.00	3.00	3.00	1.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	2.00	3.00	2.00
5	1.00	2.00	2.00	0.33	1.00	0.33	2.00	2.00	2.00	0.25	0.33	2.00	2.00	0.33
6	3.00	3.00	3.00	0.50	3.00	1.00	4.00	3.00	3.00	2.00	3.00	3.00	3.00	0.50
7	0.50	0.33	0.50	0.33	0.50	0.25	1.00	0.50	0.33	0.25	1.00	0.50	0.50	0.33
8	1.00	0.50	1.00	0.33	0.50	0.33	2.00	1.00	0.50	0.33	2.00	2.00	1.00	0.33
9	1.00	1.00	1.00	0.33	0.50	0.33	3.00	2.00	1.00	0.33	3.00	2.00	1.00	0.33
10	3.00	4.00	4.00	0.33	4.00	0.50	4.00	3.00	3.00	1.00	3.00	3.00	3.00	1.00
11	3.00	0.50	0.50	0.33	3.00	0.33	1.00	0.50	0.33	0.33	1.00	0.50	1.00	0.33
12	0.50	0.50	0.50	0.50	0.50	0.33	2.00	0.50	0.50	0.33	2.00	1.00	1.00	0.33
13	2.00	1.00	1.00	0.33	0.50	0.33	2.00	1.00	1.00	0.33	1.00	1.00	1.00	0.33
14	2.00	2.00	3.00	0.50	3.00	2.00	3.00	3.00	3.00	1.00	3.00	3.00	3.00	1.00
	23.00	20.333	23.5	5.83	21.5	8.75	34.00	23.5	20.7	10.00	26.7	26.00	22.00	8.17

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.33: Multiplication of pair-wise comparison matrix by the criteria weight (for Security)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.04	0.05	0.04	0.06	0.05	0.04	0.06	0.04	0.05	0.03	0.01	0.08	0.02	0.06	0.05	11.00	15.01
2	0.04	0.05	0.09	0.06	0.02	0.04	0.09	0.09	0.05	0.03	0.08	0.08	0.05	0.06	0.06	6.00	14.96
3	0.04	0.02	0.04	0.06	0.02	0.04	0.06	0.04	0.05	0.03	0.08	0.08	0.05	0.04	0.05	10.00	15.04
4	0.13	0.15	0.13	0.17	0.14	0.23	0.09	0.13	0.15	0.30	0.11	0.08	0.14	0.24	0.16	1.00	15.44
5	0.04	0.10	0.09	0.06	0.05	0.04	0.06	0.09	0.10	0.03	0.01	0.08	0.09	0.04	0.06	5.00	15.07
6	0.13	0.15	0.13	0.09	0.14	0.11	0.12	0.13	0.15	0.20	0.11	0.12	0.14	0.06	0.13	3.00	15.53
7	0.02	0.02	0.02	0.06	0.02	0.03	0.03	0.02	0.02	0.03	0.04	0.02	0.02	0.04	0.03	14.00	15.04
8	0.04	0.02	0.04	0.06	0.02	0.04	0.06	0.04	0.02	0.03	0.08	0.08	0.05	0.04	0.04	12.00	15.03
9	0.04	0.05	0.04	0.06	0.02	0.04	0.09	0.09	0.05	0.03	0.11	0.08	0.05	0.04	0.06	7.00	15.13
10	0.13	0.20	0.17	0.06	0.19	0.06	0.12	0.13	0.15	0.10	0.11	0.12	0.14	0.12	0.13	2.00	15.49
11	0.13	0.02	0.02	0.06	0.14	0.04	0.03	0.02	0.02	0.03	0.04	0.02	0.05	0.04	0.05	8.00	15.58
12	0.02	0.02	0.02	0.09	0.02	0.04	0.06	0.02	0.02	0.03	0.08	0.04	0.05	0.04	0.04	13.00	14.99
13	0.09	0.05	0.04	0.06	0.02	0.04	0.06	0.04	0.05	0.03	0.04	0.04	0.05	0.04	0.05	9.00	15.00
14	0.09	0.10	0.13	0.09	0.14	0.23	0.09	0.13	0.15	0.10	0.11	0.12	0.14	0.12	0.12	4.00	15.39
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	15.19

CI = 9.18

CR = 5.85 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.34: Pair-wise comparison matrix of the technologies (with respect to Service Year)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	0.50	0.33	1.00	0.25	0.50	0.33	0.33	0.14	0.33	0.33	1.00	0.25
2	1.00	1.00	0.50	0.25	1.00	0.25	0.33	0.33	0.33	0.14	0.33	0.33	1.00	0.25
3	2.00	2.00	1.00	0.33	3.00	2.00	1.00	1.00	0.50	0.14	0.50	1.00	2.00	0.50
4	3.00	4.00	3.00	1.00	3.00	2.00	2.00	2.00	1.00	0.50	2.00	2.00	4.00	1.00
5	1.00	1.00	0.33	0.33	1.00	0.33	0.33	0.25	0.33	0.13	0.25	0.33	0.33	0.25
6	4.00	4.00	0.50	0.50	3.00	1.00	1.00	0.50	0.50	0.17	0.50	0.33	1.00	0.50
7	2.00	3.00	1.00	0.50	3.00	1.00	1.00	0.50	0.33	0.20	0.50	0.33	2.00	0.50
8	3.00	3.00	1.00	0.50	4.00	2.00	2.00	1.00	0.50	0.25	2.00	2.00	4.00	0.50
9	3.00	3.00	2.00	1.00	3.00	2.00	3.00	2.00	1.00	0.33	3.00	2.00	4.00	0.50
10	7.00	7.00	7.00	2.00	8.00	6.00	5.00	4.00	3.00	1.00	3.00	3.00	6.00	1.00
11	3.00	3.00	2.00	0.50	4.00	2.00	2.00	0.50	0.33	0.33	1.00	0.50	3.00	0.50
12	3.00	3.00	1.00	0.50	3.00	3.00	3.00	0.50	0.50	0.33	2.00	1.00	3.00	0.50
13	1.00	1.00	0.50	0.25	3.00	1.00	0.50	0.25	0.25	0.17	0.33	0.33	1.00	0.50
14	4.00	4.00	2.00	1.00	4.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	1.00
SUM	38.00	40.00	22.33	9.00	44.00	24.83	23.67	15.17	10.92	4.84	17.75	15.50	34.33	7.75

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.35: Multiplication of pair-wise comparison matrix by the criteria weight (for Service Year)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.03	0.03	0.02	0.04	0.02	0.01	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.36	14.62
2	0.03	0.03	0.02	0.03	0.02	0.01	0.01	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.35	14.64
3	0.05	0.05	0.04	0.04	0.07	0.08	0.04	0.07	0.05	0.03	0.03	0.06	0.06	0.06	0.05	0.78	14.95
4	0.08	0.10	0.13	0.11	0.07	0.08	0.08	0.13	0.09	0.10	0.11	0.13	0.12	0.13	0.11	1.57	14.97
5	0.03	0.03	0.01	0.04	0.02	0.01	0.01	0.02	0.03	0.03	0.01	0.02	0.01	0.03	0.02	0.31	14.50
6	0.11	0.10	0.02	0.06	0.07	0.04	0.04	0.03	0.05	0.03	0.03	0.02	0.03	0.06	0.05	0.71	14.31
7	0.05	0.08	0.04	0.06	0.07	0.04	0.04	0.03	0.03	0.04	0.03	0.02	0.06	0.06	0.05	0.68	14.51
8	0.08	0.08	0.04	0.06	0.09	0.08	0.08	0.07	0.05	0.05	0.11	0.13	0.12	0.06	0.08	1.18	15.01
9	0.08	0.08	0.09	0.11	0.07	0.08	0.13	0.13	0.09	0.07	0.17	0.13	0.12	0.06	0.10	1.52	15.16
10	0.18	0.18	0.31	0.22	0.18	0.24	0.21	0.26	0.27	0.21	0.17	0.19	0.17	0.13	0.21	3.17	15.09
11	0.08	0.08	0.09	0.06	0.09	0.08	0.08	0.03	0.03	0.07	0.06	0.03	0.09	0.06	0.07	0.98	14.79
12	0.08	0.08	0.04	0.06	0.07	0.12	0.13	0.03	0.05	0.07	0.11	0.06	0.09	0.06	0.07	1.12	15.01
13	0.03	0.03	0.02	0.03	0.07	0.04	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.06	0.03	0.45	14.50
14	0.11	0.10	0.09	0.11	0.09	0.08	0.08	0.13	0.18	0.21	0.11	0.13	0.06	0.13	0.12	1.71	14.85
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.78

CI = 9.18

CR = 5.85 % CR<10 % shows that the evaluation acceptable consistency

Table 4.36: Pair-wise comparison matrix of the technologies (with respect to Mobility)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	0.50	0.50	7.00	3.00	7.00	0.33	0.50	2.00	0.33	0.33	0.33	4.00	5.00
2	2.00	1.00	0.50	7.00	3.00	7.00	0.33	0.50	2.00	0.33	0.33	0.33	4.00	5.00
3	2.00	2.00	1.00	8.00	3.00	7.00	0.50	1.00	2.00	1.00	0.50	2.00	5.00	5.00
4	0.14	0.14	0.13	1.00	0.25	0.13	0.13	0.13	0.14	0.13	0.11	0.13	0.17	0.17
5	0.33	0.33	0.33	4.00	1.00	3.00	0.20	0.25	0.33	0.20	0.17	0.20	0.50	0.25
6	0.14	0.14	0.14	8.00	0.33	1.00	0.14	0.17	0.20	0.13	0.13	0.13	0.25	0.25
7	3.00	3.00	2.00	8.00	5.00	7.00	1.00	2.00	3.00	1.00	1.00	2.00	5.00	4.00
8	2.00	2.00	1.00	8.00	4.00	6.00	0.50	1.00	2.00	1.00	1.00	1.00	4.00	3.00
9	0.50	0.50	0.50	7.00	3.00	5.00	0.33	0.50	1.00	0.50	0.33	0.50	3.00	2.00
10	3.00	3.00	1.00	8.00	5.00	8.00	1.00	1.00	2.00	1.00	0.50	1.00	5.00	3.00
11	3.00	3.00	2.00	9.00	6.00	8.00	1.00	1.00	3.00	2.00	1.00	1.00	6.00	4.00
12	3.00	3.00	0.50	8.00	5.00	8.00	0.50	1.00	2.00	1.00	1.00	1.00	4.00	3.00
13	0.25	0.25	0.20	6.00	2.00	4.00	0.20	0.25	0.33	0.20	0.17	0.25	1.00	1.00
14	0.20	0.20	0.20	6.00	4.00	4.00	0.25	0.33	0.50	0.33	0.25	0.33	1.00	1.00
SUM	20.57	19.07	10.00	95.00	44.58	75.13	6.42	9.63	20.51	9.15	6.82	10.20	42.92	36.67

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.37: Multiplication of pair-wise comparison matrix by the criteria weight (for Mobility)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.05	0.03	0.05	0.07	0.07	0.09	0.05	0.05	0.10	0.04	0.05	0.03	0.09	0.14	0.06	1.02	15.77
2	0.10	0.05	0.05	0.07	0.07	0.09	0.05	0.05	0.10	0.04	0.05	0.03	0.09	0.14	0.07	1.12	15.99
3	0.10	0.10	0.10	0.08	0.07	0.09	0.08	0.10	0.10	0.11	0.07	0.20	0.12	0.14	0.10	1.63	15.62
4	0.01	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.01	0.02	0.01	0.00	0.00	0.01	0.14	14.59
5	0.02	0.02	0.03	0.04	0.02	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.35	15.01
6	0.01	0.01	0.01	0.08	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.24	14.21
7	0.15	0.16	0.20	0.08	0.11	0.09	0.16	0.21	0.15	0.11	0.15	0.20	0.12	0.11	0.14	2.17	15.33
8	0.10	0.10	0.10	0.08	0.09	0.08	0.08	0.10	0.10	0.11	0.15	0.10	0.09	0.08	0.10	1.50	15.37
9	0.02	0.03	0.05	0.07	0.07	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.07	0.05	0.05	0.80	15.24
10	0.15	0.16	0.10	0.08	0.11	0.11	0.16	0.10	0.10	0.11	0.07	0.10	0.12	0.08	0.11	1.72	15.62
11	0.15	0.16	0.20	0.09	0.13	0.11	0.16	0.10	0.15	0.22	0.15	0.10	0.14	0.11	0.14	2.15	15.42
12	0.15	0.16	0.05	0.08	0.11	0.11	0.08	0.10	0.10	0.11	0.15	0.10	0.09	0.08	0.10	1.64	15.67
13	0.01	0.01	0.02	0.06	0.04	0.05	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.43	15.14
14	0.01	0.01	0.02	0.06	0.09	0.05	0.04	0.03	0.02	0.04	0.04	0.03	0.02	0.03	0.04	0.53	14.92
SUM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Average	15.28

CI = 9.84

CR = 6.27 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.38: Pair-wise comparison matrix of the technologies (with respect to Pumping Height)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.50	0.50	0.25	0.25	0.25	2.00	2.00
2	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.50	0.50	0.25	0.25	0.25	2.00	2.00
3	1.00	2.00	1.00	1.00	1.00	1.00	0.33	0.50	1.00	0.25	0.25	0.25	2.00	2.00
4	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.50	1.00	0.25	0.25	0.25	2.00	2.00
5	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.50	1.00	0.25	0.25	0.25	2.00	1.00
6	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.50	1.00	0.25	0.25	0.25	2.00	2.00
7	3.00	3.00	3.00	3.00	3.00	3.00	1.00	2.00	2.00	0.50	0.50	0.50	4.00	4.00
8	2.00	2.00	2.00	2.00	2.00	2.00	0.50	1.00	2.00	0.50	0.50	0.50	4.00	2.00
9	2.00	2.00	1.00	1.00	1.00	1.00	0.50	0.50	1.00	0.50	0.50	0.50	2.00	2.00
10	4.00	4.00	4.00	4.00	4.00	4.00	2.00	2.00	2.00	1.00	1.00	1.00	6.00	3.00
11	4.00	4.00	4.00	4.00	4.00	4.00	2.00	2.00	2.00	1.00	1.00	1.00	6.00	3.00
12	4.00	4.00	4.00	4.00	4.00	4.00	2.00	2.00	2.00	1.00	1.00	1.00	6.00	3.00
13	0.50	0.50	0.50	0.50	0.50	0.50	0.25	0.25	0.50	0.17	0.17	0.17	1.00	0.33
14	0.50	0.50	0.50	0.50	1.00	0.50	0.25	0.50	0.50	0.33	0.33	0.33	3.00	1.00
SUM	26.00	27.00	25.00	25.00	25.50	25.00	10.50	13.25	17.00	6.50	6.50	6.50	44.00	29.33

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.39: Multiplication of pair-wise comparison matrix by the criteria weight (for Pumping Height)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.05	0.07	0.04	0.58	14.39
2	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.05	0.07	0.04	0.58	14.39
3	0.04	0.07	0.04	0.04	0.04	0.04	0.03	0.04	0.06	0.04	0.04	0.04	0.05	0.07	0.04	0.65	14.40
4	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.06	0.04	0.04	0.04	0.05	0.07	0.04	0.61	14.35
5	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.06	0.04	0.04	0.04	0.05	0.03	0.04	0.57	14.36
6	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.06	0.04	0.04	0.04	0.05	0.07	0.04	0.61	14.35
7	0.12	0.11	0.12	0.12	0.12	0.12	0.10	0.15	0.12	0.08	0.08	0.08	0.09	0.14	0.11	1.58	14.48
8	0.08	0.07	0.08	0.08	0.08	0.08	0.05	0.08	0.12	0.08	0.08	0.08	0.09	0.07	0.08	1.13	14.34
9	0.08	0.07	0.04	0.04	0.04	0.04	0.05	0.04	0.06	0.08	0.08	0.08	0.05	0.07	0.06	0.82	14.33
10	0.15	0.15	0.16	0.16	0.16	0.16	0.19	0.15	0.12	0.15	0.15	0.15	0.14	0.10	0.15	2.17	14.48
11	0.15	0.15	0.16	0.16	0.16	0.16	0.19	0.15	0.12	0.15	0.15	0.15	0.14	0.10	0.15	2.17	14.48
12	0.15	0.15	0.16	0.16	0.16	0.16	0.19	0.15	0.12	0.15	0.15	0.15	0.14	0.10	0.15	2.17	14.48
13	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.01	0.02	0.31	14.36
14	0.02	0.02	0.02	0.02	0.04	0.02	0.02	0.04	0.03	0.05	0.05	0.05	0.07	0.03	0.03	0.49	14.13
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.38

CI = 2.93

CR = 1.87 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.40: Pair-wise comparison matrix of the technologies (with respect to Pumping Volume)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	0.33	0.20	3.00	0.20	0.25	0.33	0.20	0.17	0.17	0.17	1.00	0.33
2	1.00	1.00	0.33	0.20	3.00	0.20	0.33	0.33	0.20	0.17	0.17	0.17	2.00	0.33
3	3.00	3.00	1.00	0.25	3.00	0.33	0.33	1.00	0.25	0.25	0.25	0.17	3.00	0.33
4	5.00	5.00	4.00	1.00	5.00	3.00	3.00	4.00	2.00	2.00	2.00	2.00	5.00	2.00
5	0.33	0.33	0.33	0.20	1.00	0.20	0.50	0.33	0.33	0.33	0.33	0.33	0.50	0.33
6	5.00	5.00	3.00	0.33	5.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00	4.00	0.50
7	4.00	3.00	3.00	0.33	2.00	0.50	1.00	2.00	0.50	1.00	1.00	0.50	3.00	0.50
8	3.00	3.00	1.00	0.25	3.00	0.50	0.50	1.00	0.50	0.50	0.50	0.33	2.00	0.33
9	5.00	5.00	4.00	0.50	3.00	0.50	2.00	2.00	1.00	2.00	2.00	2.00	5.00	0.50
10	6.00	6.00	4.00	0.50	3.00	0.50	1.00	2.00	0.50	1.00	1.00	1.00	5.00	0.50
11	6.00	6.00	4.00	0.50	3.00	0.50	1.00	2.00	0.50	1.00	1.00	1.00	5.00	0.33
12	6.00	6.00	6.00	0.50	3.00	0.50	2.00	3.00	0.50	1.00	1.00	1.00	5.00	0.50
13	1.00	0.50	0.33	0.20	2.00	0.25	0.33	0.50	0.20	0.20	0.20	0.20	1.00	0.20
14	3.00	3.00	3.00	0.50	3.00	2.00	2.00	3.00	2.00	2.00	3.00	2.00	5.00	1.00
SUM	49.33	47.83	34.33	5.47	42.00	10.18	16.25	23.50	10.68	13.62	14.62	12.87	46.50	7.70

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.41: Multiplication of pair-wise comparison matrix by the criteria weight (for Pumping Volume)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.02	0.02	0.01	0.04	0.07	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.04	0.02	0.34	14.50
2	0.02	0.02	0.01	0.04	0.07	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.04	0.04	0.03	0.37	14.47
3	0.06	0.06	0.03	0.05	0.07	0.03	0.02	0.04	0.02	0.02	0.02	0.01	0.06	0.04	0.04	0.58	14.98
4	0.10	0.10	0.12	0.18	0.12	0.29	0.18	0.17	0.19	0.15	0.14	0.16	0.11	0.26	0.16	2.46	15.17
5	0.01	0.01	0.01	0.04	0.02	0.02	0.03	0.01	0.03	0.02	0.02	0.03	0.01	0.04	0.02	0.33	14.86
6	0.10	0.10	0.09	0.06	0.12	0.10	0.12	0.09	0.19	0.15	0.14	0.16	0.09	0.06	0.11	1.73	15.51
7	0.08	0.06	0.09	0.06	0.05	0.05	0.06	0.09	0.05	0.07	0.07	0.04	0.06	0.06	0.06	0.98	15.42
8	0.06	0.06	0.03	0.05	0.07	0.05	0.03	0.04	0.05	0.04	0.03	0.03	0.04	0.04	0.04	0.67	15.16
9	0.10	0.10	0.12	0.09	0.07	0.05	0.12	0.09	0.09	0.15	0.14	0.16	0.11	0.06	0.10	1.61	15.57
10	0.12	0.13	0.12	0.09	0.07	0.05	0.06	0.09	0.05	0.07	0.07	0.08	0.11	0.06	0.08	1.28	15.49
11	0.12	0.13	0.12	0.09	0.07	0.05	0.06	0.09	0.05	0.07	0.07	0.08	0.11	0.04	0.08	1.26	15.52
12	0.12	0.13	0.17	0.09	0.07	0.05	0.12	0.13	0.05	0.07	0.07	0.08	0.11	0.06	0.09	1.47	15.55
13	0.02	0.01	0.01	0.04	0.05	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.03	0.02	0.32	14.67
14	0.06	0.06	0.09	0.09	0.07	0.20	0.12	0.13	0.19	0.15	0.21	0.16	0.11	0.13	0.13	1.93	15.43
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	15.16

CI = 8.96

CR = 5.70 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.42: Pair-wise comparison matrix of the technologies (with respect to Literature Coverage)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	2.00	2.00	2.00	2.00	0.50	2.00	1.00	0.17	0.50	0.33	2.00	2.00
2	1.00	1.00	2.00	2.00	2.00	2.00	1.00	2.00	1.00	0.20	0.50	0.50	5.00	3.00
3	0.50	0.50	1.00	1.00	1.00	1.00	0.50	1.00	1.00	0.13	0.33	0.25	2.00	2.00
4	0.50	0.50	1.00	1.00	1.00	1.00	0.33	1.00	0.50	0.11	0.33	0.20	1.00	1.00
5	0.50	0.50	1.00	1.00	1.00	1.00	0.33	1.00	0.50	0.11	0.25	0.17	1.00	1.00
6	0.50	0.50	1.00	1.00	1.00	1.00	0.50	1.00	1.00	0.11	0.33	0.20	1.00	1.00
7	2.00	1.00	2.00	3.00	3.00	2.00	1.00	2.00	2.00	0.25	1.00	0.50	3.00	3.00
8	0.50	0.50	1.00	1.00	1.00	1.00	0.50	1.00	1.00	0.11	0.33	0.20	2.00	2.00
9	1.00	1.00	1.00	2.00	2.00	1.00	0.50	1.00	1.00	0.14	0.50	0.25	2.00	2.00
10	6.00	5.00	8.00	9.00	9.00	9.00	4.00	9.00	7.00	1.00	3.00	2.00	9.00	9.00
11	2.00	2.00	3.00	3.00	4.00	3.00	1.00	3.00	2.00	0.33	1.00	0.50	5.00	4.00
12	3.00	2.00	4.00	5.00	6.00	5.00	2.00	5.00	4.00	0.50	2.00	1.00	7.00	7.00
13	0.50	0.20	0.50	1.00	1.00	1.00	0.33	0.50	0.50	0.11	0.20	0.14	1.00	1.00
14	0.50	0.33	0.50	1.00	1.00	1.00	0.33	0.50	0.50	0.11	0.25	0.14	1.00	1.00
SUM	19.5	16.03	28.00	33.00	35.00	31.00	12.83	30.00	23.00	3.385	10.53	6.386	42.00	39.00

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.43Table 4.43: Multiplication of pair-wise comparison matrix by the criteria weight (for Literature Coverage)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.05	0.06	0.07	0.06	0.06	0.06	0.04	0.07	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.78	14.23
2	0.05	0.06	0.07	0.06	0.06	0.06	0.08	0.07	0.04	0.06	0.05	0.08	0.12	0.08	0.07	0.95	14.19
3	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.03	0.04	0.05	0.05	0.04	0.51	14.20
4	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.42	14.22
5	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03	0.40	14.21
6	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.03	0.45	14.25
7	0.10	0.06	0.07	0.09	0.09	0.06	0.08	0.07	0.09	0.07	0.09	0.08	0.07	0.08	0.08	1.12	14.24
8	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.04	0.03	0.03	0.03	0.05	0.05	0.04	0.50	14.21
9	0.05	0.06	0.04	0.06	0.06	0.03	0.04	0.03	0.04	0.04	0.05	0.04	0.05	0.05	0.05	0.65	14.23
10	0.31	0.31	0.29	0.27	0.26	0.29	0.31	0.30	0.30	0.30	0.28	0.31	0.21	0.23	0.28	4.05	14.26
11	0.10	0.12	0.11	0.09	0.11	0.10	0.08	0.10	0.09	0.10	0.09	0.08	0.12	0.10	0.10	1.42	14.24
12	0.15	0.12	0.14	0.15	0.17	0.16	0.16	0.17	0.17	0.15	0.19	0.16	0.17	0.18	0.16	2.28	14.23
13	0.03	0.01	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.34	14.13
14	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.35	14.16
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.21

CI = 1.64

CR = 1.04 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.44: Pair-wise comparison matrix of the technologies (with respect to Flow Volume Requirement)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	0.25	0.33	0.25	0.50	0.20	0.25	0.33	0.11	0.14	0.11	0.17	0.50
2	1.00	1.00	0.25	0.33	0.25	0.50	0.20	0.25	0.11	0.11	0.14	0.11	0.17	0.50
3	4.00	4.00	1.00	3.00	0.50	3.00	0.50	1.00	2.00	0.13	0.14	0.13	0.50	3.00
4	3.00	3.00	0.33	1.00	0.33	3.00	0.33	0.33	0.33	0.17	0.17	0.17	0.17	1.00
5	4.00	4.00	2.00	3.00	1.00	3.00	1.00	2.00	2.00	0.33	0.33	0.33	1.00	3.00
6	2.00	2.00	0.33	0.33	0.33	1.00	0.33	0.33	0.33	0.14	0.14	0.14	0.14	1.00
7	5.00	5.00	2.00	3.00	1.00	3.00	1.00	1.00	2.00	1.00	1.00	2.00	1.00	3.00
8	4.00	4.00	1.00	3.00	0.50	3.00	1.00	1.00	2.00	0.33	0.50	1.00	0.50	3.00
9	3.00	3.00	0.50	3.00	0.50	3.00	0.50	0.50	1.00	0.33	1.00	0.33	0.33	3.00
10	9.00	9.00	8.00	6.00	3.00	7.00	1.00	3.00	3.00	1.00	2.00	3.00	1.00	5.00
11	7.00	7.00	7.00	6.00	3.00	7.00	1.00	2.00	1.00	0.50	1.00	2.00	1.00	5.00
12	9.00	9.00	8.00	6.00	3.00	7.00	0.50	1.00	3.00	0.33	0.50	1.00	1.00	5.00
13	6.00	6.00	2.00	6.00	1.00	7.00	1.00	2.00	3.00	1.00	1.00	1.00	1.00	5.00
14	2.00	2.00	0.33	1.00	0.33	1.00	0.33	0.33	0.33	0.20	0.20	0.20	0.20	1.00
SUM	60.00	60.00	33.00	42.00	15.00	49.00	8.90	15.00	20.44	5.69	8.27	11.52	8.18	39.00

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.45: Multiplication of pair-wise comparison matrix by the criteria weight (for Flow Volume Requirement)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.22	14.62
2	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.21	14.59
3	0.07	0.07	0.03	0.07	0.03	0.06	0.06	0.07	0.10	0.02	0.02	0.01	0.06	0.08	0.05	0.77	14.62
4	0.05	0.05	0.01	0.02	0.02	0.06	0.04	0.02	0.02	0.03	0.02	0.01	0.02	0.03	0.03	0.41	14.35
5	0.07	0.07	0.06	0.07	0.07	0.06	0.11	0.13	0.10	0.06	0.04	0.03	0.12	0.08	0.08	1.12	14.80
6	0.03	0.03	0.01	0.01	0.02	0.02	0.04	0.02	0.02	0.03	0.02	0.01	0.02	0.03	0.02	0.31	14.35
7	0.08	0.08	0.06	0.07	0.07	0.06	0.11	0.07	0.10	0.18	0.12	0.17	0.12	0.08	0.10	1.50	15.28
8	0.07	0.07	0.03	0.07	0.03	0.06	0.11	0.07	0.10	0.06	0.06	0.09	0.06	0.08	0.07	1.01	14.93
9	0.05	0.05	0.02	0.07	0.03	0.06	0.06	0.03	0.05	0.06	0.12	0.03	0.04	0.08	0.05	0.78	14.73
10	0.15	0.15	0.24	0.14	0.20	0.14	0.11	0.20	0.15	0.18	0.24	0.26	0.12	0.13	0.17	2.75	15.96
11	0.12	0.12	0.21	0.14	0.20	0.14	0.11	0.13	0.05	0.09	0.12	0.17	0.12	0.13	0.13	2.12	15.99
12	0.15	0.15	0.24	0.14	0.20	0.14	0.06	0.07	0.15	0.06	0.06	0.09	0.12	0.13	0.13	2.00	15.99
13	0.10	0.10	0.06	0.14	0.07	0.14	0.11	0.13	0.15	0.18	0.12	0.09	0.12	0.13	0.12	1.75	14.91
14	0.03	0.03	0.01	0.02	0.02	0.02	0.04	0.02	0.02	0.04	0.02	0.02	0.02	0.03	0.02	0.36	14.54
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.98

CI = 7.51

CR = 4.79 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.46: Pair-wise comparison matrix of the technologies (with respect to Operational Head Requirement)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	2.00	5.00	3.00	7.00	5.00	2.00	5.00	3.00	3.00	3.00	0.50	5.00
2	1.00	1.00	2.00	5.00	3.00	7.00	5.00	2.00	5.00	3.00	3.00	3.00	0.50	5.00
3	0.50	0.50	1.00	3.00	3.00	4.00	3.00	1.00	3.00	3.00	3.00	3.00	1.00	4.00
4	0.20	0.20	0.33	1.00	0.50	1.00	0.50	0.33	0.50	0.33	0.33	0.33	0.20	1.00
5	0.33	0.33	0.33	2.00	1.00	2.00	2.00	0.33	0.50	0.33	0.33	0.33	0.20	2.00
6	0.14	0.14	0.25	1.00	0.50	1.00	0.33	0.20	0.33	0.33	0.33	0.33	0.14	1.00
7	0.20	0.20	0.33	2.00	0.50	3.00	1.00	0.33	1.00	1.00	1.00	1.00	0.25	2.00
8	0.50	0.50	1.00	3.00	3.00	5.00	3.00	1.00	2.00	2.00	2.00	2.00	0.50	5.00
9	0.20	0.20	0.33	2.00	2.00	3.00	1.00	0.50	1.00	0.50	0.50	0.50	0.50	3.00
10	0.33	0.33	0.33	3.00	3.00	3.00	1.00	0.50	2.00	1.00	2.00	1.00	0.50	3.00
11	0.33	0.33	0.33	3.00	3.00	3.00	1.00	0.50	2.00	0.50	1.00	0.50	0.50	3.00
12	0.33	0.33	0.33	3.00	3.00	3.00	1.00	0.50	2.00	1.00	2.00	1.00	0.50	3.00
13	2.00	2.00	1.00	5.00	5.00	7.00	4.00	2.00	2.00	2.00	2.00	2.00	1.00	5.00
14	0.20	0.20	0.25	1.00	0.50	1.00	0.50	0.20	0.33	0.33	0.33	0.33	0.20	1.00
SUM	7.28	7.28	9.83	39.00	31.00	50.00	28.33	11.40	26.67	18.33	20.83	18.33	6.49	43.00

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly's Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.47: Multiplication of pair-wise comparison matrix by the criteria weight (for Operational Head Requirement)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.14	0.14	0.20	0.13	0.10	0.14	0.18	0.18	0.19	0.16	0.14	0.16	0.08	0.12	0.15	2.18	14.90
2	0.14	0.14	0.20	0.13	0.10	0.14	0.18	0.18	0.19	0.16	0.14	0.16	0.08	0.12	0.15	2.18	14.90
3	0.07	0.07	0.10	0.08	0.10	0.08	0.11	0.09	0.11	0.16	0.14	0.16	0.15	0.09	0.11	1.61	14.90
4	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.34	14.61
5	0.05	0.05	0.03	0.05	0.03	0.04	0.07	0.03	0.02	0.02	0.02	0.02	0.03	0.05	0.04	0.52	14.55
6	0.02	0.02	0.03	0.03	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.28	14.55
7	0.03	0.03	0.03	0.05	0.02	0.06	0.04	0.03	0.04	0.05	0.05	0.05	0.04	0.05	0.04	0.59	14.66
8	0.07	0.07	0.10	0.08	0.10	0.10	0.11	0.09	0.08	0.11	0.10	0.11	0.08	0.12	0.09	1.36	14.77
9	0.03	0.03	0.03	0.05	0.06	0.06	0.04	0.04	0.04	0.03	0.02	0.03	0.08	0.07	0.04	0.62	14.40
10	0.05	0.05	0.03	0.08	0.10	0.06	0.04	0.04	0.08	0.05	0.10	0.05	0.08	0.07	0.06	0.91	14.70
11	0.05	0.05	0.03	0.08	0.10	0.06	0.04	0.04	0.08	0.03	0.05	0.03	0.08	0.07	0.05	0.79	14.54
12	0.05	0.05	0.03	0.08	0.10	0.06	0.04	0.04	0.08	0.05	0.10	0.05	0.08	0.07	0.06	0.91	14.70
13	0.27	0.27	0.10	0.13	0.16	0.14	0.14	0.18	0.08	0.11	0.10	0.11	0.15	0.12	0.15	2.16	14.69
14	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.02	0.31	14.56
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.67

CI = 5.18

CR = 3.3 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.48: Pair-wise comparison matrix of the technologies (with respect to Patent Right)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
2	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
3	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
4	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
5	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
6	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
7	0.33	0.33	0.33	0.33	0.33	0.33	1.00	0.33	0.33	0.50	1.00	1.00	1.00	0.50
8	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
9	1.00	1.00	1.00	1.00	1.00	1.00	3.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00
10	0.50	0.50	0.50	0.50	0.50	0.50	2.00	0.50	0.50	1.00	2.00	2.00	2.00	1.00
11	0.33	0.33	0.33	0.33	0.33	0.33	1.00	0.33	0.33	0.50	1.00	1.00	1.00	0.50
12	0.33	0.33	0.33	0.33	0.33	0.33	1.00	0.33	0.33	0.50	1.00	1.00	1.00	0.50
13	0.33	0.33	0.33	0.33	0.33	0.33	1.00	0.33	0.33	0.50	1.00	1.00	1.00	0.50
14	0.33	0.33	0.33	0.33	0.33	0.33	2.00	0.33	0.33	1.00	2.00	2.00	2.00	1.00
SUM	10.17	10.17	10.17	10.17	10.17	10.17	32.00	10.17	10.17	20.00	32.00	32.00	32.00	28.00

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.49: Multiplication of pair-wise comparison matrix by the criteria weight (for Patent Right)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
2	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
3	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
4	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
5	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
6	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.43	14.03
8	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
9	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.09	0.09	0.09	0.11	0.10	1.38	14.15
10	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.06	0.06	0.06	0.04	0.05	0.73	14.05
11	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.43	14.03
12	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.43	14.03
13	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.43	14.03
14	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.03	0.03	0.05	0.06	0.06	0.06	0.04	0.04	0.60	14.08
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.10

CI = 0.78

CR = 0.5 % CR<10 % shows that the evaluation has acceptable consistency

Table 4.50: Pair-wise comparison matrix of the technologies (with respect to Commercial Manufacturing)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	0.5	2	2	2	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
2	2	1	1	4	4	2	1	1	1	1	1	1	1	1
3	0.5	1	1	4	4	2	1	1	1	1	1	1	1	1
4	0.5	0.25	0.25	1	1	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
5	0.5	0.25	0.25	1	1	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
6	1	0.5	0.5	2	2	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
7	2	1	1	4	4	2	1	1	1	1	1	1	1	1
8	2	1	1	4	4	2	1	1	1	1	1	1	1	1
9	2	1	1	4	4	2	1	1	1	1	1	1	1	1
10	2	1	1	4	4	2	1	1	1	1	1	1	1	1
11	2	1	1	4	4	2	1	1	1	1	1	1	1	1
12	2	1	1	4	4	2	1	1	1	1	1	1	1	1
13	2	1	1	4	4	2	1	1	1	1	1	1	1	1
14	2	1	1	4	4	2	1	1	1	1	1	1	1	1
SUM	21.5	11.5	13	46	46	23	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5

1	Hydro-powered Coil Pump (Wirtz Pump)		8	Hydrobine Pump
2	Hydro-powered Spiral Pump		9	Bunyip Pump
3	Hydro-powered Helix Pump		10	Hydraulic Ram Pump
4	Lambach Pump		11	Glockmann Pump
5	Hydrautomat Pump		12	Venturi Pump (Papa Pump)
6	Cherepnov Pump		13	Full Belly’s Gravity Pump
7	High Lifter Pump		14	Chinese Water Turbine Pump

Table 4.51: Multiplication of pair-wise comparison matrix by the criteria weight (for Commercial Manufacturing)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Criteria Weight	Matrix Multiplication	Eigenvalue
1	0.05	0.04	0.15	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.73	14.25
2	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
3	0.02	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	1.15	14.05
4	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.31	14.13
5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.31	14.13
6	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.61	14.13
7	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
8	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
9	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
10	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
11	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
12	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
13	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
14	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1.22	14.13
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Average	14.14

CI = 1.04

CR = 0.66 % CR<10 % shows that the evaluation has acceptable consistency

4.2.6.4 Checking Consistency of the Evaluation:

Consistency is examined to check if the evaluation is unswerving. It is measured by a Consistency Index. Some literatures also name it as Inconsistency Index. There are 14 types of Consistency Index calculation methods in Pair-wise Comparison Method. The methods basically measure consistency based on transitivity in the pair-wise comparison. Although there are different consistency index calculation methods, the other methods, except Saaty and Crawford and Williams method, do not specify threshold values to gauge acceptability of the Consistency Index obtained [45].

Saaty [46] uses Consistency Index, CI (Equation 4.1) and Consistency Ratio, CR [47] (Equation 4.2) employing Eigen Value and Eigen Vector of the pair-wise comparison matrices and their derivatives. According to Satty's, eigenvector method, the evaluations are fully consistent if the maximum eigenvalue (λ_{max}) of the pair-wise comparison matrix is equal to the number of evaluation criteria "n".

$CI = \dfrac{\lambda_{max} - n}{n - 1}$	*Eqn. 4.1*
Where:	
$CI =$	Consistency Index
λ_{max}=	average of the numbers in the product vector (multiplication vector of the un-normalized comparison matrix with the criteria weight)
n=	The number of criteria of comparison

To calculate the eignevalue, the un-normalized pair-wise comparison matrix is multiplied by the vector which represents the criteria weight. The ratio of the Consistency Index (CI) with the Random Index (RI) gives the Consistency Ratio (CR).

$CR = \dfrac{CI}{RI}$	*Eqn. 4.2*
Where:	
$CR =$	Consistency Ratio
$CI =$	Consistency Index
$RI =$	Random Index

Random Index for a given number of evaluation criteria is made by:

- forming many Pair-wise Comparison Matrices with randomly generated numbers ranging from 1 to 9 (Satty's range of Criteria Weight);

- finding the Consistency Index for the randomly generated matrices; and
- averaging the Consistency Indices.

Saaty established Random Consistency Index by randomly generating a large number of matrices of varying order (number of criteria) and averaging same [47] Table 4.52 shows Random Index for number of criteria 1 through 15.

Table 4.52: Random Index for varying number of criteria [48]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.58

Saaty sets the threshold for Consistency Ratio to be 0.1 (or 10 %) [47]. A comparison with a Consistency Ratio of 0.1 (10 %) and below is considered to be fairly consistent. If the Consistency Ratio becomes greater than 0.1 (10 %), then the comparison is to be done again. The reasonableness of Saaty's eigenvector method could be verified with the following theoretical example.

Let W_A, W_B, W_C, and W_D be the perfect Criteria Weight for four criteria A, B, C, and D. The Correct Pair-wise Matrix will be as shown in Table 4.53.

Table 4.53: Theoretical four by four pair-wise comparison matrix

$$\begin{bmatrix} . & \boldsymbol{A} & \boldsymbol{B} & \boldsymbol{C} & \boldsymbol{D} \\ . & \boldsymbol{W_A} & \boldsymbol{W_B} & \boldsymbol{W_C} & \boldsymbol{W_D} \\ \boldsymbol{A} & \dfrac{\boldsymbol{W_A}}{\boldsymbol{W_A}} = \mathbf{1} & \dfrac{\boldsymbol{W_A}}{\boldsymbol{W_B}} & \dfrac{\boldsymbol{W_A}}{\boldsymbol{W_C}} & \dfrac{\boldsymbol{W_A}}{\boldsymbol{W_D}} \\ \boldsymbol{B} & \dfrac{\boldsymbol{W_B}}{\boldsymbol{W_A}} & \dfrac{\boldsymbol{W_B}}{\boldsymbol{W_B}} = \mathbf{1} & \dfrac{\boldsymbol{W_B}}{\boldsymbol{W_C}} & \dfrac{\boldsymbol{W_B}}{\boldsymbol{W_D}} \\ \boldsymbol{C} & \dfrac{\boldsymbol{W_C}}{\boldsymbol{W_A}} & \dfrac{\boldsymbol{W_C}}{\boldsymbol{W_B}} & \dfrac{\boldsymbol{W_C}}{\boldsymbol{W_C}} = \mathbf{1} & \dfrac{\boldsymbol{W_C}}{\boldsymbol{W_D}} \\ \boldsymbol{D} & \dfrac{\boldsymbol{W_D}}{\boldsymbol{W_A}} & \dfrac{\boldsymbol{W_D}}{\boldsymbol{W_B}} & \dfrac{\boldsymbol{W_D}}{\boldsymbol{W_C}} & \dfrac{\boldsymbol{W_D}}{\boldsymbol{W_D}} = \mathbf{1} \end{bmatrix}$$

When a matrix is multiplied by a vector, and the product is the vector multiplied by a factor, then the vector is the eigenvector, and the factor is the eigenvalue of that matrix. For an absolutely correct comparison (such as the one shown in Table 4.53), multiplying the pair-wise comparison matrix by the Criteria Weight vector yields the Criteria Weight vector multiplied by the Eigen Value, and the Eigen Value takes a magnitude equal to the number of alternatives compared. So, the level of consistency is measure by the closeness of the (multiplying) factor to the number of alternatives.

Table 4.54: Pair-wise comparison matrix, criteria weight, Eigen Value and Eigen Vector

Pair wise Comparison Matrix		Criteria Weight	Eigen Value	Eigen Vector
$\begin{bmatrix} \frac{W_A}{W_A} & \frac{W_A}{W_B} & \frac{W_A}{W_C} & \frac{W_A}{W_D} \\ \frac{W_B}{W_A} & \frac{W_B}{W_B} & \frac{W_B}{W_C} & \frac{W_B}{W_D} \\ \frac{W_C}{W_A} & \frac{W_C}{W_B} & \frac{W_C}{W_C} & \frac{W_C}{W_D} \\ \frac{W_D}{W_A} & \frac{W_D}{W_B} & \frac{W_D}{W_C} & \frac{W_D}{W_D} \end{bmatrix}$	**X**	$\begin{bmatrix} W_A \\ W_B \\ W_C \\ W_D \end{bmatrix}$	**4** $\star$	$\begin{bmatrix} W_A \\ W_B \\ W_C \\ W_D \end{bmatrix}$

Satty's consistency evaluation method yields an intermediate vector of size equal to the number of elements under pair-wise comparison. Dividing the vector with the number of elements in the criteria weight vector yields the eigenvalue and the eigenvector. The result of the multiplication is depicted in Table 4.54. As a perfect evaluation with absolute consistency is considered, the Eigen Value equals the number of alternatives, four (4) in this case example. Satty's Consistency Index and Consistency Ratio are used as the other method (Crawford and Williams method) accepts the Satty's Consistency Ratio[48]. Sharing same threshold value indicates similarity of the two consistency measuring methods.

A matrix of order n has "n" by "n" elements of which "n" elements are diagonal. The diagonal of a matrix is filled with a value 1 (one) as it compares a given value with itself. The remaining elements are {(n x n) - n}. Of the remaining elements, only half are filled by the evaluator as the remaining half is the reciprocal of the corresponding elements. The number of elements to be filled is given by Equation 4.3.

$$\frac{n(n-1)}{2} \qquad \textit{Eqn. 4.3}$$

λ being the actual factor of each raw of the multiplication matrix, the average of all such values in the vector gives λ_{max}. The deviation from result of the ideal evaluation is reflected by the value $(\lambda_{max} - n)$as n reflects the Eigen Value for the perfectly consistent evaluation.

To check consistency of the comparisons for the evaluation criteria, the initial (non-normalized) comparison matrix, (I in Table 4.23) is multiplied by the Criteria Weight vector (II in Table 4.23) to get a multiplication vector (III in Table 4.23). The ratio of the Criteria Weight (II in Table 4.23) to the Multiplication Vector (III in Table 4.23) yields an eigenvalue vector (IV in Table 4.23). Average of the eigenvalue vector and the number of criteria are then used to compute the Consistency Index. The Consistency Index is divided by the

Random Index (in Table 4.23) to get the Consistency Ratio. For a number of criteria of 14, the Random Index is 1.57. The Consistency Ratio so computed (for the evaluation criteria) turned out to be 2.2 %. For a Consistency Ratios as high as 10 % are acceptable, a Consistency Ratio of 2.26 % (closer to zero – which represents perfect consistency) shows a very good Consistency in the comparison.

Consistency of the pair-wise comparisons among the Technologies (alternatives) made under each criteria of evaluation follow exactly similar procedure, and the resulting consistency ratios are depicted in each table.

4.2.6.5 Aggregation of the Evaluation

There are two models used to determine the final Preference/Ranking of the Technologies. Weighted Sum Model and Weighted Product Model. Analytical Hierarchy Process employs Weighted Sum Model. In a Weighted Sum Model, the Preference P_i of Alternative is calculated by Equation 4.4. The Equation (4.4) multiplies points obtained for each Technology for each criterion by the weight of the corresponding criteria and sums up the products. The Technology with the highest sum is ranked as first preference.

$P_i = \sum_{J=1}^{N} a_{ij} W_j$	*for i = 1,2,3, …,M*	*Eqn.4.4*

Table 4.55 aggregates the comparison process and ranks the Technologies.

Table 4.55: Ranking of the technologies employing results of the Multi Criteria Decision Making analysis

I	II	III	IV (A – N)														V	VI
Criterion Code	**Criteria Weight**	**Technology Code**	**Points Obtained for Each Technology (Code 1 through 14) against Each Criterion (Code A through N)**														**Sum of Products**	**Rank**
			A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**		
A	0.138	**1**	0.149	0.103	0.093	0.064	0.045	0.025	0.065	0.040	0.023	0.055	0.015	0.146	0.098	0.052	0.076	5
B	0.115	**2**	0.156	0.098	0.093	0.065	0.057	0.024	0.070	0.040	0.025	0.067	0.014	0.146	0.098	0.087	0.078	4
C	0.115	**3**	0.065	0.155	0.060	0.066	0.046	0.052	0.104	0.045	0.039	0.036	0.053	0.108	0.098	0.082	0.072	7
D	0.097	**4**	0.009	0.017	0.019	0.037	0.155	0.105	0.010	0.042	0.162	0.029	0.029	0.023	0.098	0.022	0.050	12
E	0.032	**5**	0.119	0.033	0.079	0.029	0.061	0.022	0.024	0.040	0.022	0.028	0.076	0.036	0.098	0.022	0.053	11
F	0.124	**6**	0.016	0.016	0.059	0.028	0.126	0.049	0.017	0.042	0.111	0.032	0.022	0.019	0.098	0.043	0.043	14
G	0.026	**7**	0.023	0.060	0.055	0.050	0.027	0.047	0.141	0.109	0.064	0.079	0.098	0.040	0.031	0.087	0.058	10
H	0.072	**8**	0.044	0.134	0.053	0.081	0.045	0.078	0.097	0.079	0.044	0.035	0.068	0.092	0.098	0.087	0.073	6
I	0.072	**9**	0.060	0.063	0.032	0.083	0.056	0.100	0.053	0.057	0.103	0.046	0.053	0.043	0.098	0.087	0.066	8
J	0.055	**10**	0.206	0.099	0.191	0.193	0.127	0.210	0.110	0.150	0.083	0.284	0.173	0.062	0.052	0.087	0.161	1
K	0.055	**11**	0.065	0.065	0.034	0.098	0.047	0.066	0.140	0.150	0.081	0.100	0.133	0.054	0.031	0.087	0.078	3
L	0.054	**12**	0.032	0.075	0.066	0.102	0.039	0.075	0.105	0.150	0.095	0.160	0.125	0.062	0.031	0.087	0.083	2
M	0.028	**13**	0.044	0.054	0.035	0.041	0.046	0.031	0.029	0.021	0.022	0.024	0.117	0.147	0.031	0.087	0.047	13
N	0.017	**14**	0.012	0.028	0.131	0.063	0.122	0.115	0.036	0.035	0.125	0.025	0.025	0.021	0.043	0.087	0.063	9

1. The Criteria Weight (Column II) is obtained from Pair-wise comparison matrix among the Criteria (A to N)
2. The points given to each Technology (1 to 14) against each criterion are summarized from Multi Criteria Decision Making Analysis (Tables 4.25 through 4.51)
3. Sum of Products (Column V) is the sum of the multiplication of the weight of each criteria (A – N, under Column II) with the corresponding point obtained by the technology for the corresponding criterion (A - N, under Column IV)

4.3 Step III: Sensitivity Analysis

4.3.1 Sensitivity Analysis on Criteria Weight

Sensitivity is a measure of robustness of the conclusions arrived at by conducting analysis of comparisons among the candidate technologies. It measures how sensitive the result of a ranking obtained, to changes made to points won by the criteria. As the evaluations made by an expert are under some influence of subjectivity, the points given at each stage cannot be taken as precise as points obtained through a predetermined formula. There needs to be a margin in which the points are allowed to vary without influencing the end result. If the ranking obtained is likely to be altered with slight variation of the criteria weight, then the result cannot be considered robust as the points, given by the expert, could have varied by slight amount due to the influence of subjectivity.

The degree of variation can be measured in absolute or relative terms/changes. As an absolute term may have different significance when weighed against different values, it cannot show the actual degree of variation it causes. A difference of 1 does have different implications as compared to 2 and 10. One, as compared to two shows a 50 % difference while it shows a 10 % difference as compared to ten. Therefore, relative terms are preferred to absolute terms. To address the Sensitivity issue, the following definitions are used ([49].

Given a pair-wise comparison matrix with M Alternatives (Technologies) and N Criteria of comparison, with their respective Weight of Criteria, the following definitions (1 – 5) and Theorem(1) are used in subsequent sensitivity analysis on Criteria Weight [49]):

Definition 1: Let $\delta_{k,i,j}(1 \leq i < j \leq M \; and \; i \leq k \leq N)$ denote the minimum change in the current weight W_k of criterion C_k such that the ranking of alternatives A_i and A_j will be reversed.

Let $\delta'_{k,i,j} = \delta_{k,i,j} * \frac{100}{W_k} for\ any\ 1 \leq i < j \leq M \; and \; 1 \leq k \leq N$. That is $\delta'_{k,i,j}$ expresses changes of the Criteria weight in relative terms.

Definition 2: The Percent – Top (or PT) Critical Criterion is the Criterion which corresponds to the smallest $\left|\delta'_{k,1,j}\right|$ $(1 \leq j \leq M \; and \; 1 \leq k \leq N)$ value.

Definition 3: The Percent Any (or PA) Critical Criterion is the Criterion which corresponds to the smallest $\left|\delta'_{k,i,j}\right|(1 \leq i < J \leq M \; and \; 1 \leq k \leq N)$ value.

Definition 4: The Criticality Degree of CriterionC_k , denoted as D'_k is the smallest percent amount by which the current amount of W_k must change such that the existing ranking of the alternatives will change. That is the following relation is true.

$$D'_k = \min_{1 \leq i < j \leq M} \{\left|\delta'_{k,i,j}\right|\} \; for\ all\ N \geq k \geq 1.$$

Definition 5: The Sensitivity Coefficient of Criterion C_k, denoted as sense (C_k), is it's the reciprocal of its criticality degree. That is the following relation is true.

$$\boldsymbol{Sense}(C_k) = \frac{1}{D'_k}\ , for\ any\ N \geq k \geq 1.$$

If the Criticality degree is infeasible (i.e., impossible to change any alternative rank with any weight change), then the sensitivity coefficient is set to be zero.

Theorem 1: When Analytical Hierarchy Process method is used, the quantity $\delta_{k,i,j}$ $(1 \leq i < j \leq M\ and\ 1 \leq k \leq N)$ by which the current weight W_k of criterion C_k needs to be modified (after normalization) so that the ranking of the Alternatives A_i and A_j will be reversed is given by Equation 4.5[1].

$\delta_{k,i,j} < \frac{P_j - P_i}{a_{jk} - a_{ik}} * \frac{100}{W_k}, if\ (a_{jk} > a_{ik})$ or	*Eqn. 4.5*
$\delta_{k,i,j} > \frac{P_j - P_i}{a_{jk} - a_{ik}} * \frac{100}{W_k}, if\ (a_{jk} < a_{ik})$	

Furthermore, the condition in Equation 4.6 should also be satisfied for the value $\delta'_{k,i,j}$ to be feasible:

$\frac{P_j - P_i}{a_{jk} - a_{ik}} \leq W_k$	*Eqn. 4.6*

Tables 4.57 through 4.69 depict the relative increments (in percent) required to reverse ranks of the candidate technologies. For those where it is not feasible to reverse the order (the conditions set by Equations 4.5 and 4.6 are not fulfilled), the symbol N/F (not feasible) is written. The Criticality Degrees and Sensitivity Coefficients of the 14 Criteria are as shown in Table 4.56.

[1]Proof of Theorem 1 is given in Appendix I

Table 4.56: Criticality degree (%) and sensitivity coefficients of the fourteen criteria

Criterion	Criticality Degree D'_k (%)	Swapping Technologies	Sensitivity Coefficient $Sense\ (C_k)$
A	**2.2**	**T2 and T11**	**0.455**
B	7.3	T2 and T11	0.137
C	4.2	T2 and T11	0.238
D	8.8	T2 and T11	0.114
E	58	T4 and T13	0.017
F	5.3	T2 and T11	0.189
G	15.5	T2 and T11	0.065
H	3.5	T2 and T11	0.286
I	6.9	T2 and T11	0.145
J	15.7	T2 and T11	0.064
K	4.3	T2 and T11	0.233
L	5.6	T2 and T11	0.179
M	14.9	T2 and T11	0.067
N	186	T4 – T13	0.005

Table 4.57: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T1 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T1-T2	N/F	-385	-5,608	N/F	N/F	-1,486	N/F	N/F	N/F	N/F	-5,044	N/F	N/F	N/F	-385
T1-T3	33	-64	100	-2,157	-19,236	-112	-373	-1,111	-340	N/F	-185	N/F	N/F	-754	33
T1-T4	N/F	N/F	N/F	N/F	-736	-262	N/F	-	-260	N/F	-3,460	N/F	N/F	N/F	-260
T1-T5	N/F	N/F	N/F	N/F	-4,519	N/F	N/F	N/F	N/F	N/F	-690	N/F	N/F	N/F	-690
T1-T6	N/F	N/F	N/F	N/F	-1,275	-1,088	N/F	-	-519	N/F	-9,319	N/F	N/F	N/F	-519
T1-T7	100	N/F	N/F	N/F	N/F	-637	-872	-349	-595	-1,308	-382	N/F	N/F	-	100
T1-T8	18	-75	58	-164	N/F	-40	-316	-96	-176	N/F	-93	91	N/F	-455	18
T1-T9	74	N/F	N/F	-483	-2,617	-97	N/F	-743	-157	N/F	-433	N/F	N/F	-	74
T1-T10	N/F	-16,259	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,875	-6,725	N/F	-1,875
T1-T11	-21	-55	-36	74	N/F	47	N/F	31	58	99	38	-49	-129	N/F	-21
T1-T12	-44	-224	-229	N/F	-3,840	N/F	N/F	90	N/F	N/F	N/F	-156	-382	N/F	-44
T1-T13	N/F	N/F	N/F	N/F	-	-3,506	N/F	N/F	N/F	N/F	-502	-73,760	N/F	-	-502
T1-T14	65	N/F	-284	N/F	-496	-110	N/F	N/F	-167	N/F	-2,325	N/F	N/F	-	65

Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.

Table 4.58: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T2 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T2-T3	48	-91	N/F	-5,652	N/F	-168	-676	-1,736	-606	N/F	-283	N/F	N/F	N/F	48
T2-T4	N/F	N/F	N/F	N/F	-894	-279	N/F	-18,567	-286	N/F	-3,545	N/F	N/F	N/F	-279
T2-T5	N/F	N/F	N/F	N/F	-20,337	N/F	N/F	N/F	N/F	N/F	-744	N/F	N/F	N/F	-744
T2-T6	N/F	N/F	N/F	N/F	-1,596	-1,106	N/F	-23,115	-566	N/F	-8,861	N/F	N/F	N/F	-566
T2-T7	N/F	N/F	N/F	N/F	N/F	-680	-1,053	-392	-702	-2,973	-425	N/F	N/F	N/F	-392
T2-T8	31	-117	N/F	-309	N/F	-71	-681	-174	-349	N/F	-164	N/F	N/F	N/F	31
T2-T9	85	N/F	N/F	-621	N/F	-118	N/F	-919	-199	N/F	-525	N/F	N/F	N/F	85
T2-T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,828	-6,557	N/F	-1,828
T2-T11	-2.25	-7.3	-4.2	8.8	-83.0	5.3	15.5	3.5	6.9	15.7	4.3	-5.6	-14.9	N/F	-2.25
T2-T12	-29	-190	-162	N/F	-878	79	N/F	63	N/F	99	83	-110	-268	N/F	-29
T2-T13	N/F	N/F	N/F	N/F	N/F	-3,198	N/F	N/F	N/F	N/F	-537	-79,394	N/F	N/F	-537
T2-T14	73	N/F	-331	N/F	-690	-127	N/F	N/F	-200	N/F	-2,527	N/F	N/F	N/F	73

Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.

Table 4.59: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T3 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T3-T4	N/F	N/F	N/F	N/F	-632.1	-339.7	N/F	N/F	-	N/F	N/F	N/F	N/F	N/F	-250.1
T3-T5	-259	N/F	-882	N/F	-3,925	N/F	N/F	N/F	N/F	N/F	-	N/F	N/F	N/F	-259.3
T3-T6	N/F	N/F	N/F	N/F	-1,136.1	N/F	N/F	N/F	-	N/F	N/F	N/F	N/F	N/F	-558.0
T3-T7	N/F	N/F	N/F	N/F	N/F	N/F	-1,396	-292	-755.1	-580.5	-545.48	N/F	N/F	-16,196	-292.3
T3-T8	-39	-46.9	-144	77.9	-3,117.1	35.1	-653.5	46.6	N/F	-2,437	N/F	-127.95	N/F	N/F	-38.5
T3-T9	N/F	49.3	N/F	-309	-1,608.7	-88.6	N/F	-599	-112.7	-985.	-18,634	N/F	N/F	-6,282	49.3
T3-T10	N/F	-1,379	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-	-7,023	N/F	-1,379.0
T3-T11	N/F	-60.07	-210	N/F	N/F	N/F	N/F	82.2	N/F	N/F	N/F	-213.02	-332.4	N/F	-60.1
T3-T12	-238	-119.5	N/F	N/F	-5,317.6	N/F	N/F	N/F	N/F	N/F	N/F	-433.98	-585.2	N/F	-119.5
T3-T13	N/F	N/F	N/F	N/F	-2,404,688	N/F	N/F	N/F	N/F	N/F	-688.61	-1,159	N/F	-29,033	-688.6
T3-T14	N/F	57.98	-104	N/F	-345.09	-108.8	N/F	N/F	-	N/F	N/F	N/F	N/F	-10,150	58.0

Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.

Table 4.60: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T4 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T4-T5	20	N/F	44	-370	-100	-29	N/F	-1,726	-30	-5,935	N/F	N/F	N/F	N/F	20
T4-T6	-681	N/F	-152	N/F	N/F	100	-3,540	N/F	N/F	-5,104	N/F	N/F	N/F	-1,900	100
T4-T7	N/F	N/F	N/F	N/F	-211	-120	N/F	N/F	-123	N/F	N/F	N/F	-464	N/F	-120
T4-T8	N/F	N/F	N/F	N/F	-657	-703	N/F	N/F	-275	N/F	N/F	N/F	N/F	N/F	-275
T4-T9	N/F	N/F	N/F	N/F	-532	-2,735	N/F	N/F	-401	N/F	N/F	N/F	N/F	N/F	-401
T4-T10	N/F	N/F	N/F	N/F	-12,154	N/F	N/F	N/F	-1,961	N/F	N/F	N/F	-8,763	N/F	-1,961
T4-T11	N/F	N/F	N/F	N/F	-816	-591	N/F	N/F	-489	N/F	N/F	N/F	-1,518	N/F	-489
T4-T12	N/F	N/F	N/F	N/F	-892	-883	N/F	N/F	-681	N/F	N/F	N/F	-1,771	N/F	-681
T4-T13	-42	-48	-111	-549	58	22	-410	N/F	20	N/F	-42	-30	N/F	-186	20
T4-T14	N/F	N/F	N/F	N/F	-1,298	N/F	N/F	-2,467	-518	-5,713	-6,137	-13,420	-893	N/F	-518

Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.

Table 4.61: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T5 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T5-T6	70	N/F	N/F	N/F	-479	-291	N/F	-5,650	-154	-5,332	N/F	N/F	N/F	-2,736	70
T5-T7	-43	N/F	-207	N/F	-520	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-302	N/F	-43
T5-T8	-197	N/F	-686	N/F	-3,868	N/F	N/F	N/F	N/F	N/F	-4,582	N/F	N/F	N/F	-197
T5-T9	-173	N/F	-260	N/F	-8,561	N/F	N/F	N/F	N/F	N/F	-1,121	N/F	N/F	N/F	-173
T5-T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-8,525	N/F	-8,525
T5-T11	-345	N/F	-494	N/F	-5,512	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,356	N/F	-345
T5-T12	-251	N/F	-2,011	N/F	-4,337	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,609	N/F	-251
T5-T13	49	-213	N/F	-426	N/F	-424	-3,789	N/F	N/F	N/F	-225	-84	N/F	-465	49
T5-T14	-73	-1,793	N/F	N/F	N/F	92	N/F	-2,809	N/F	-5,653	-382	-1,374	-696	N/F	-73

Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.

Table 4.62: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T6 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T6-T7	N/F	N/F	-3,735	N/F	-493	-5,111	N/F	N/F	-455	N/F	N/F	N/F	-832	N/F	-455
T6-T8	N/F	N/F	-4,700	N/F	-1,164	N/F	N/F	N/F	-627	N/F	N/F	N/F	N/F	N/F	-627
T6-T9	N/F	N/F	-783	N/F	-1,067	N/F	N/F	N/F	-4,238	N/F	N/F	N/F	N/F	N/F	-783
T6-T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-5,818	N/F	N/F	N/F	-9,303	N/F	-5,818
T6-T11	N/F	N/F	-1,251	N/F	-1,394	N/F	N/F	N/F	-1,641	N/F	N/F	N/F	-1,886	N/F	-1,251
T6-T12	N/F	N/F	N/F	N/F	-1,448	N/F	N/F	N/F	-3,327	N/F	N/F	N/F	-2,139	N/F	-1,448
T6-T13	N/F	N/F	-180	N/F	-190	-219	N/F	-324	-75	-1,142	93	70	-260	N/F	70
T6-T14	-3,687	N/F	N/F	N/F	-19,357	N/F	N/F	-3,705	N/F	-5,494	N/F	N/F	-1,341	N/F	-1,341

Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.

Table 4.63: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T7 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T7-T8	N/F	N/F	-6,483	N/F	N/F	N/F	-1,283	-667	-1,051	-617	-888	N/F	N/F	N/F	-617
T7-T9	N/F	N/F	-315	N/F	N/F	N/F	-359	-221	N/F	-461	-338	N/F	N/F	N/F	-221
T7-T10	N/F	N/F	N/F	N/F	N/F	N/F	-12,712	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-12,712
T7-T11	N/F	N/F	-820	N/F	N/F	N/F	-46,169	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-820
T7-T12	N/F	N/F	N/F	N/F	N/F	N/F	-2,561	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-2,561
T7-T13	-373	N/F	N/F	N/F	-1,786	N/F	N/F	N/F	N/F	N/F	-1,029	-185	N/F	N/F	-185
T7-T14	-333	-138	58	N/F	N/F	60	-184	-94	N/F	-171	-126	-493	N/F	N/F	58
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 4.64: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T8 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T8-T9	-281	78	N/F	-2,625	-1,760	-236	N/F	N/F	-150	-1,102	N/F	N/F	N/F	N/F	78
T8-T10	N/F	-2,167	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-5,394	-6,934	N/F	-2,167
T8-T11	N/F	-64	-233	N/F	N/F	-342	N/F	99	N/F	N/F	N/F	-250	-272	N/F	-64
T8-T12	-587	-145	N/F	N/F	-5,788	-2,242	N/F	N/F	N/F	N/F	N/F	-599	-525	N/F	-145
T8-T13	N/F	N/F	N/F	N/F	-67,975	N/F	N/F	N/F	N/F	N/F	-942	-852	N/F	N/F	-852
T8-T14	N/F	79	-108	N/F	-385	-210	N/F	N/F	-165	N/F	N/F	N/F	N/F	N/F	79
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 4.65: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T9 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T9-T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-6,419	N/F	N/F	N/F	-7,434	N/F	-6,419
T9-T11	N/F	N/F	N/F	N/F	-3,847	-274	N/F	N/F	-721	N/F	N/F	N/F	-612	N/F	-274
T9-T12	-411	N/F	N/F	N/F	-3,045	-517	N/F	N/F	-2,527	N/F	N/F	N/F	-865	N/F	-411
T9-T13	N/F	N/F	-5,653	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-544	-338	N/F	N/F	-544
T9-T14	48	81	-29	N/F	-152	-173	N/F	N/F	-205	N/F	N/F	N/F	N/F	N/F	-29
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 4.66: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T10 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T10-T11	N/F	N/F	N/F	N/F	N/F	N/F	-10,851	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-10,851
T10-T12	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-9,402	N/F	N/F	N/F	N/F	N/F	-9,402
T10-T13	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-2,467	N/F	N/F	-2,467
T10-T14	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-3,215	N/F	N/F	N/F	N/F	N/F	-3,215
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 4.67: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T11 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T11-T12	-102	N/F	N/F	N/F	-2,024	N/F	-518	N/F	N/F	N/F	-1,159	N/F	N/F	N/F	-102
T11-T13	N/F	N/F	-26,736	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-608	N/F	N/F	-608
T11-T14	N/F	N/F	-133	N/F	-606	-243	N/F	N/F	-465	N/F	N/F	N/F	-4,389	N/F	-133
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 4.68: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T12 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T12-T13	-2,114	N/F	N/F	N/F	-16,991	N/F	N/F	N/F	N/F	N/F	N/F	-762	N/F	N/F	-762
T12-T14	N/F	N/F	-261	N/F	-730	-388	N/F	N/F	-877	N/F	N/F	N/F	-5,803	N/F	-261
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 4.69: Relative increments (in %) required by the criteria weights to swap ranks of the candidate technologies (T13 with the remaining)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T13-T14	-359	-530	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-312	-231	N/F	N/F	-231
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

4.3.2 Sensitivity Analysis on Measure of Performance:

Sensitivity analysis measures the alteration on measure of performance of the technologies (as revealed by the relative weights of the criteria) required for the ranking of a technology swaps with the rest of competing technology/ies. The following definitions (6 – 9) and Theorem (2) are used in subsequent sensitivity analysis on Measure of Performance [49]:

DEFINITION 6: Given a pair-wise comparison matrix with M Alternatives (M=14 Technologies) and N Criteria of comparison (N=14), with their respective Weight of Criteria, let $\cdot_{i,j,k}\ (1 \leq i < k \leq M\ and\ 1 \leq j \leq N)$ denote the threshold value of a_{ij} that is the minimum change which has to occur on the current value of a_{ij} such that the current rankingbetween Alternatives (Technologies)A_i and A_k will change.

For M Alternatives (Technologies), a total of M-1 such threshold values are possible. The relative term threshold values, denoted by $'_{i,j,k}$are (with similar consideration given to Equation 4.6) given by

$'_{i,j,k} =\cdot_{i,j,k} * \dfrac{100}{a_{ij}}\, for\ any\ 1 \leq i,k \leq M, and\ 1 \leq j \leq N$	*Eqn. 4.7*

The **most sensitive Alternative (Technology)** is the one which is associated with the smallest threshold value. Also as earlier, one may be interested in changes of the ranking of (only) the best alternative, or in changes in the ranking of any alternative.

Based on Definition 6, the following three definitions (7, 8, and 9) are introduced.

DEFINITION 7: The **Criticality Degree of Alternative A_i,** denoted as $'_{ij}$, in terms of Criteria C_j is the smallest amount (in %) by which the current value A_{ij} must change such that the existing ranking of Alternative A_i will change which implies that the following relation holds true

$$'_{ij} = \min_{k \neq i}\{|\,'_{i,j,k}|\}, for\ all\ M \geq i \geq 1, and\ N \geq j \geq 1$$

From definition 7, it follows that the smaller the criticality degree is, the easier the ranking of alternative A_i can change.

DEFINITION 8: Alternative A_L is **the most critical alternative** if it is associated with the smallest criticality degree. And this is true if and only if the following relation is true.

$$'_{Lk} = \min_{M \geq i \geq 1}\{\min_{N \geq j \geq 1}(\,'_{ij})\}\ for\ some\ N \geq k \geq 1$$

DEFINITION 9: The sensitivity coefficient of Alternative in terms of CriterionC_j, denoted as $\boldsymbol{sense}(A_{ij})$ is the reciprocal of its criticality degree which implies that the following relation is true.

$$\boldsymbol{sense}\left(A_{ij}\right) = \frac{1}{'_{ij}}, \qquad for\ any\ M \geq i \geq 1, and\ N \geq j \geq 1$$

From definition 9, it is seen that, contrary to Criticality Degree, the higher the sensitivity coefficients are, the easier ranking changes will be. If the criticality degree is infeasible, then the sensitivity coefficient is set to be zero.

On the other hand, combining Definition 8 with Definition 9 yields that the most sensitive alternative is the one with the **highest** sensitivity coefficient.

Theorem 2: When the AHP method is used, the threshold value $'_{i,j,k}$(in %) by which the measure of performance of alternative $A_i$in terms of criterion $C_i$needs to be modified so that the ranking of Alternatives $A_i$and $A_k$will change, is given by Equation 4.8[2].

$'_{i,j,k} = \frac{P_i - P_k}{[P_i - P_k + W_j\left(a_{kj} - a_{ij} + 1\right)]} * \frac{100}{a_{ij}}$	*Eqn. 4.8*

For the threshold value to be feasible, the condition in Equation 4.9 should also be satisfied.

$'_{i,j,k} \leq 100$	*Eqn. 4.9*

Using the definitions (6 through 9) and employing Theorem 2, sensitivity analysis on measure of performance has been made and the results are depicted in Table 4.71 through 4.84. The results are summarized in Table 4.70.

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[2] Proof Theorem 2 is given in Appendix II

Table 4.70: Criticality degree of alternatives (technologies), criteria of criticality, swapping technology, sensitivity coefficient, and the most critical alternatives

Technology (Alternative)	Criticality Degree	Criticality Observed at Criteria	Swap with Technology	Sensitivity Coefficient	Critical Alternatives
T1	N/F	N/F	N/F	N/F	
T2	41.1	H	T3	0.0243	
T3	2.8	A	T4	0.357	T3 (2.8)
T4	1.4	A	T3	0.714	T4 (1.4)
T5	10.5	A	T4	0.095	T5 (10.5)
T6	7.1	B	T7	0.141	T6 (7.1)
T7	6.5	B	T6	0.154	T7 (6.5)
T8	25	F	T9	0.04	T8 (25)
T9	23.6	F	T8	0.042	
T10	74.2	H	T11	0.013	
T11	20.3	A	T12	0.049	
T12	16.5	F	T13	0.061	
T13	30.3	L	T12	0.033	
T14	72	I	T13	0.014	

Table 4.71: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 1 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 1 and the rest of alternatives (2-14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	2
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	3
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	4
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	5
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	6
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	7
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	8
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	9
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	10
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.72: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 2 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 2 and the rest of alternatives (1, 3-14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
2	-2,982	-2,669	-2,350	-2,809	N/F	-1,702	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	1
2	N/F	53	61.9	45.7	N/F	49.7	N/F	**41.1**	65.9	52.9	63.2	N/F	N/F	N/F	3
2	98.7	54.2	61.8	49.8	N/F	54.8	N/F	48.3	73.5	57.5	74.6	N/F	N/F	N/F	4
2	N/F	75.7	86.7	69.7	N/F	76.7	N/F	66.9	N/F	80	N/F	N/F	N/F	N/F	5
2	N/F	99	N/F	91.8	N/F	98.1	N/F	85.3	N/F	N/F	N/F	N/F	N/F	N/F	6
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	96.8	N/F	N/F	N/F	N/F	N/F	N/F	7
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	8
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	9
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	10
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.73: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 3 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 3 and the rest of alternatives (1-2, 4-14) swap

Technology (Alternative)	Criteria of Comparison (A-N)and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
3	-1,730	-	-	-3,684	N/F	-2,165	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	1
3	-56.3	-65.3	-121.4	-52.1	-374.1	-59.5	-167	-46.8	-85.1	-89.6	-72.0	-174.2	-664.3	-455	2
3	**2.8**	3.6	6.7	3.0	18.3	3.6	8.2	2.9	5.0	5.3	4.3	8.6	30.3	19.0	4
3	24.4	30.5	56.9	25.7	N/F	30.2	65.6	24.2	42.3	44.6	36.0	72.1	N/F	N/F	5
3	55.6	61.1	N/F	51.7	N/F	59.0	N/F	47.1	83.9	91.2	68.2	N/F	N/F	N/F	6
3	66.1	72.7	N/F	63.4	N/F	73.2	N/F	58.7	N/F	N/F	82.9	N/F	N/F	N/F	7
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	99.5	N/F	N/F	N/F	N/F	N/F	N/F	8
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	9
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	10
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.74: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 4 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 4 and the rest of alternatives (1 - 3, 5 - 14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
4	-881.2	-2,706	-2,112	-4,940	N/F	-5,589	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	1
4	-27.8	-47.5	-50.5	-80.4	-331.0	-169.0	-327	-166	-274	-138	-630	-76.8	-244	-493	2
4	**-1.4**	-2.6	-2.8	-4.3	-15.6	-9.2	-14.5	-8.7	-14.5	-7.5	-32.2	-3.9	-11.1	-19.6	3
4	9.9	18.5	19.7	33.2	N/F	71.6	N/F	71.7	N/F	57.2	N/F	26.0	72.8	N/F	5
4	24.3	39.5	45.0	71.4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	58.7	N/F	N/F	6
4	29.1	47.4	54.7	88.5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	70.0	N/F	N/F	7
4	52.9	93.1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	8
4	69.9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	9
4	89.9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	10
4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.75: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 5 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 5 and the rest of alternatives (1 - 4, 6 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
5	-964	-2,893	-2,274	-5,567	N/F	-5,670	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
5	-41.9	-66.2	-73.4	-118.7	-640	-234.2	-556.8	-244.1	-435.1	-247.0	-887.4	-115.2	-387.2	-1,363	**2**
5	-13.1	-21.7	-24.6	-38.4	-180	-76.9	-146.6	-77.6	-139.7	-81.4	-274.0	-35.4	-104.8	-315	**3**
5	**-10.5**	-18.5	-20.4	-35.0	-156	-70.8	-137.9	-76.1	-130.2	-74.0	-270.9	-28.1	-84.9	-273	**4**
5	14.2	21.4	25.4	40.9	N/F	80.7	N/F	85.7	N/F	87.3	N/F	33.9	89.3	N/F	**6**
5	19.6	29.5	35.5	58.4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	46.5	N/F	N/F	**7**
5	45.1	73.4	83.0	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**8**
5	62.8	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**9**
5	84.4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**10**
5	98.4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**11**
5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**12**
5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**13**
5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**14**

Table 4.76: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 6 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 6 and the rest of alternatives (1 - 5, 7 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
6	-2,816	-2,930	-	-5,548	N/F	-2,192	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
6	-177.2	-74.4	-	-135.5	-996.6	-110.6	-	-	-	-	-301.7	-	-	-1,639	**2**
6	-85.5	-37.2	-88.9	-67.0	-421.5	-55.5	-	-89.8	-	-	-141.2	-	-	-504.3	**3**
6	-73.9	-33.8	-78.8	-65.3	-389.5	-54.8	-	-94.9	-	-	-151.1	-99.9	-	-465.4	**4**
6	-40.7	-18.3	-43.0	-35.5	-203.3	-29.8	-	-51.0	-88.5	-	-80.1	-53.3	-	-228.6	**5**
6	18.2	**7.1**	18.2	14.4	76.2	11.9	42.6	20.3	34.9	57.6	30.3	21.9	39.8	73.4	**7**
6	99.1	42.0	N/F	75.7	N/F	61.3	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**8**
6	N/F	63.7	N/F	N/F	N/F	88.9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**9**
6	N/F	90.1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**10**
6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**11**
6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**12**
6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**13**
6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**14**

Table 4.77: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 7 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 7 and the rest of alternatives (1 - 6, 8 - 14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
7	-2,036	-3,045	-	-	N/F	-3,195	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	1
7	-137.5	-74.4	-	-	-	-181.3	-702.0	-	-	-	-	-	-	-	2
7	-72.5	-40.8	-98.0	-	-	-99.8	-289.7	-	-	-	-	-	-	-	3
7	-63.2	-37.4	-87.8	-98.6	-	-99.5	-298.7	-	-	-	-	-	-	-	4
7	-40.1	-23.3	-55.1	-61.7	-	-62.4	-173.0	-	-	-	-	-66.9	-	-	5
7	-13	**-6.5**	-16.7	-17.5	-79.9	-17.2	-44.1	-34.3	-40.7	-58.7	-39.5	-20.0	-43.2	-88.2	6
7	56.5	30.8	74.6	76.1	N/F	74.3	N/F	N/F	N/F	N/F	N/F	86.5	N/F	N/F	8
7	93.5	50.1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	9
7	N/F	74.1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	10
7	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
7	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
7	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
7	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.78: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 8 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 8 and the rest of alternatives (1 - 7, 9 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
8	-2,498	-6,213	-7,632	-8,689	N/F	-2,231	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	1
8	-228.1	-257.7	-488.4	-234.0	-1,889	-155.0	-2,774	-453.2	-283.2	-793.0	-717.2	-958.2	-1,682	-34,308	2
8	-149.5	-176.2	-342.1	-157.4	-1,009	-106.0	-1,301	-298.2	-187.6	-543.8	-452.7	-610.4	-804.1	-2,506.5	3
8	-132.6	-165.3	-312.6	-158.9	-955.6	-108.4	-1,396	-328.1	-195.5	-548.5	-507.9	-531.1	-683.6	-2,322.2	4
8	-106.3	-130.4	-247.9	-125.4	-712.8	-85.7	-998	-256.1	-152.5	-429.3	-390.1	-411.3	-490.0	-1,467.5	5
8	-81.7	-87.0	-177.7	-84.2	-449.5	-55.5	-584	-165.9	-100.2	-292.1	-243.7	-291.3	-302.5	-709.0	6
8	-65.2	-69.4	-143.7	-69.5	-353.4	-46.5	-452	-139.1	-81.4	-234.5	-199.2	-230.4	-236.4	-529.6	7
8	39.8	45.1	77.1	39.2	N/F	**25.0**	N/F	76.7	40.6	N/F	N/F	N/F	N/F	N/F	9
8	97.2	N/F	N/F	96.9	N/F	65.9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	10
8	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
8	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
8	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
8	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.79: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 9 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 9 and the rest of alternatives (1 - 8, 10 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
9	-	-13,891	-	-13,108	N/F	-2,278	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	1
9	-1,339	-683.5	-	-375.4	-	-169.8	-	-	-	-	-	-	-	N/F	2
9	-939.9	-499.5	-	-269.7	-	-123.9	-	-	-	-	-	-	-	-	3
9	-840.0	-471.5	-	-273.8	-	-127.7	-	-	-	-	-	-	-	-	4
9	-709.3	-391.7	-95.4	-227.5	-	-106.2	-	-	-	-	-	-	-	-	5
9	-604.3	-290.2	-76.1	-169.4	-	-76.1	-	-	-	-849.8	-819.1	-936.2	-	-	6
9	-517.2	-248.5	-65.9	-150.0	-	-68.4	-	-	-	-730.7	-718.0	-792.9	-944.7	-	7
9	-190.7	-99.1	-24.6	-53.0	-98.8	**-23.6**	-390	-	-38.3	-247.8	-246.4	-292.2	-288.1	-275.5	8
9	N/F	N/F	34.7	78.8	N/F	36.4	N/F	N/F	55.4	N/F	N/F	N/F	N/F	N/F	10
9	N/F	N/F	68.4	N/F	N/F	75.6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	11
9	N/F	N/F	90.6	N/F	N/F	87.5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	12
9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	13
9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	14

Table 4.80: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 10 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 10 and the rest of alternatives (1 - 9, 11 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
10	-7,504	-10,484	-6,777	-25,672	N/F	-	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
10	-929.7	-442.0	-483.3	-633.8	-	-	-34,014	-443.4	-	-	-	-	-23,085.5	N/F	**2**
10	-693.1	-343.3	-385.3	-484.3	-5,619	-	-	-327.1	-	-	-	-	-7,850.3	N/F	**3**
10	-619.6	-324.5	-353.2	-495.0	-5,287	-	-	-374.0	-	-	-	-	-6,127.4	N/F	**4**
10	-546.6	-281.3	-307.6	-429.3	-4,165	-	-	-318.6	-	-	-	-	-4,517.4	N/F	**5**
10	-505.6	-224.3	-265.1	-344.9	-3,001	-	-	-242.9	-	-	-	-863.1	-3,146.5	-	**6**
10	-451.9	-200.4	-240.0	-319.4	-2,600	-	-834.2	-229.5	-	-	-	-760.2	-2,701.7	-	**7**
10	-267.2	-128.9	-144.0	-180.8	-1,233	-	-380.7	-126.2	-	-	-	-448.0	-1,250.9	-	**8**
10	-167.2	-79.1	-77.1	-108.8	-618	-84.7	-196.5	-75.0	-	-	-	-261.7	-707.3	-497.4	**9**
10	N/F	82.9	89.7	N/F	N/F	97.6	N/F	**74.2**	N/F	N/F	104.9	N/F	N/F	N/F	**11**
10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**12**
10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**13**
10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**14**

Table 4.81: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 11 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 11 and the rest of alternatives (1 - 10, 12 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
11	-2,237	-23,630	-7,176	-84,492	N/F	-13,101	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
11	-265.0	-1,007.4	-457.6	-1,410	-40,468	-1,385	N/F	-1,513	-2,908	-3,372	-1,455	-3,324	N/F	N/F	**2**
11	-203.4	-816.9	-380.8	-1,123	-6,717.9	-1,126	-30,341	-1,165	-2,269	-2,719	-1,032	-2,395	-39,568	N/F	**3**
11	-179.4	-773.8	-347.7	-1,154	-6,041.2	-1,170	-52,513	-1,339	-2,423	-2,817	-1,262	-2,014	-9,144	N/F	**4**
11	-162.5	-688.8	-310.7	-1,027	-4,392.1	-1,046	-24,202	-1,171	-2,126	-2,462	-1,066	-1,736	-4,746	N/F	**5**
11	-159.4	-573.0	-280.3	-860.1	-2,962.2	-846.7	-11,428	-932.1	-1,732	-2,073	-787.4	-1,545	-2,724	N/F	**6**
11	-145.0	-523.7	-259.3	-815.4	-2,533.3	-814.9	-9,202	-901.5	-1,613	-1,893	-736.9	-1,384	-2,240	N/F	**7**
11	-101.2	-400.1	-184.3	-546.1	-1,269.6	-536.8	-4,639	-587.6	-991	-1,184	-464.0	-963.0	-1,018	-16,454	**8**
11	-80.1	-309.6	-122.9	-413.6	-751.2	-395.5	-2,925	-439.5	-708	-866.2	-342.0	-704.7	-698	-6,921	**9**
11	-40.0	-150.9	-67.2	-210.0	-365.8	-214.9	-1,030	-198.5	-371	-386.9	-148.2	-326.2	-284	-2,143	**10**
11	**20.3**	78.3	34.5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	72.4	N/F	N/F	N/F	**12**
11	32.1	N/F	55.7	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**13**
11	62.5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**14**

Table 4.82: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 12 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 12 and the rest of alternatives (1 - 11, 13 -14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
12	-24,235	-52,218	-25,008	-478,863	N/F	-4,272	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
12	-3,538	-2,215.0	-1,957	-1,266.3	N/F	-363.3	N/F	-1,676.9	-600	-3,982	-4,297	-6,212	N/F	N/F	**2**
12	-2,790	-1,825.9	-1,657	-1,022.7	-141,272	-298.8	-332,852	-1,305.4	-463	-3,250	-3,091	-4,485	N/F	N/F	**3**
12	-2,492	-1,730.7	-1,5209	-1,053.6	-24,249	-313.1	N/F	-1,517.5	-509	-3,389	-3,797	-3,729	N/F	N/F	**4**
12	-2,281	-1,555.5	-1,373	-946.2	-6,682.1	-281.7	-197,966	-1,336.8	-444	-2,976	-3,234	-3,234	-13,867	N/F	**5**
12	-2,250	-1,313.1	-1,257	-802.3	-2,909.0	-228.6	-49,641	-1,072.5	-357	-2,533	-2,420	-2,924	-5,199	N/F	**6**
12	-2,070	-1,208.7	-1,172	-766.6	-2,257.0	-222.3	-37,273	-1,046.9	-334	-2,323	-2,282	-2,629	-3,968	N/F	**7**
12	-1,525	-971.4	-876.9	-537.7	-917.0	-152.0	-17,448	-712.8	-205	-1,508	-1,508	-1,918	-1,582	-89,532	**8**
12	-1,269	-792.3	-619.6	-428.9	-511.9	-117.4	-11,070	-561.1	-152	-1,158	-1,171	-1,475	-1,110	-15,449	**9**
12	-762.3	-462.0	-404.9	-260.2	-290.3	-76.6	-4,365.0	-300.8	-95.1	-611.9	-606	-811	-511.6	-4,383.1	**10**
12	-232.6	-157.6	-131.3	-87.3	-75.0	-26.1	-1,353.6	-104.0	-31.7	-201.5	-194	-254	-124.6	-1,020.4	**11**
12	N/F	98.8	87.7	54.7	42.6	**16.5**	N/F	65.9	19.5	N/F	N/F	N/F	73.8	N/F	**13**
12	N/F	N/F	N/F	N/F	N/F	53.0	N/F	N/F	56.5	N/F	N/F	N/F	N/F	N/F	**14**

Table 4.83: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 13 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 13 and the rest of alternatives (1 - 12, and 14) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
13	-5,621	-33,005	-16,855	N/F	N/F	-11,350	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
13	-795.2	-792.1	-1,198.0	-1,262	N/F	-1,195.1	N/F	-3,545.6	-	-	-1,507	-	N/F	N/F	**2**
13	-629.7	-657.2	-1,023.5	-1,027	-41,066	-995.3	N/F	-2,783.6	-	-	-1,037	-	N/F	N/F	**3**
13	-559.4	-621.5	-936.4	-1,060	-29,444	-1,039.2	N/F	-3,243.9	-	-	-1,365	-	N/F	N/F	**4**
13	-514.6	-560.6	-849.7	-956.5	-15,311	-942.2	N/F	-2,871.8	-	-	-1,136	-	-	N/F	**5**
13	-514.5	-475.2	-784.8	-816.2	-8,316	-776.4	-37,444	-2,320.4	-	-	-813.4	-	-	N/F	**6**
13	-474.4	-438.3	-734.4	-783.1	-6,757	-757.0	-23,048	-2,274.8	-	-	-768.3	-	-	N/F	**7**
13	-357.7	-362.5	-563.2	-562.1	-3,092	-534.7	-8,743	-1,586.9	-	-	-503.5	-	-5,715	N/F	**8**
13	-305.5	-303.2	-405.8	-459.4	-1,832	-424.7	-5,304	-1,280.2	-	-	-397.3	-	-4,102	-18,396	**9**
13	-196.7	-189.1	-285.3	-299.1	-1,126	-297.3	-2,060	-736.6	-	-	-213.1	-	-2,026	-	**10**
13	-80.6	-87.1	-124.9	-135.6	-401.2	-137.3	-850.5	-344.4	-	-	-91.2	-79.8	-665.4	-550.5	**11**
13	-35.3	-34.5	-51.7	-52.1	-131.6	-49.4	-301.7	-131.7	-	-	-36.2	**-30.3**	-237.4	-171.4	**12**
13	80.0	78.1	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	76.6	63.6	N/F	N/F	**14**

Table 4.84: The threshold value, $'_{i,j,k}$ (in %) by how much the measures of performance of alternative 14 (under criteria A-N) need to be modified such that the ranking of alternative (technology) 14 and the rest of alternatives (1 - 13) swap

Technology (Alternative)	Criteria of Comparison (A-N) and their Relative Weight														with Technology (Alternative)
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
	0.138	0.115	0.115	0.097	0.032	0.124	0.026	0.072	0.072	0.055	0.055	0.054	0.028	0.017	
14	-16,384	-126,787	-17,402	N/F	N/F	-9,664	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	**1**
14	-2,499	-3,087.0	-898.7	-2,203	N/F	-935.3	N/F	-2,376	-1,166	-5,892	-9,175	-12,795	N/F	N/F	**2**
14	-2,015	-2,609.3	-781.3	-1,820	N/F	-791.2	N/F	-1,873	-915.7	-4,869	-6,455	-8,932.7	N/F	N/F	**3**
14	-1,790	-2,469.8	-710.4	-1,886	N/F	-830.7	N/F	-2,242	-1,019	-5,171	-8,467	-7,076.1	N/F	N/F	**4**
14	-1,664	-2,251.1	-650.1	-1,717	N/F	-759.7	N/F	-1,989	-898.5	-4,541	-7,139	-6,139.5	N/F	N/F	**5**
14	-1,691	-1,937.4	-610.9	-1,483	N/F	-631.2	N/F	-1,605	-732.4	-3,896	-5,208	-5,694.3	N/F	N/F	**6**
14	-1,571	-1,800.1	-575.0	-1,434	-60,446	-621.0	N/F	-1,591	-691.3	-3,577	-4,957	-5,112.5	N/F	N/F	**7**
14	-1,239	-1,558.1	-460.4	-1,072	-3,186.7	-455.6	-46,323	-1,143	-449.3	-2,393	-3,406	-3,964.4	-5,996	N/F	**8**
14	-1,103	-1,357.8	-341.8	-912.5	-1,450.2	-375.9	-20,774	-957	-353.0	-1,941	-2,802	-3,221.9	-3,663	N/F	**9**
14	-788.6	-940.3	-267.7	-658.9	-931.4	-292.9	-6,695.6	-600	-263.6	-1,184	-1,674	-2,062.7	-1,522	-19,037	**10**
14	-435.6	-584.6	-157.2	-402.3	-393.8	-182.3	-3,581.0	-378	-160.0	-705	-967	-1,156.8	-564.1	-3,549	**11**
14	-330.9	-401.8	-113.2	-267.7	-210.0	-113.0	-2,134.7	-250	-90.0	-458	-665	-763.6	-335.3	-	**12**
14	-222.0	-268.2	-77.1	-184.2	-157.3	-84.7	-1,329.9	-175	**-72.0**	-312	-411	-455.6	-235.1	-891.8	**13**

CHAPTER 5

5. Discussion

5.1 Determining the Criteria Weight

5.1.1 Pair-wise Comparison of the Evaluation Criteria

The fourteen evaluation criteria arrived at cannot have equal importance. Determining criteria weights is a problem that arises frequently in multi-criteria decision making techniques [50]. Because of the fact that the relative weights of criteria significantly influence the outcome of the decision making process, it is important to pay particular attention to the method to be used to allocate relative importance (weight) of each evaluation criteria. There are three main categories of weighing methods: subjective weighing methods; objective weighing methods; and integrated weighing methods [50]. As it is practically impossible to allocate abjectly measured quantities for almost all the criteria of comparison, subjective weighing category is the chosen weighing method. Of the variety of methods under subjective weighing method, the pair-wise comparison method of the Analytical Hierarchy Process has been selected as:

1. It allows comparison of a criterion with the rest of the candidates several times both directly and indirectly through transitivity. According to Equation 4.3 (Chapter 4), for the fourteen criteria, 91 direct and independent comparisons are made.
2. The 1-9 range of the scale Analytical Hierarchy Process uses is in line with the now-classical observation that the mind is limited to 7±2 factors for simultaneous comparison [46 pg 234].
3. Its consistency measurement provision, and the associated threshold value, tell whether the pair-wise comparisons made are acceptably consistent or not.
4. The method has provisions for measuring the most critical criteria based on sensitivity to criteria weight, and the most critical measure of performance based on sensitivity to measure of performance.

5.1.2 Consistency of the Evaluation

Taking into account the influence of criteria weight on the final ranking of the technologies, several trials have been attempted to bring Consistency Ratio (CR), of the pair wise comparisons of criteria weight, close to the ideal. The allowable being 10, a Consistency Ratio of 2.2 has been achieved, which shows a very consistent comparison.

5.1.3 Relative Weights of the Evaluation Criteria

The criteria weights obtained by pair – wise comparison are summarized in Table 5.1. As read from the Table, Ease of Manufacturing, Service Year, Ease of Operation, Maintenance Requirement, and Frequency of Supervision rank first to fifth. As the weights are relative, the weights of all the fourteen technologies sum up to unity.

In the ranking, Pumping Height and Pumping Volume, which are very important characteristics of pumps stand sixth and seventh. The reason why this is so is explained as follows.

All the fourteen pumping technologies to which weighing criteria are developed could be clustered into four groups based their mechanics of operation.

Group I

Code 1 – Hydro-powered Coil Pump (Wirtz Pump),
Code 2 – Hydro-powered Spiral Pump,
Code 3 – Hydro-powered Helix Pump,
Code 8 – Hydrobine Pump, and
Code 14 – Chinese Water Turbine Pump

Table 5.1: Weighing criteria, criteria weights and ranks of the criteria (obtained through AHP, pair-wise comparison)

Criteria Code	Criteria	Criteria Weight	Rank
A	Ease of Manufacturing	0.138	1
F	Service Year	0.124	2
B	Ease of Operation	0.115	3
C	Maintenance Requirement	0.115	3
D	Frequency of Supervision	0.097	5
H	Pumping Height	0.072	6
I	Pumping Volume	0.072	6
K	Operational Flow Volume Requirement	0.055	8
J	Literature Coverage	0.055	9
L	Operational Head Requirement	0.054	10
E	Security (theft)	0.032	11
M	Patent Right	0.028	12
G	Mobility	0.026	13
N	Manufactured for Commerce	0.017	14
	SUM	1.000	

Technologies in Group I use the kinetic energy of the flowing stream to pump portion of the water that is passing through. They need to be partly submerged into the flowing water and hence require the channel depth to be large enough to partly submerge them and the velocity is also to be fast enough to move (rotate) the pumps (pumps' parts). The technologies in this group generally do not have high delivery head and require relatively higher depth volume for their operation. They do not require falls at spots. Due to these peculiarities, pumps in Group

I are generally suitable for low land areas where flow depths are large, flow velocities and delivery head requirements are low.

Group II

Code 4 – Lambach Pump,
Code 7 – High Lifter Pump,
Code 9 – Bunyip Pump, and
Code 13 – Full Belly's Gravity Pump

The technologies in Group II convert the pressure head contained in the water to piston-pressures. The piston pressure is amplified based on the area ratio of the receiving and delivering pistons. With the minor exception of Full Belly's Gravity Pump, which converts the potential energy of the stored water to equivalent piston pressure, without amplification, all the rest augment their pressure through varying area of piston. As the lines to the pistons could be filled with relatively small discharges, such technologies do not require canals with high depth and high flow volume. Due to pressure augmentation, their delivery heights are relatively high. Such characteristics of the pumps in Group II make them suitable for sloppy areas and rugged terrain.

Group III

Code 5 – Hydrautomat Pump
Code 6 – Cherepnov Pump

Technologies in Group III use sealed tanks to create pressure difference (using the upstream and downstream water levels differences) and pump water. Like the technologies in group II, small discharges (supplied via small canals or pipes) are sufficient to fill the tanks and hence do not require bigger canals and high flow depth and volume. Their delivery heights are medium to high. Hence pumps in Group III are preferable to rugged terrains.

Group IV

Code 10 – Hydraulic Ram Pump
Code 11 – Glockmann Pump
Code 12 – Venturi Pump (Papa Pump)

The technologies in Group IV use water hammer effect of the flowing/falling water to create high pressure and pump portion of the water that passes through. Such technologies can operate at varying flow rates and a range of elevation differences. Due to the water hammer effect, their delivery heights are high. Their operability at varying flows and their high delivery head make them suitable for areas with high slope and rugged terrain.

The technologies in the above four groups can further be clustered into two broader groups based on their characteristics depicted in Table 5.2. The Table shows characteristics of the pumping technologies with respect to:

1. Operational head requirement;
2. Operational flow volume requirement; and
3. Delivery head.

Group A: incorporates pumping technologies that:

1. do not require high slope canals or concentrated falls;
2. require bigger depth of flow to partly submerge the pumps / pumps' parts;
3. have relatively low delivery head.

Technologies under Group I belong to Group A.

Group B: embraces technologies that:

1. require elevation difference (fall) for their operation;
2. can operate in varying flow rates; and
3. have relatively high delivery heads.

Technologies under Groups II, III and IV fall in Group B. Table 5.3 shows the grouping, rank of each technology in the General Ranking and Rank of each technology by considering the respective Group as self-standing. For simultaneous comparison of the Rankings, Radar Charts of the General Ranking and Rankings within each Group (Group A and B) are provided in Figures 5.1 through 5.8 (at the end of the Chapter). To reduce congestion of the lines, the rankings are sub-grouped as required.

Table 5.2: Characteristics of the technologies with respect to qualitative: a) operational head requirements; b) delivery head and c) operational flow depth requirements

Se. No.	Pump	Operational Head Requirement			Delivery Head			Operational Flow Depth Requirement		
		High	Medium	Low	High	Medium	Low	High	Medium	Low
1	Hydro-powered Coil Pump			■			■	■	■	
2	Hydro-powered Spiral Pump			■			■	■	■	
3	Hydro-powered Helix Pump			■			■	■	■	
4	Lambach Pump		■	■	■	■			■	■
5	Hydrautomat Pump		■	■		■	■			■
6	Cherepnov Pump	■	■		■	■		■	■	■
7	High Lifter Pump	■	■		■	■			■	■
8	Hydrobine Pump		■	■		■	■		■	■
9	Bunyip Pump		■	■	■	■			■	■
10	Hydraulic Ram Pump		■	■	■	■			■	■
11	Glockemann Pump		■	■	■	■			■	■
12	Venturi Pump (Papa Pump)		■	■	■	■			■	■
13	Full Belly's Gravity Pump			■			■		■	■
14	Chinese Water Turbine Pump		■	■		■	■	■	■	

Flow volumes of streams/cricks, available falls and delivery head requirements vary based on geographic area of application. Technologies in Group A are generally preferred for low land areas where the terrain is generally flat, the depth of flow is generally high and the required delivery head (form location of the pump to the point of use) is generally low. Technologies in Group B are generally preferred for high lands where the terrain is rugged and hence: a) falls are available to provide the necessary working / operational heads; b) high delivery heads are required from the pumps to cover big elevation differences; and c) high seasonal variation of flows are frequently encountered.

This is the reason why, while making pair-wise comparisons among the criteria, very high points are not given to the three criteria of comparison. Given suitability of the technologies for different geographical and hydrological conditions, allocating high points to the three criteria of comparison may create imbalance of ranking by unnecessarily attaching exaggerated weight for the criteria that are not of proportional importance.

Table 5.3: Grouping of technologies (with general and group-wise ranking) based on: operational head requirements; delivery head and operational flow depth requirements

Group A				Group B			
Code	**Technology**	**Rank (A+B)**	**Rank (A)**	**Code**	**Technology**	**Rank (A+B)**	**Rank (B)**
2	Hydro-powered Spiral Pump,	**4**	**1**	**10**	Hydraulic Ram Pump	**1**	**1**
1	Hydro-powered Coil Pump (Wirtz Pump),	**5**	**2**	**12**	Venturi Pump (Papa Pump)	**2**	**2**
8	Hydrobine Pump	**6**	**3**	**11**	Glockmann Pump	**3**	**3**
3	Hydro-powered Helix Pump,	**7**	**4**	**9**	Bunyip Pump	**8**	**4**
14	Chinese Water Turbine Pump	**9**	**5**	**7**	High Lifter Pump	**10**	**5**
				5	Hydrautomat Pump	**11**	**6**
				4	Lambach Pump	**12**	**7**
				13	Full Belly's Gravity Pump	**13**	**8**
				6	Cherepnov Pump	**14**	**9**

Pumping volume has not also been given big point during the pair-wise comparison as all the technologies can work non-stop and the extended hours of work can compensate the deficiency in pumping rate (particularly for small holding agriculture).
The rest of the weighing criteria are equally applicable to all the technologies irrespective of their groups (both by mechanics of operation and zone of appropriate application)

5.2 Comparison of the Technologies

5.2.1 Pair-wise Comparison of the Technologies under Each Evaluation Criteria

Pair-wise comparison of the technologies against the selected fourteen criteria yielded the rank (as expressed in terms of relative weight) of each technology for the criteria.

5.2.2 Consistency of the Pair-wise Comparison

Validation of the comparisons and the final ranking shows that all the results fall within the acceptable limit of Consistency Ratio (≤ 10 percent).

5.2.3 Aggregation of the Pair-wise Comparison

After obtaining the relative weight of each technology for all the criteria, the aggregate result is obtained by multiplying points obtained for each Technology, for each criterion, by the weight of the corresponding criteria and summing up the products. Summary of the result so obtained is depicted in Table 5.4.

Table 5.4: Technologies, relative weights and ranks of the technologies based on relative weight (group A and B evaluated together)

Technology Code	Technology	Relative Weight	Rank
10	Hydraulic Ram Pump	0.161	1
12	Venturi Pump (Papa Pump)	0.083	2
11	Glockmann Pump	0.078	3
2	Hydro-powered Spiral Pump	0.078	4
1	Hydro-powered Coil Pump (Wirtz Pump)	0.076	5
8	Hydrobine Pump	0.073	6
3	Hydro-powered Helix Pump	0.072	7
9	Bunyip Pump	0.066	8
14	Chinese Water Turbine Pump	0.063	9
7	High Lifter Pump	0.058	10
5	Hydrautomat Pump	0.053	11
4	Lambach Pump	0.050	12
13	Full Belly's Gravity Pump	0.047	13
6	Cherepnov Pump	0.043	14
	SUM	**1.000**	

5.3 Sensitivity Analysis

5.3.1 Critical Criteria (Sensitivity with respect to the Criteria Weight)

5.3.1.1 Percent Top Critical Criteria

Identification of critical criterion is divided into two, Percent – Top (PT) and Percent –Any (PA). Percent - Top Critical Criteria can be found by looking for the smallest perturbation (in percent) to be made on criteria weight to alter ranking of the technology that ranked first with the rest the technology [49]. For the case under consideration, Percent Top critical criteria is identified in two ways. First by considering all the technologies as one group, and second by considering the technologies in the two groups (Group A and Group B) independently.

Table 5.5 extracts (from Tables 4.57 through 4.69 - under Chapter 4) the rows of relative increments (in %) required by the Criteria Weights to reverse rank of the top-ranking technology with the rest. From the Table, it is seen that the Percent – Top (or PT) Critical Criterion – the Criterion which corresponds to the smallest percentage of change in criteria weight to cause a swap between the first ranked Technology – (T10 – Hydraulic Ram Pump) and any other is 1,379. This minimum is obtained at Criteria B (ease of operation) and the swap is with T3 (Hydro-powered Helix Pump). As 1,379 percent is a rather big perturbation, it can be concluded that the ranking made is very robust against Percent – Top (PT).

Considering the two broad classification (Group A and B), Hydro-powered spiral pump ranks top from Group A and Hydraulic Ram Pump from Group B. Percent Top Critical Criterion for each group is also as follows.

Table 5.6 extracts (from Tables 4.57 through 4.69 - under Chapter 4) the rows of relative increment (in %) required by the Criteria Weights to reverse rank of the top ranking technology (in Group A) with the rest of technologies in same group. From the Table, it is seen that the Percent – Top (or PT) Critical Criterion – the Criterion which corresponds to the smallest percentage of change in criteria weight to cause a swap between the first ranked Technology from Group A (T2- Hydro-powered Spiral Pump) with the rest of the technologies in same group – is 31 percent. This minimum is obtained at Criteria A (ease of manufacturing) and the swap is with T3 (Hydro-powered Helix Pump). A $\boldsymbol{D_k'}$ of 31 percent shows fairly robust ranking.

Table 5.7 extracts (from Tables 4.57 through 4.69 - under Chapter 4) the rows of relative increment (in percent) required by the Criteria Weights to reverse rank of the top ranking technology (in Group B) with the rest the technologies in same group. From the Table, it is seen that the Percent – Top Critical Criterion – the Criterion which corresponds to the smallest percentage of change in criteria weight to cause a swap between the first ranked Technology from Group B (T10 – Hydraulic Ram Pump) with the rest in same group is 1961, which exhibits ranking with very high robustness.

Table 5.5: Relative increments (in %) required by the criteria weights to reverse ranks of the best alternative (T10) with the remaining (Group A and B evaluate together).

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T10-T1	N/F	-16,259	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,875	-6,725	N/F	-1,875
T10-T2	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,828	-6,557	N/F	-1,828
T10-T3	N/F	-1,379	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-	-7,023	N/F	-1,379
T10-T4	N/F	N/F	N/F	N/F	-12,154	N/F	N/F	N/F	-1,961	N/F	N/F	N/F	-8,763	N/F	-1,961
T10-T5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-8,525	N/F	-8,525
T10-T6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-5,818	N/F	N/F	N/F	-9,303	N/F	-5,818
T10-T7	N/F	N/F	N/F	N/F	N/F	N/F	-12,712	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-12,712
T10-T8	N/F	-2,167	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-5,394	-6,934	N/F	-2,167
T10-T9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-6,419	N/F	N/F	N/F	-7,434	N/F	-6,419
T10-T11	N/F	N/F	N/F	N/F	N/F	N/F	-10,851	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-10,851
T10-T12	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-9,402	N/F	N/F	N/F	N/F	N/F	-9,402
T10-T13	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-2,467	N/F	N/F	-2,467
T10-T14	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-3,215	N/F	N/F	N/F	N/F	N/F	-3,215

Table 5.6: Relative increments (in %) required by the criteria weights to reverse ranks of the best alternative in Group A (T2) with the remaining in the Group

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T2-T1	N/F	-385	-5,608	N/F	N/F	-1,486	N/F	N/F	N/F	N/F	-5,044	N/F	N/F	N/F	-385
T2-T8	31	-117	N/F	-309	N/F	-71	-681	-174	-349	N/F	-164	N/F	N/F	N/F	31
T2-T3	48	-91	N/F	-5,652	N/F	-168	-676	-1,736	-606	N/F	-283	N/F	N/F	N/F	48
T2-T14	73	N/F	-331	N/F	-690	-127	N/F	N/F	-200	N/F	-2,527	N/F	N/F	N/F	73
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 5.7: Relative increments (in %) required by the criteria weights to reverse ranks of the best alternative in Group B (T10) with the remaining in the Group

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T10 - T12	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-9,402	N/F	N/F	N/F	N/F	N/F	-9,402
T10 - T11	N/F	N/F	N/F	N/F	N/F	N/F	-10,851	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-10,851
T10 - T9	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-6,419	N/F	N/F	N/F	-7,434	N/F	-6,419
T10 - T7	N/F	N/F	N/F	N/F	N/F	N/F	-12,712	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-12,712
T10 - T5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-8,525	N/F	-8,525
T10 - T4	N/F	N/F	N/F	N/F	-12,154	N/F	N/F	N/F	-1,961	N/F	N/F	N/F	-8,763	N/F	-1,961
T10 - T13	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-2,467	N/F	N/F	-2,467
T10 - T6	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-5,818	N/F	N/F	N/F	-9,303	N/F	-5,818

Table 5.8: Percent Any (PA) sensitivity of the ranking (group A and B evaluated together), as measured by criticality degree D'_k (in %)

Criteria Code	Criteria	Criticality Degree D'_k (%)	Swapping Technologies (by Code)	Swapping Technologies
A	**Ease of Manufacturing**	2.3	**T2 and T11**	**Spiral and Glockmann**
B	**Ease of Operation**	7.3	T2 and T11	**Spiral and Glockmann**
C	**Maintenance Requirement**	4.2	T2 and T11	**Spiral and Glockmann**
D	**Frequency of Supervision**	8.8	T2 and T11	**Spiral and Glockmann**
E	**Security (theft)**	58	T4 and T13	**Lambach and Full Belly's**
F	**Service Year**	5.3	T2 and T11	**Spiral and Glockmann**
G	**Mobility**	15.5	T2 and T11	**Spiral and Glockmann**
H	**Pumping Height**	3.5	T2 and T11	**Spiral and Glockmann**
I	**Pumping Volume**	6.9	T2 and T11	**Spiral and Glockmann**
J	**Literature Coverage**	15.7	T2 and T11	**Spiral and Glockmann**
K	**Operational Flow Volume**	4.3	T2 and T11	**Spiral and Glockmann**
L	**Operational Head**	5.6	T2 and T11	**Spiral and Glockmann**
M	**Patent Right**	14.9	T2 and T11	**Spiral and Glockmann**
N	**Manufactured for Commerce**	186	T4 – T13	**Lambach and Full Belly's**

Table 5.9: Relative increments (in %) required by the criteria weights to reverse ranks of the candidate technologies (T1 with the remaining in Group A)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T1-T2	N/F	-385	-5,608	N/F	N/F	-1,486	N/F	N/F	N/F	N/F	-5,044	N/F	N/F	N/F	-385
T1-T3	33	-64	100	-2,157	-19,236	-112	-373	-1,111	-340	N/F	-185	N/F	N/F	-754	33
T1-T8	18	-75	58	-164	N/F	-40	-316	-96	-176	N/F	-93	91	N/F	-455	18
T1-T14	65	N/F	-284	N/F	-496	-110	N/F	N/F	-167	N/F	-2,325	N/F	N/F	-2,089	65
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 5.10: Relative increments (in %) required by the criteria weights to reverse ranks of the candidate technologies (T2 with the remaining in Group A)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T2-T3	48	-91	N/F	-5,652	N/F	-168	-676	-1,736	-606	N/F	-283	N/F	N/F	N/F	48
T2-T8	31	-117	N/F	-309	N/F	-71	-681	-174	-349	N/F	-164	N/F	N/F	N/F	31
T2-T14	73	N/F	-331	N/F	-690	-127	N/F	N/F	-200	N/F	-2,527	N/F	N/F	N/F	73
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 5.11: Relative increments (in %) required by the criteria weights to reverse ranks of the candidate technologies (T3 with the remaining in Group A)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T3-T8	-39	-46.9	-144	77.9	-3,117.1	35.1	-653.5	46.6	N/F	-2,437	N/F	-127.95	N/F	N/F	-38.5
T3-T14	N/F	57.98	-104	N/F	-345.1	-108.8	N/F	N/F	-136.1	N/F	N/F	N/F	N/F	-10,150	58.0
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 5.12: Relative increments (in %) required by the criteria weights to reverse ranks of the candidate technologies (T8 with the remaining in Group A)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T8-T14	N/F	79	-108	N/F	-385	-210	N/F	N/F	-165	N/F	N/F	N/F	N/F	N/F	79
Note: N/F (not feasible) shows that it is not feasible to reverse the order of importance by modifying the respective Criteria Weight.															

Table 5.13: Summary of Percent Any sensitivity of the ranking (Group A), as measured by Criticality Degree D'_k (in %)

Criteria Code	Criteria	Criticality Degree D'_k (%)	Swapping Technologies (by Code)	Swapping Technologies
A	Ease of Manufacturing	**18**	**T1 and T8**	Coil and Hydrobine
B	Ease of Operation	47	T3 and T8	Hydrobine and Helix
C	Maintenance Requirement	58	**T1 and T8**	Coil and Hydrobine
D	Frequency of Supervision	78	T3 and T8	Hydrobine and Helix
E	Security (theft)	345	T3 and T14	Helix and Chinese
F	Service Year	35	T3 and T8	Hydrobine and Helix
G	Mobility	316	**T1 and T8**	Coil and Hydrobine
H	Pumping Height	47	T3 and T8	Hydrobine and Helix
I	Pumping Volume	136	T3 and T14	Helix and Chinese
J	Literature Coverage	2437	T3 and T8	Hydrobine and Helix
K	Operational Flow Volume	93	**T1 and T8**	Coil and Hydrobine
L	Operational Head	91	**T1 and T8**	Coil and Hydrobine
M	Patent Right	N/F	N/F	N/F
N	Manufactured for Commerce	455	**T1 and T8**	Coil and Hydrobine

Table 5.14: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T12) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T12 - T11	-102	N/F	N/F	N/F	-2,024	N/F	-518	N/F	N/F	N/F	-	N/F	N/F	N/F	-102
T12 – T9	-411	N/F	N/F	N/F	-3,045	-517	N/F	N/F	-	N/F	N/F	N/F	-865	N/F	-411
T12 – T7	N/F	N/F	N/F	N/F	N/F	N/F	-2,561	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-2,561
T12 – T5	-251	N/F	-2,011	N/F	-4,337	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,609	N/F	-251
T12 – T4	N/F	N/F	-261	N/F	-730	-388	N/F	N/F	-877	N/F	N/F	N/F	-5,803	N/F	-261
T12 – T13	-2,114	N/F	N/F	N/F	-	N/F	N/F	N/F	N/F	N/F	N/F	-762	N/F	N/F	-762
T12 – T6	N/F	N/F	N/F	N/F	-1,448	N/F	N/F	N/F	-	N/F	N/F	N/F	-2,139	N/F	-1,448
T12 – T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-	N/F	N/F	N/F	N/F	N/F	-9,402

Table 5.15: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T11) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T11 – T9	N/F	N/F	N/F	N/F	-3,847	-274	N/F	N/F	-721	N/F	N/F	N/F	-612	N/F	-274
T11 – T7	N/F	N/F	-820	N/F	N/F	N/F	-46,169	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-820
T11 – T5	-345	N/F	-494	N/F	-5,512	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-1,356	N/F	-345
T11 – T4	N/F	N/F	N/F	N/F	-816	-591	N/F	N/F	-489	N/F	N/F	N/F	-1,518	N/F	-489
T11 – T13	N/F	N/F	-	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-608	N/F	N/F	-608
T11-T10	N/F	N/F	N/F	N/F	N/F	N/F	-10,851	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-10,851
T11 – T6	N/F	N/F	-1,251	N/F	-1,394	N/F	N/F	N/F	-1,641	N/F	N/F	N/F	-1,886	N/F	-1,251

Table 5.16: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T9) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T9 – T7	N/F	N/F	-315	N/F	N/F	N/F	-359	-221	N/F	-461	-338	N/F	N/F	N/F	-221
T9 – T5	-	N/F	-260	N/F	-8,561	N/F	N/F	N/F	N/F	N/F	-1,121	N/F	N/F	N/F	-173
T9 – T4	N/F	N/F	N/F	N/F	-532	-2,735	N/F	N/F	-401	N/F	N/F	N/F	N/F	N/F	-401
T9 – T13	N/F	N/F	-5,653	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-544	-338	N/F	N/F	-338
T9 – T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-6,419	N/F	N/F	N/F	-7,434	N/F	-6,419
T9 – T6	N/F	N/F	-783	N/F	-1,067	N/F	N/F	N/F	-4,238	N/F	N/F	N/F	N/F	N/F	-783

Table 5.17: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T7) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T7 – T5	-43	N/F	-207	N/F	-520	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-302	N/F	-43
T7 – T4	N/F	N/F	N/F	N/F	-211	-120	N/F	N/F	-123	N/F	N/F	N/F	-464	N/F	-120
T7 – T10	N/F	N/F	N/F	N/F	N/F	N/F	-12,712	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-12,712
T7 – T13	-373	N/F	N/F	N/F	-1,786	N/F	N/F	N/F	N/F	N/F	-1,029	-185	N/F	N/F	-185
T7 – T6	N/F	N/F	-3,735	N/F	-493	-	N/F	N/F	-455	N/F	N/F	N/F	-832	N/F	-455

Table 5.18: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T5) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T5 – T4	20	N/F	44	-370	-100	-29	N/F	-	-30	-5,935	N/F	N/F	N/F	N/F	20
T5 – T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-8,525	N/F	-8,525
T5 – T13	49	-213	N/F	-426	N/F	-424	-3,789	N/F	N/F	N/F	-225	-84	N/F	-465	49
T5 – T6	70	N/F	N/F	N/F	-479	-291	N/F	-	-154	-5,332	N/F	N/F	N/F	-2,736	70

Table 5.19: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T4) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T4 – T10	N/F	N/F	N/F	N/F	-12,154	N/F	N/F	N/F	-1,961	N/F	N/F	N/F	-8,763	N/F	-1,961
T4 – T13	-42	-48	-	-549	58	22	-410	N/F	20	N/F	-42	-30	N/F	-186	20
T4 – T6	-681	N/F	-	N/F	N/F	100	-3,540	N/F	N/F	-5,104	N/F	N/F	N/F	-	100

Table 5.20: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T13) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T13 – T6	N/F	N/F	-	N/F	-190	-219	N/F	-324	-75	-	93	70	-260	N/F	70
T13 – T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-2,467	N/F	N/F	-2,467

Table 5.21: Relative increments (in %) required by the criteria weights to reverse ranks of alternative (T13) with the remaining in Group B

Technologies	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Minimum
T6 – T10	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	-5,818	N/F	N/F	N/F	-9,303	N/F	-5,818

Table 5.22: Sensitivity of the ranking (Group B), as measured by Criticality Degree D'_k (in %)

Criteria Code	Criteria	Criticality Degree D'_k (%)	Swapping Technologies (by Code)	Swapping Technologies
A	**Ease of Manufacturing**	**20**	**T5 and T4**	**Hydrautomat and Lambach**
B	**Ease of Operation**	48	T4 and T13	**Lambach and Full Belly's**
C	**Maintenance Requirement**	44	**T5 and T4**	**Hydrautomat and Lambach**
D	**Frequency of Supervision**	370	**T5 and T4**	**Hydrautomat and Lambach**
E	**Security (theft)**	58	T4 and T13	**Lambach and Full Belly's**
F	**Service Year**	22	T4 and T13	**Lambach and Full Belly's**
G	**Mobility**	359	T9 and T7	**Bunyip and Highlifter**
H	**Pumping Height**	221	T9 and T7	**Bunyip and Highlifter**
I	**Pumping Volume**	**20**	T4 and T13	**Lambach and Full Belly's**
J	**Literature Coverage**	461	T9 and T7	**Bunyip and Highlifter**
K	**Operational Flow Volume Requirement**	42	T4 and T13	**Lambach and Full Belly's**
L	**Operational Head**	30	T4 and T13	**Lambach and Full Belly's**
M	**Patent Right**	260	T13 and T6	**Full Belly's and Cherepnov**
N	**Manufactured for Commerce**	186	T4 and T13	**Lambach and Full Belly's**

5.3.1.2 Percent Any (PA) Critical Criteria

The Percent Any (or PA) Critical Criterion – the Criterion which corresponds to the smallest perturbation on criteria weight to cause a swap between any two Technologies – can be found by tracing the smallest value of relative increment (in percent), required by the criteria, coded A through N, computed in Tables 4.57 through 4.69 (Chapter 4). Extract of the minimum values for each criteria (by considering both Group A and B together) is given in Table 5.8.

As seen from the Table (5.8), the Percent Any Critical Criteria is Criteria A (ease of manufacturing). The criticality degree is 2.3, and the swap is between T2 (Hydro-powered Spiral Pump) and T11 (Glockemann Pump). The rest of minimum values also swap T2 and T11 with the exception of the two criteria (E – Security, and N – Commercial Manufacturing) the alteration of which swap T4 and T13.

For all the criteria (except *Security* and *Commercial Manufacturing),* for the minimum criticality degrees (that range between 2.2 and 15.7), the swap is expected between Spiral and Glockmann. For *Security* the criticality degree is 58 percent (Sensitivity Coefficient of 0.017), and the swap is between Lambach (which ranks 12th, with relative weight of 0.050) and Full Belly's Gravity Pump (which ranks 13th, with relative weight of 0.047). For *Commercial Manufacturing*, the criticality degree is 186 percent (Sensitivity Coefficient of 0.005) and the swap is again between Lambach and Full Belly's Gravity Pumps. As 58 and 186 percent are fairly big alterations, the Sensitivity Coefficients can be considered as low and the ranking can still be confirmed to be robust.

The relative weight for Spiral and Glockmann Pumps are identical to the third decimal places. Their ranks are third (for Glockmann with relative weight 0.0780), and fourth (for Spiral with relative weight 0.0777). Given the tiny difference between their relative weight, swapping between the two with slight alteration is expected. However, Spiral Pump belongs to Group A and Glockmann Pump falls under Group B. When the total ranking is seen in line with the two categories, there will not be swapping as the two technologies fall in the two different groups. From the aforementioned discussion, it is seen that the ranking (Group A and B evaluated together) is robust against perturbation of criteria weight.

The Percent Any (or PA) Critical Criterion for technologies in Group A – the Criterion which corresponds to the smallest percentage of change in criteria weight to cause a swap between any two Technologies in the Group – can be found by looking for the smallest value of relative increment, in percent, required by the criteria, coded A through N – computed in Tables 4.57 through 4.69 (Chapter 4). For ease of identification, the relevant rows for technologies in Group A are extracted from Tables 4.57 through 4.69 (Chapter 4), and are presented in Tables 5.9 – 5.12. Summary the minimum values are depicted in Table 5.13.

As seen from the Table, the Percent Any Critical Criteria is Criteria A (ease of manufacturing). The criticality degree is 18, and the swap is between T1 (Hydro-powered Coil Pump) that stands 2nd, and T8 (Hydrobine Pump) that stands 3rd with relative weights of 0.076 and 0.073, respectively. For such close relative weight, criticality degree of 18 percent shows a fair robustness of the pair-wise comparisons and the resulting ranking. The swap does not alter the entire ranking. Rather it swaps technologies with consecutive ranks.

The next Critical Criteria is Criteria B (Ease of Operation) with Criticality Degree of 47 percent. Alteration of the weight of this critical criteria by 58 percent causes swap between T3 and T8 (Helix and Hydrobine), that have relative weights of 0.073 and 0.072 respectively. For such even closer relative weight, criticality degree of 47 percent shows good robustness.

The Percent Any (or PA) Critical Criterion for technologies in Group B – the Criterion which corresponds to the smallest percentage of change in criteria weight to cause a swap between any two Technologies in the Group – can be found by looking for the smallest value of relative increment, in percent, required by the criteria, coded A through N – computed in Tables 4.57 through 4.69 (Chapter 4). For ease of identification, the relevant rows for technologies in Group B are extracted from the Tables, and are presented in Tables 5.14 – 5.21. Summary of the minimum values are depicted in Table 5.22.

As seen from the Table (5.22), the Percent Any Critical Criteria are (obtained from Tables 5.18 and 5.19) are Criterion A (Ease of Manufacturing) and Criterion I (Pumping Volume).

The criticality degree is 20 for both, and the swaps are: a) between T5 (Hydrautomat) that stands 6th and T4 (Lambach) that stands 7th, with relative weights of 0.053 and 0.050, respectively for Criterion A; and b) between T4 (Lambach) that stands 7th and T13 (Full Belly's) that stands 8th, with relative weights of 0.05 and 0.047. For relative weights of such proximity, criticality degree of 20 percent shows a fair robustness. The swap does not alter the entire ranking. Rather it swaps technologies with consecutive ranks.

The next Critical Criterion is Criterion K (Operational Flow Volume Requirement) with Criticality Degree of 42 percent. Alteration of the weight of this critical criterion by 42 percent causes swap between T4 and T13 (Lambach and Full Belly's), which is similar to the swap caused by Criterion I. The previous conclusion, therefore, holds true.

5.3.2 Sensitivity with respect to Measure of Performance

Sensitivity with respect to Measure of Performance is gauged with the minimum change required by the measure of performances, under the criteria, to swap ranking between any two alternatives. The values computed for all measures of performance are depicted in Tables 4.71 through 4.84 (Chapter 4). For the total analysis (Group A and B considered together), the full Tables are referred. For Group A, parts of the Tables shaded with yellow (light grey in black and white) are used. For Group B, parts of the Tables shaded with light green (medium-dark grey in black and white) are considered.

Table 5.23 summarizes the result for both Groups (Group A and B considered together). From the Table, it is seen that the most critical alternative (Technology) is T4 (under Criterion A) with a Criticality Degree of 1.4, followed by T3 (under Criteria A, H and D), with Criticality Degree 2.8, 2.9, 3.0, T7 (under Criterion B), with Criticality Degree 6.5, T6 (under Criterion B), with Criticality Degree 7.1, T5 (under Criterion A), with Criticality Degree 10.5, and T8 (under Criterion F), with Criticality Degree 25. The most critical alternative ranks 12th, and the possibility of its rank-swapping is with Technology T3 which itself ranks 7th. Alternatives with the top five criticality degrees rank: 12th; 7th; 10th; 14th; and 11th, respectively. The swaps are with technologies that rank: 7th; 12th; 14th; 10th; and 12th respectively.

The first two most critical technologies (T4 and T3) are likely to swap with T3 and T4, respectively. Table 5.3 shows that T4 belongs to Group B, and T3 belongs to Group A. The technologies that swap are not within same Group. The 3rd and the 4th possible swaps are between T7 and T6, and T6 and T7, all in Group B. These swaps do not affect the first four ranks of Group B. Due to these facts, the ranking can be concluded to be fairly robust against Measure of Performance.

Table 5.24 summarizes the result of Group A. From the Table, it is seen that the most critical alternative (Technology) is T2(under Criterion H)with Criticality Degree of 41, followed by T3 (again under H), with Criticality Degree 47, T8 (under Criterion F), with Criticality

Degree 106, and T14 (under Criterion I), with Criticality Degree 449. For the alternative which ranks 1^{st}, the possibility of its rank-swapping is with Technology T3 which itself ranked 4^{th}. Alternatives with the top three criticality degree rank: 1^{st}; 4^{th}; 3^{rd}; respectively. The swaps are with technologies that rank: 4^{th}; 1^{st}; and 4^{th}, respectively. The minimum criticality degree (41 percent) is reasonably high that the ranking can be considered robust.

Table 5.25 summarizes the result of Group B. From the Table, it is seen that the most critical alternative (Technology) is T7 (under Criterion B) with a Criticality Degree of 6.5, followed by T6 (again under Criterion B) with Criticality Degree 7.1, T4 (under Criterion A) with Criticality Degree 9.9, T5 (again under Criterion A) with Criticality Degree 10.5, and T12 (under Criterion F), with Criticality Degree 16.5. The most critical Alternative ranks 5^{th}, and the possibility of its rank-swapping is with Technology T6 which itself ranked 9^{th}. Alternatives with the top five criticality degree rank: 5^{th}; 9^{th}; 7^{th}; 6^{th}; and 2^{nd}, respectively. The swaps are with technologies that rank: 9^{th}; 5^{th}; 6^{th}; 7^{th}; and 8^{th} , respectively. The minimum criticality degree (6.5 percent) is not high, but the technologies affected are those that rank 5^{th} and above. Hence, the ranking can still be considered robust for the first four technologies.

Table 5.23: Criticality Degree of alternatives (Technologies), Criteria of Criticality, Swapping Technology, Sensitivity Coefficient, and the Most Critical Alternatives (Technologies in Group A and B considered together)

Technology (Alternative)	Criticality Degree (%)	Criticality Observed at Criteria	Swap with Technology	Sensitivity Coefficient	Critical Alternatives
Hydro-powered Coil Pump (Wirtz Pump)	N/F	N/F	N/F	N/F	
Hydro-powered Spiral Pump (2 with 3)	41.1 (H)	**Pumping Height**	**Hydro-powered Helix Pump**	0.243	
Hydro-powered Helix Pump (3 with 4)	2.8, 2.9, 3.0 (A, H, D)	**Ease of Manufacturing, Pumping Height, Frequency of Supervision**	**Lambach Pump**	0.357	T3
Lambach Pump (4 with 3)	1.4 (A)	**Ease of Manufacturing**	**Hydro-powered Helix Pump**	0.714	T4
Hydrautomat Pump (5 with 4)	10.5 (A)	**Ease of Manufacturing**	**Lambach Pump**	0.095	T5
Cherepnov Pump (6 with 7)	7.1 (B)	**Ease of Operation**	**High Lifter Pump**	0.141	T6
High Lifter Pump (7 with 6)	6.5 (B)	**Ease of Operation**	**Cherepnov Pump**	0.154	T7
Hydrobine Pump (8 with 9)	25 (F)	**Service Year**	**Bunyip Pump**	0.04	
Bunyip Pump (9 with 8)	23.6 (F)	**Service Year**	**Hydrobine Pump**	0.042	
Hydraulic Ram Pump (10 with 11)	74.2 (H)	**Pumping Height**	**Glockmann Pump**	0.013	
Glockemann Pump (11 with 12)	20.3 (A)	**Ease of Manufacturing**	**Venturi Pump (Papa Pump)**	0.049	
Venturi Pump (Papa Pump) [12 with 13]	16.5 (F)	**Service Year**	**Full Belly's Gravity Pump**	0.061	
Full Belly's Gravity Pump (13 with 12)	30.3 (L)	**Operational Head Requirement**	**Venturi Pump (Papa Pump)**	0.033	
Chinese Water Turbine Pump (14 with 13)	72 (I)	**Pumping Volume**	**Full Belly's Gravity Pump**	0.014	

Table 5.24: Criticality Degree of alternatives (Technologies), Criteria of Criticality, Swapping Technology, Sensitivity Coefficient, and the Most Critical Alternatives (Technologies in Group A)

Technology (Alternative)	Criticality Degree (%)	Criticality Observed at Criteria	Swap with Technology	Sensitivity Coefficient	Critical Alternatives
Hydro-powered Coil Pump (Wirtz Pump)	N/F	N/F	N/F	N/F	
Hydro-powered Spiral Pump (2 with 3)	41 (H)	**Pumping Height**	**Hydro-powered Helix Pump**	0.024	**Pumping Height**
Hydro-powered Helix Pump (3 with 2)	47 (H)	**Pumping Height**	**Hydro-powered Spiral Pump**	0.021	**Pumping Height**
Hydrobine Pump (8 with 3)	106 (F)	**Service Year**	**Hydro-powered Helix Pump**	0.009	**Service Year**
Chinese Water Turbine Pump (14 with 8)	449 (I)	**Pumping Volume**	**Hydrobine Pump**	0.002	**Pumping Volume**

Table 5.25: Criticality Degree of alternatives (Technologies), Criteria of Criticality, Swapping Technology, Sensitivity Coefficient, and the Most Critical Alternatives (Technologies in Group B)

Technology (Alternative)	Criticality Degree (%)	Criticality Observed at Criteria	Swap with Technology	Sensitivity Coefficient	Critical Alternatives
High Lifter Pump (7 with 6)	6.5 (B)	**Ease of Operation**	**Cherepnov Pump**	0.15	**High Lifter**
Cherepnov Pump (6 with 7)	7.1 (B)	**Ease of Operation**	**High Lifter Pump**	0.14	**Cherepnov**
Lambach Pump (4 with 5)	9.9 (A)	**Ease of Manufacturing**	**Hydrautomat Pump**	0.10	**Lambach**
Hydrautomat Pump (5 with 4)	10.5 (A)	**Ease of Manufacturing**	**Lambach Pump**	0.10	**Hydrautomat**
Venturi Pump (Papa Pump) [12 with 13]	16.5 (F)	**Service Year**	**Full Belly's Gravity Pump**	0.06	**Venturi**
Glockmann Pump (11 with 12)	20.3 (A)	**Ease of Manufacturing**	**Venturi Pump (Papa Pump)**	0.049	
Full Belly's Gravity Pump (13 with 12)	30.3 (L)	**Operational Head Requirement**	**Venturi Pump (Papa Pump)**	0.03	
Bunyip Pump (9 with 10)	36.4 (F)	**Service Year**	**Hydraulic Ram Pump**	0.03	
Hydraulic Ram Pump (10 with 11)	74.2 (H)	**Pumping Height**	**Glockmann Pump**	0.013	

5.4 Summary of the Discussion

Comparative Analysis made among Hydro-powered Pumping Technologies yielded the ranking given in Tables 4.55 (Chapter 4) and 5.1 (Chapter 5). Both the intermediate and final results have been found to be acceptable in line with the three barometers: consistencies of the pair-wise comparison matrices; robustness of the ranking against: a) sensitivity of criteria weight; and b) measure of performance.

To avoid replication of the processes, the ranking has been made by treating both Technologies in Group A and B together. After the ranking, the Technologies are grouped into two (Group A and B) as per their operational head requirement; flow depth requirement; and delivery head. Keeping the order in the general ranking, the Technologies in the two Groups are re-ranked in their respective groups.

The Technologies that ranked 1st through 3rd belongs to Group IV of classification based on mechanics of operation. The 2nd and 3rd ranking Technologies (both in General Ranking and Ranking of Group B) are the improved versions of Hydraulic Ram Pump. Despite the additional features the Technologies incorporate, Hydraulic Ram Pump outweighed the remaining two in the ranking due mainly to simplicity of manufacturing, ease of operation and maintenance requirement that are considered to be of very high value (priority) for the farmers with small holding.

The next chapter (Case Study / Adaptation) discusses the features that made the difference in more detail and addresses possibilities of imparting important features of the second and third ranking Technologies into the most preferred Technology (T10 – Hydraulic Ram Pump),under the contexts considered in this research, thereby complementing its paucities.

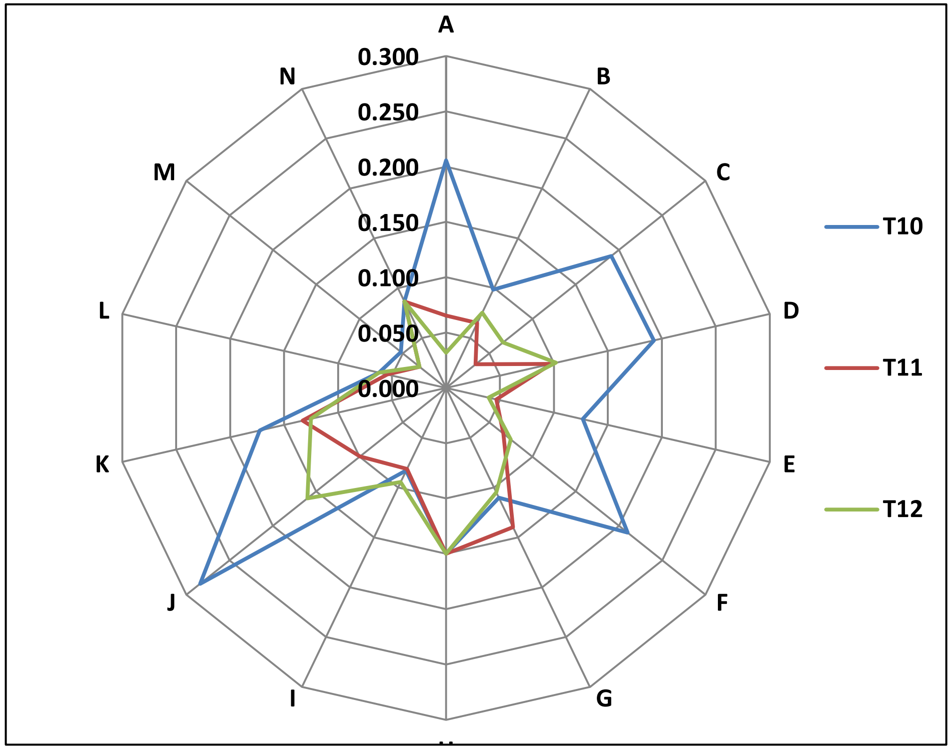

Figure 5.1:General Ranking – 1st through 3rd– Hydraulic Ram (T10), Venturi / Papa (T12), and Glockmann (T11), respectively

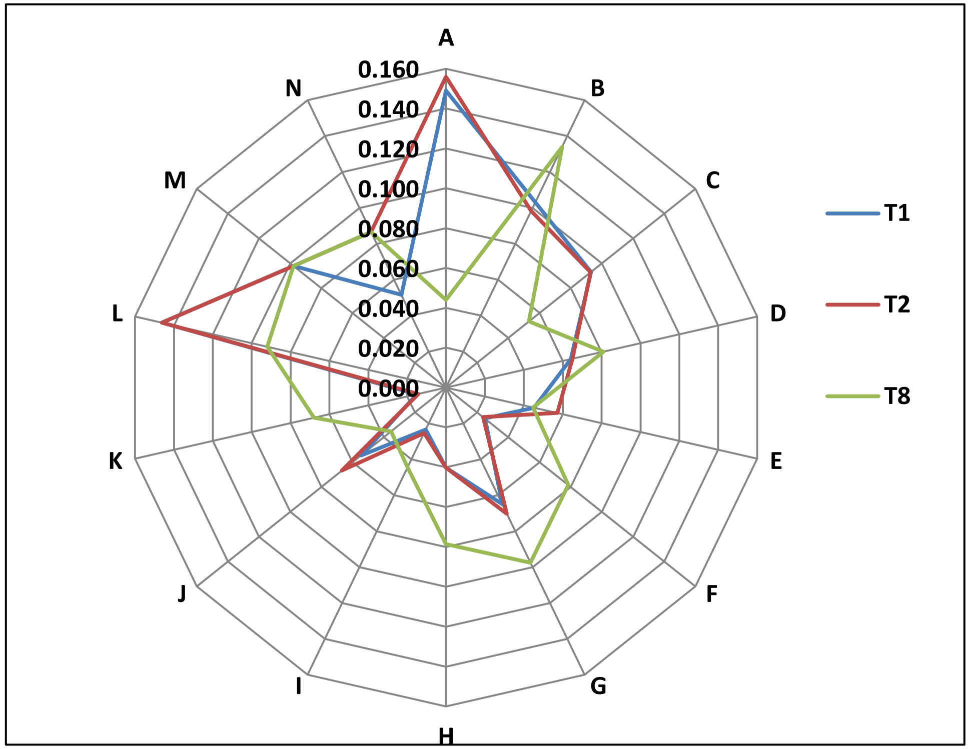

Figure 5.2: General Ranking – 4th through 6th– Spiral (T2), Coil (T1), and Hydrobine (T8), respectively

A	**Ease of Manufacturing**
B	**Ease of Operation**
C	**Maintenance Requirement**
D	**Frequency of Supervision**
E	**Security**
F	**Service Year**
G	**Mobility**
H	**Pumping Height**
I	**Pumping Volume**
J	**Literature Coverage**
K	**Operational Flow Volume Requirement**
L	**Operational Head Requirement**
M	**Patent Right**
N	**Manufactured for Commerce**

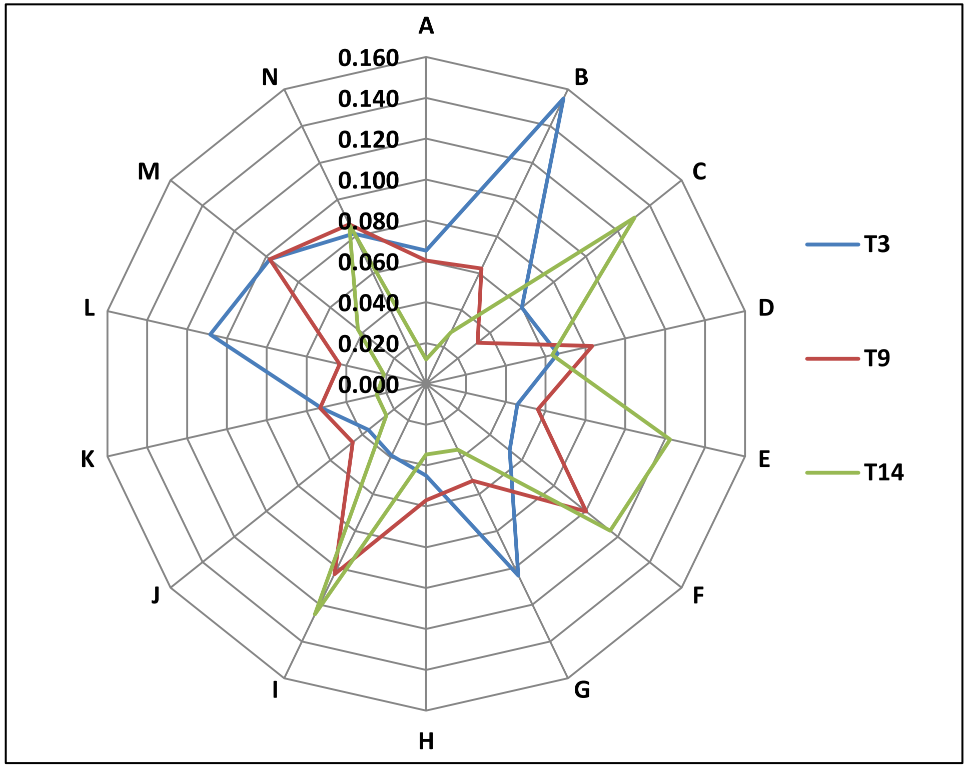

Figure 5.3: General Ranking – 7th through 9th– Helix (T3), Bunyip (T9), and Chinese Water Turbine (T14), respectively

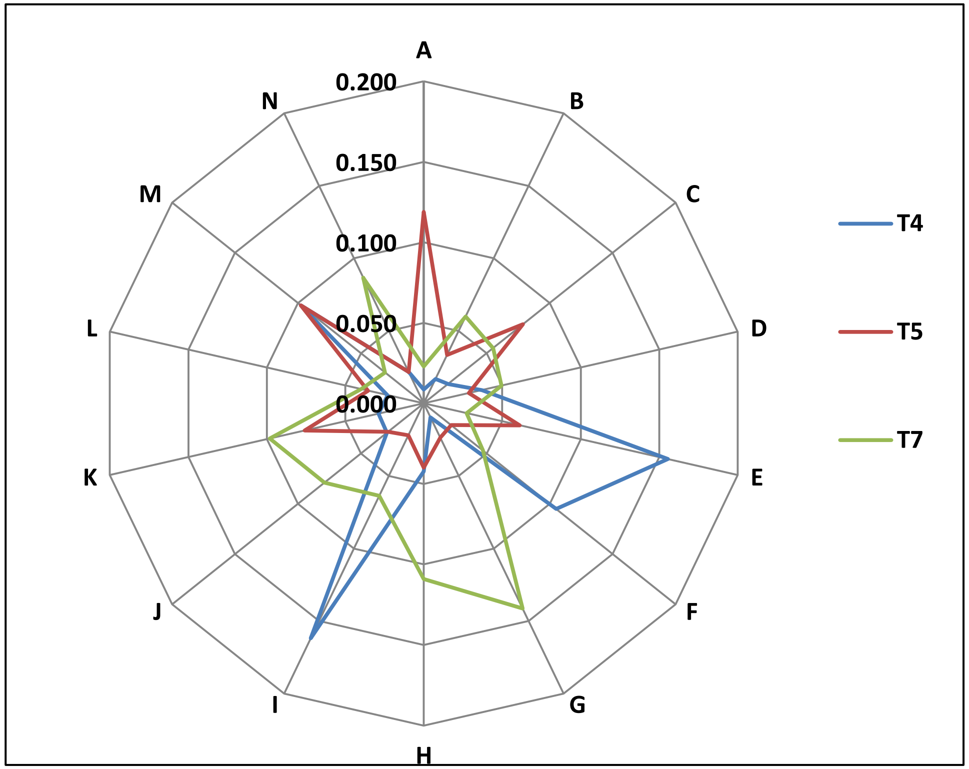

Figure 5.4: General Ranking – 10th through 12th– High Lifter (T7), Hydrautomat (T5), and Lambach (T4), respectively

A	Ease of Manufacturing	H	Pumping Height
B	Ease of Operation	I	Pumping Volume
C	Maintenance Requirement	J	Literature Coverage
D	Frequency of Supervision	K	Operational Flow Volume Requirement
E	Security	L	Operational Head Requirement
F	Service Year	M	Patent Right
G	Mobility	N	Manufactured for Commerce

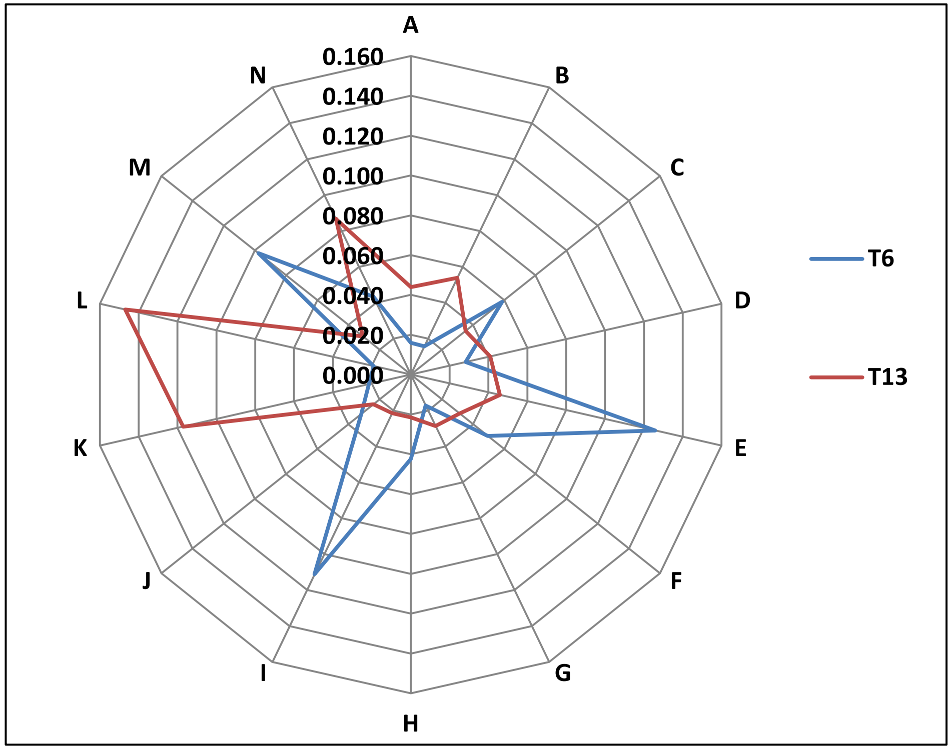

Figure 5.5: General Ranking – 13th and 14th– Full Belly's Gravity (T13) and Cherepnov (T6), respectively

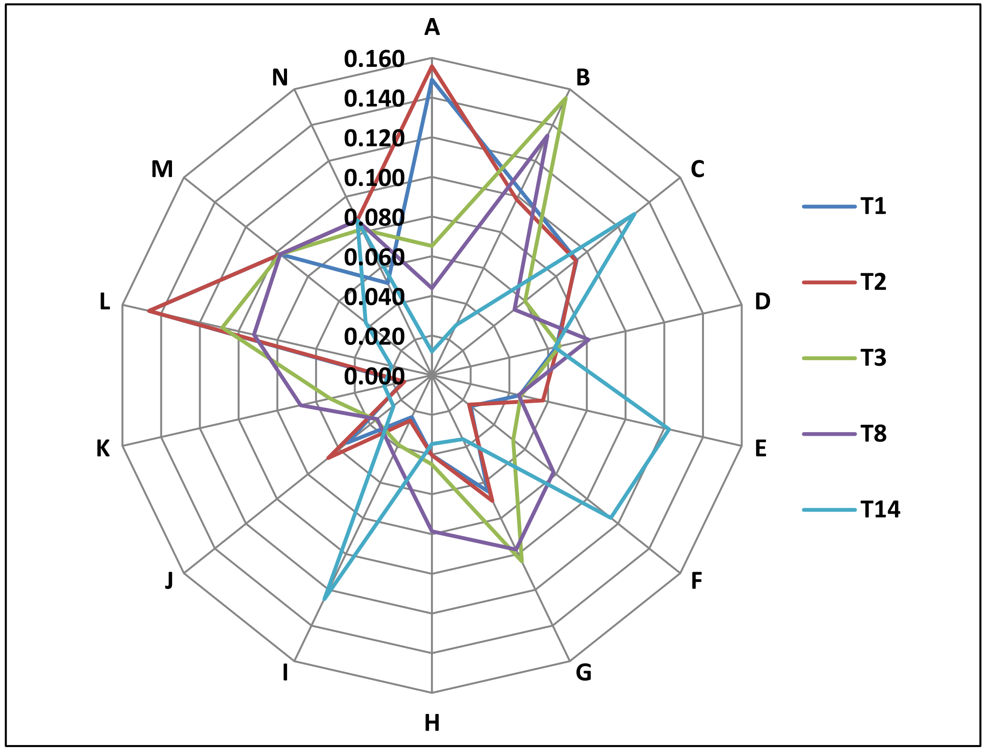

Figure 5.6: Group A Ranking – 1st through 5th– Spiral (T2), Coil (T1), Hydrobine (T8), Helix (T3), Chinese Water Turbine (T14), respectively

A	**Ease of Manufacturing**
B	**Ease of Operation**
C	**Maintenance Requirement**
D	**Frequency of Supervision**
E	**Security**
F	**Service Year**
G	**Mobility**
H	**Pumping Height**
I	**Pumping Volume**
J	**Literature Coverage**
K	**Operational Flow Volume Requirement**
L	**Operational Head Requirement**
M	**Patent Right**
N	**Manufactured for Commerce**

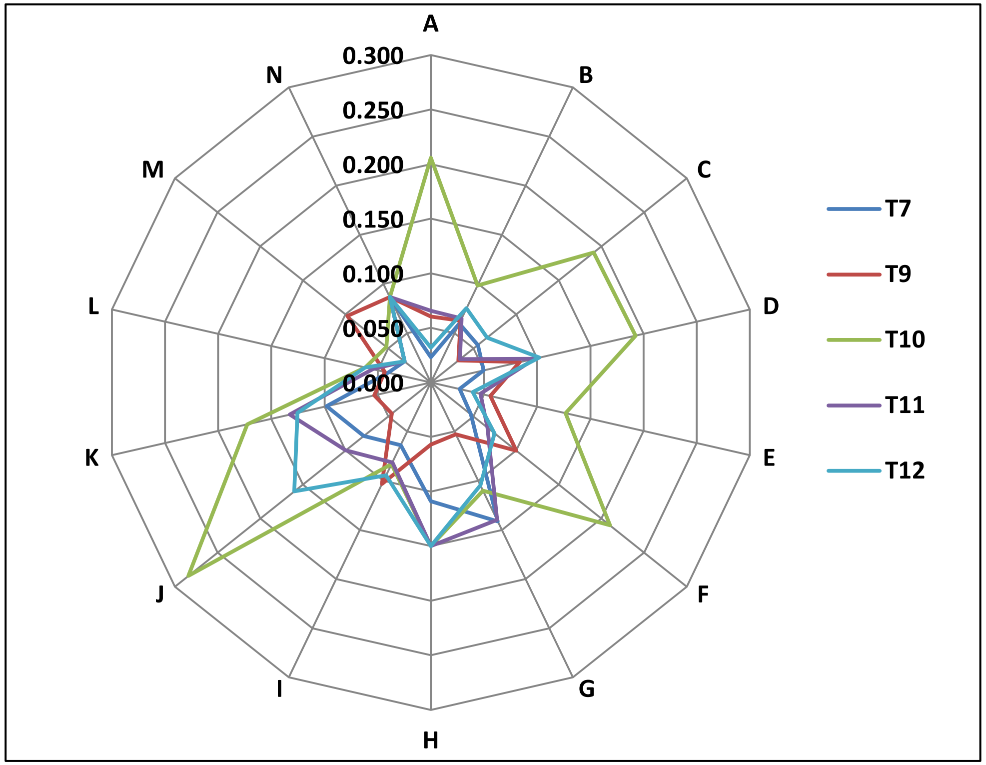

Figure 5.7: Group B Ranking – 1st through 5th – Hydraulic Ram (T10), Venturi / Papa (T12), Glockemann (T11), Bunyip (T9), High Lifter (T7), respectively

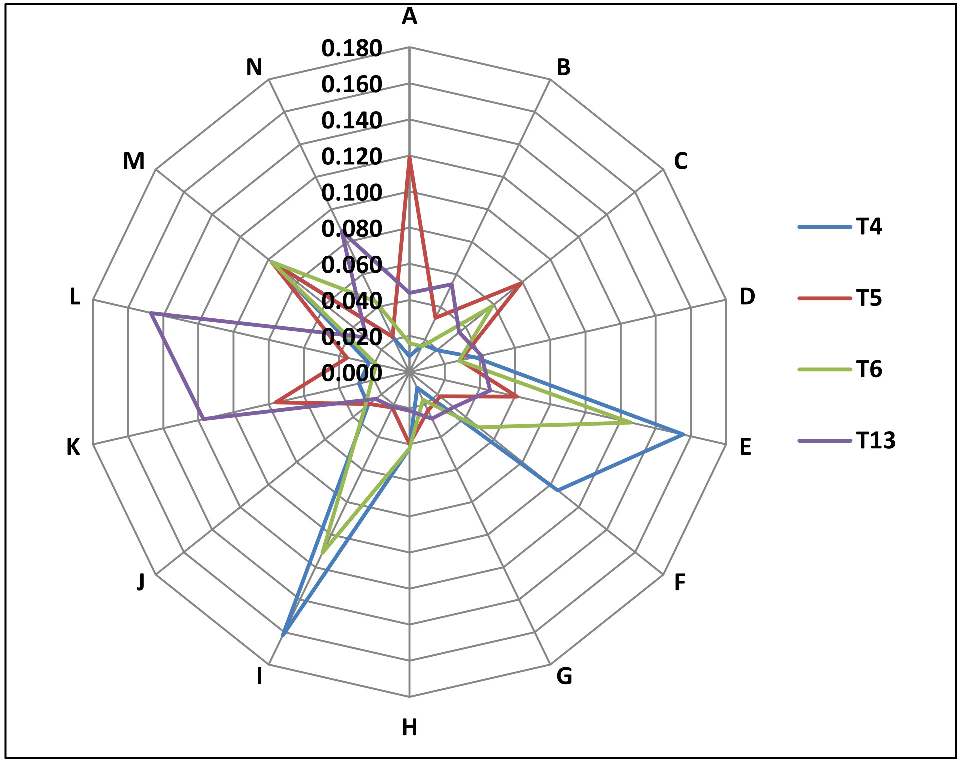

Figure 5.8: Group B Ranking – 6th through 9th – Hydrautomat (T5), Lambach (T4), Full Belly's Gravity (T13), Cherepnov (T6), respectively

A	**Ease of Manufacturing**
B	**Ease of Operation**
C	**Maintenance Requirement**
D	**Frequency of Supervision**
E	**Security**
F	**Service Year**
G	**Mobility**
H	**Pumping Height**
I	**Pumping Volume**
J	**Literature Coverage**
K	**Operational Flow Volume Requirement**
L	**Operational Head Requirement**
M	**Patent Right**
N	**Manufactured for Commerce**

CHAPTER 6

6. Adaptation

6.1 Introduction

The pumps that stand first to third in the general ranking of the comparative analysis all belong to Hydraulic Ram Pump family. The First-ranking alternative (Hydraulic Ram Pump) belongs to the first generation technology. Difficulty of manufacturing at local level, and patent right protection are the two main constraints against the second and third ranking technologies.

Venturi (Papa) pump, which ranks second, is an improved version of Hydraulic Ram Pump. It has been invented about a couple of decades ago. The two main features that Venturi Pump has over Hydraulic Ram Pump are the following.

1. By adjusting the core of the pump, it is possible to control opening of the passage of water to the Exhaust Port, via the impulse valve. This makes the pump fit to a range of discharges (Figure 3.3, Chapter 3).
2. The venturi action (pressure gradient) created around the impulse valve (due to its streamlined curvature), enables fast closure of the valve. Faster closure of impulse valve introduces increased pressure hike, and this makes the pump fit to a range of delivery heights. (Figure 3.30, Chapter 3).

This chapter introduces parallel mechanisms that impart these two important features of Venturi pump to the commonly used Hydraulic Ram Pump model by focusing on impulse valve, main body of the pump, delivery valve and delivery line.

6.2 Prevailing Technology and the Adaptation

Hydraulic Ram Pump, as compared to the second and third ranking alternatives, is by far easier to manufacture at local level. The operation is simpler, its maintenance requirement is not frequent and the service period is very long. These advantages of the technology are derived from its simplicity of manufacturing and mechanics of operation listed below.

1. Simple steel hollow sections can easily be converted into hydraulic ram pump.
2. It does not use piston. The pumping is mechanized by opening and closure of the impulse valve and delivery valve both of which are one way steel plate gates.
3. As the only moving parts of the pump are the two valves, it does not require frequent maintenance, and, hence, has longer service life.

These being the advantages of Hydraulic Ram Pump, it has the following deficiencies.

1. It is fit to only a narrow range of working heads, due to constant weight of its Impulse Valve.

2. It receives a fixed diameter of drive pipe and matching size of delivery pipe. Such design necessitates unique pump for one Drive Pipes size. Based on the incoming flow of water (which varies seasonally and from place to place) different drive pipe sizes may be required and this demands the corresponding number of Pumps. Such lack of flexibility challenges the applicability of a single pump to varying flow and topographic conditions.

3. Opening/passage of the impulse valve is fixed. This also constrains flexibility of the pump to be fit to sites with varying discharges.

4. It is, fully or partly, manufactured using circular sections which require circular flanges and circular plates. The development shapes of circular flanges and circular valves (plates) cause serious wastage of materials. Cutting 10 cm diameter plates from a one square meter sheet has a minimum wastage of 21.5 percent. Cutting out circular sections also requires heavy duty machines and this makes production of the Pump, at micro Enterprises level, difficult. Readymade flanges (manufactured by casting) are not adequately available. Even if available, their cost would be expensive. In the absence of heavy duty machines, circular holes are cut with welding machines. Circular cuts with a welding machine are rough (not smooth) and such roughness causes additional head loss which in turn reduces efficiency of the pump. It also increases wastage.

As a remedy to the aforementioned deficiencies, the adaptation:

1. Introduces spring that replaces weight of Impulse Valve to:
    a. fasten closure time of the pump and hence increase its delivery height;
    b. make the pump fit to different flow and terrain conditions and widen the range of application of the Pump; and
    c. replace significant weight of the impulse valve.

2. Introduces adaptors that enable the Pump to be fit to Drive Pipes and delivery pipes of varying sizes (the other requirement to make the pump fit for different flow and terrain conditions).

3. Uses square or rectangular sections throughout the pump production. Square (rectangular) plates could be cut with relative simplicity and with almost no wastage.

6.3 Model Pump

A model pump is considered for the analysis. The main body of the model pump is a 10 cm by 10 cm rectangular hollow section (RHS), fed by a 50 mm and 80 mm drive pipes. The pump has an impulse valve of dimensions 8 cm (width) and 10 cm (height). To reduce the effect of separation due to divergence, and to facilitate smooth flow transition, a tapering section is provided between the drive pipe and the body of the pump (Figure 6.1).

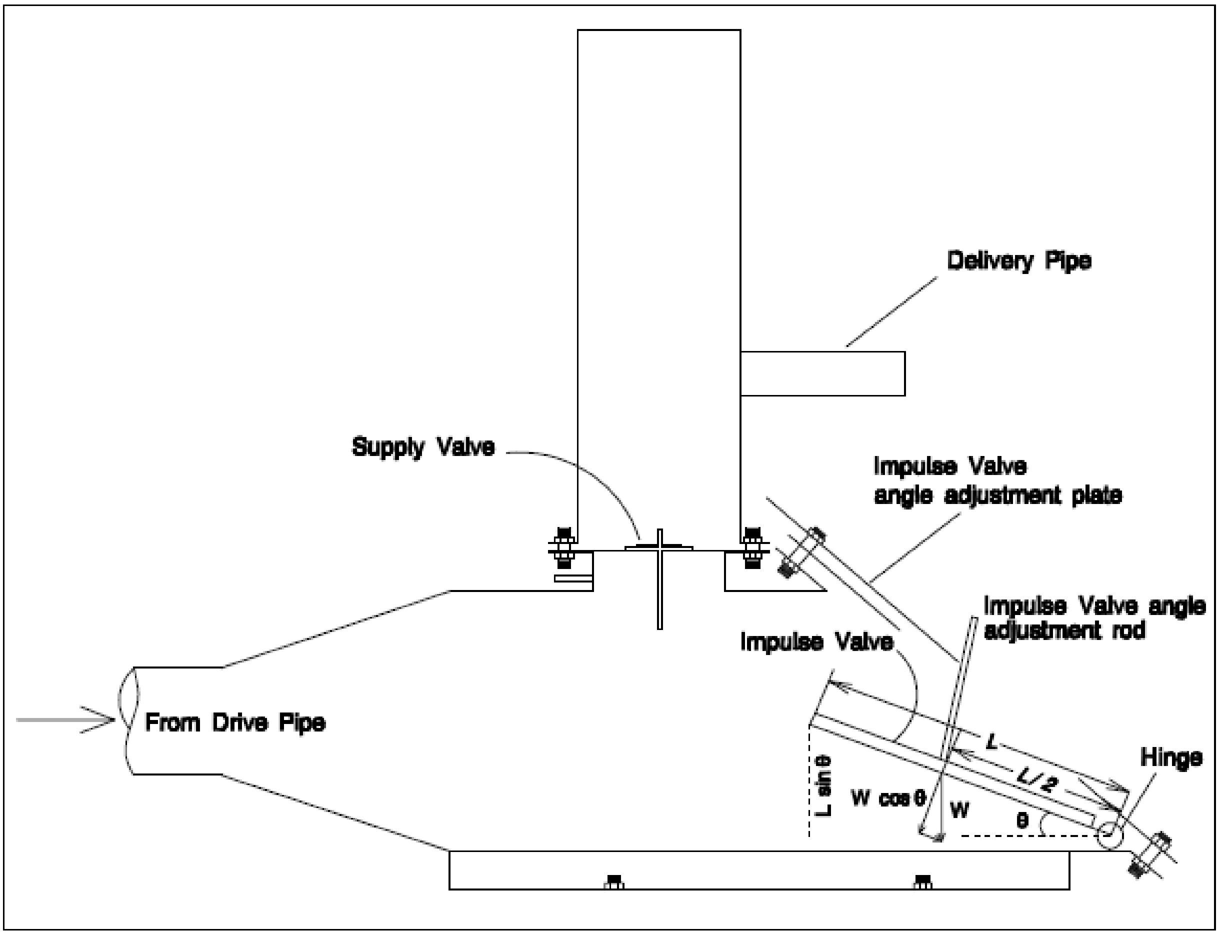

Figure 6.1: Partial section of typical Hydraulic Ram Pump model

6.3.1 Design of Drive Pipe Adapter

One of the operational requirements of hydraulic ram pump is flow from driver pipe to main body of the pump. Driver pipe can at most assume equal size as that of main body of the pump. In most of the cases drive pipe size is less than the size of main body of the pump. The difference in size causes change of velocity. If it is not properly streamlined, sudden expansion of conveyance causes flow separation that forms eddies which results in head loss. To mitigate the formation of flow separation, a transition zone, that smoothly connects the drive pipe with main body of the pump is required. Such provision, though not for very same purpose, is equivalent to a diffuser. A diffuser is an expansion intended to reduce velocity in order to recover pressure head of a flow [51].

A complete stability map of a diffuser flow patterns was published by Fox and Kline in 1962 [52 quoted in 51]. Figure 6.2 shows that there are four basic regions. A transition that fall on the region below line $a - a$ is a steady viscous flow with no separation. Region between lines $a - a$ and $b - b$ is for transitory stall with strongly unsteady flow. The region between $b - b$ and $c - c$ is a region of bistable steady stall. The region above $c - c$ is a state of jet flow.

From Figure 6-2 (b), it is seen that a flow separates if its half-angle is greater than 10. For the case at hand, where size of the drive pipe is 50 mm and dimension of main body of the pump is 100 by 100 square millimeter, the shortest transition/tapering length T is computed as follows.

First trial: Calculate the required length L by taking the half-angle to be 10° ($2\theta = 20°$). The half-angle to be 10°, the $T\ /\ W_1$ ratio need be 1. The 141.8 value of T, however, gives an $T\ /\ W_1$ ratio of 2.82. So second trial is required.	$T = \frac{[100-(2*25)]/2}{\tan(\frac{20}{2})} = 141.8$
Second trial: For a $T\ /\ W_1$ ratio of 2.82, the 2θ value is read to be 15°. For a θ value of 7.5°, T becomes 190 mm. For 190 mm, $T/\ W_1$ becomes 3.78 (different from 2.82). So third trial is required	$T = \frac{[100-(2*25)]/2}{\tan(\frac{15}{2})} = 190$
Third trial: For 3.78 value of $T/\ W_1$, the 2θ value is read to be 13.1°. For a θ value of 6.5°, T becomes 219 mm. For 219 mm, $T/\ W_1$ becomes 4.4. (different from 3.78). So fourth trial is required.	$T = \frac{[100-(2*25)]/2}{\tan(\frac{13}{2})} = 219$
Fourth Trial: For 4.4 value of $T/\ W_1$, the 2θ value is read to be 12.23°. For a θ value of 6.1°, T becomes 234 mm. For 234 mm, $T/\ W_1$ becomes 4.7 (different from 4.4). So fifth trial is required.	$T = \frac{[100-(2*25)]/2}{\tan(\frac{12}{2})} = 234$
Fifth Trial: For 4.7 value of $T/\ W_1$, the 2θ value is read to be 11.88°. For a θ value of 5.94°, T becomes 240 mm. For 240 mm, $T/\ W_1$ becomes 4.8 (different from 4.7). So sixth trial is required.	$T = \frac{\frac{[100-(2*25)]}{2}}{\tan(\frac{11.9}{2})} = 240$
Sixth Trial: For 240 mm, $T/\ W_1$ becomes 4.8. For 4.8 value of $T/\ W_1$, the 2θ value is read to be 11.2°. For a θ value of 5.6°, T becomes 255 mm. For 255 mm, $T/\ W_1$ becomes 5.1 (different	$T = \frac{[100-(2*25)]/2}{\tan(\frac{11.2}{2})} = 255$

from 4.8). So seventh trial is required	
Seventh Trial: For 255 mm, T/W_1 becomes 5.1. For 5.1 value of T/W_1, the 2θ value is read to be 11.2° (similar T/W_1 value, and similar angle with the previous trial). The trial can be stopped here.	So practically, one can take a half-angle of 5.5° for which 2θ becomes 11° and the corresponding T/W_1 ratio is 5.1, and transition length L of 30 cm.

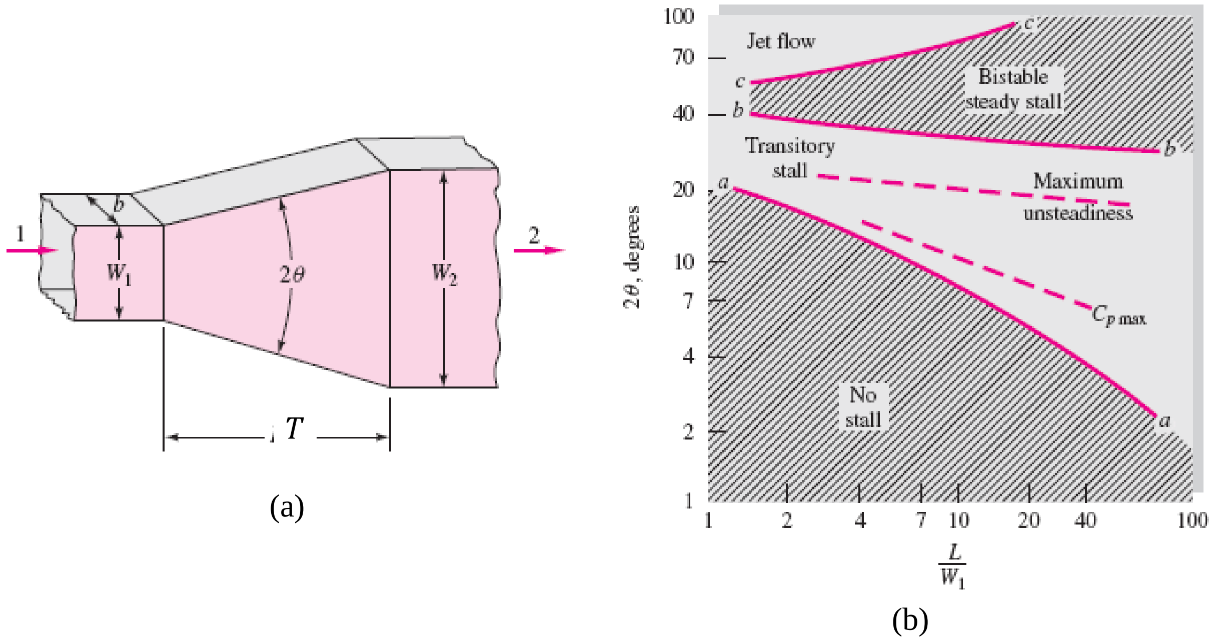

Figure 6.2: Flat diffuser stability map. Source: [52, quoted in 51]

The result is in agreement with the region for minimum loss 5°< 2θ< 15°, which is the best geometry for an efficient diffuser [51]. ASME (American Society of Mechanical Engineers) makes the lower boundary 7° [53]

6.3.2 Development of Flow in Drive Pipe

The time for flow to become established in a Drive Pipe when the Impulse Valve is opened, at every start of the pumping cycle, can be handled by employing Newton's second law [54]. For a drive pipe of diameter D, length L, angle of inclination (with the horizontal) of θ,and elevation difference(between the inlet to the Drive Pipe and body of the Pump) of H, the motion isgoverned by Equation 6.1.

$$\rho\frac{\pi d^2}{4}gH-\left(f\left(\frac{L}{d}\right)(\rho\frac{\pi d^2}{4}v^2)/2\right)=\rho\frac{\pi d^2}{4}L\frac{dv}{dt}$$	*Eqn. 6.1*

Putting A in place of $\frac{\pi d^2}{4}$, using the relationship $\gamma = \rho g$ and rearranging gives	
$$\gamma A\left(H - f\frac{L}{D}\frac{v^2}{2g}\right) = \frac{\gamma AL}{g}\frac{dv}{dt}$$	

Where:			
ρ=	Mass density of water	v=	The velocity at time t
γ=	Unit weight of water	A=	Area of the pipe
H=	Elevation difference between the inlet and body of the pump	L=	Length of the pipe
f=	Friction factor	g=	Acceleration due to gravity
L=	Effective length of the pipe that takes care of friction	$\frac{dv}{dt}$=	Acceleration of flow
d=	Diameter of the pipe		

Solving Equation 6.1 for *dt* and integrating both sides yields Equation 6.2

$$\int_0^t dt = \frac{Lv_o^2}{gH}\int_o^V \frac{dv}{v_o^2 - v^2}$$	*Eqn.6.2*
Where:	
v_o=	Steady state velocity

The left hand side of Equation 6.1 is the net force acting on the column of water in the drive pipe - gravitational force less friction force. The right hand side is the multiplication of mass of the water column in the drive pipe with its acceleration. The term subtracted from $\boldsymbol{H}$, in the bracket, is the friction force.

Performing the integration on Equation 6.2 results in Equation 6.3

$$t = \frac{Lv_o}{2gH} ln\frac{v_o + v}{v_o - v}$$	*Eqn.6.3*

As seen from the expression ($f\frac{L}{D}\frac{v^2}{2g}$) in Equation 6.1, the friction force is proportional to the velocity. This means acceleration decreases as velocity increases which leads to asymptotic approach of the velocity to the steady state condition given by Equation 6.4

$$v_{steady} = \sqrt{\frac{2gHd}{fL}}$$	*Eqn.6.4*

At steady state, the gravitational head fully balances losses (Equation 6.5).

$$H = \frac{fLv_{steady}^2}{2gd}$$	*Eqn.6.5*

For simplicity of analysis, without compromising the main area of focus, if we assume that the pipe is frictionless, the steady state velocity is governed by Torriceli's Law [55] and the velocity at time *t* can be written as Equation 6.6.

$$v(t) = g\frac{H}{L}t$$	*Eqn.6.6*

The Drive Pipe does not run vertical. It is installed at an angle with the horizontal. The water in it, therefore, travels longer than the (vertical) height. This lengthens the duration of flow in the Drive Pipe. The time required for full development of the flow in the Drive Pipe is given by Equation 6.7

$$T = \sqrt{\frac{2L^2}{gH}}$$	*Eqn. 6.7*
Where:	
$L=$	Length of the Drive Pipe
$g=$	Gravitational acceleration
$H=$	Level difference between the source and the pump

If the impulse valve starts closing earlier than the time given by Equation 6.7, then the velocity does not attain the maximum velocity that can be obtained from the given height, which means that the potential (energy) from the given location/site is not fully exploited.

Mechanics of the impulse valve that enables full exploitation of the potential is its proportional resistance to the moment caused by the drag force from the fully developed flowing water. This resistance is a function of weight of the impulse valve and its inclination angle with the horizontal (Figure 6.1)

6.3.3 Velocity Profile in Body of the Pump

Velocity of flowing water in a pipe is not uniform across a section. Around the wall, it takes zero value and increases towards the center. The velocity value we get from Torricelli Equation is only the average velocity. Velocity distribution across section of a pipe is to be worked out.

The velocity profile of a flowing water in a rectangular pipe can fairly be approximated by Prandtl power-law velocity profile developed for circular pipes [56]. The Prandtl power-law velocity profile formula for circular pipe is given by Equation 6.8 [57].

$$\frac{u}{u_{max}} = \left(1 - \frac{r}{R}\right)^{\frac{1}{n}}$$	*Eqn. 6.8*
Where:	
u=	Velocity at any distance *r* from center of the pipe
r=	distance from center of the pipe where u_r is computed
u_{max}=	Maximum velocity (at the center of the pipe)
R=	Radius of the pipe
n=	A constant

In a rectangular section of width *W* and height *H,* with origin of the coordinate at the center of the rectangle, velocity profile can be mapped using Equation 6.9 or 6.10.

$$u(w,h) = u_{max}\left(1 - \left(\frac{w}{0.5W}\right)\right)^{\frac{1}{n}}\left(1 - \left(\frac{h}{0.5H}\right)\right)^{\frac{1}{n}}$$	*Eqn. 6.9*
or	
$$u(w,h) = u_{max}\left(1 - \left(\frac{w}{0.5W}\right)^2\right)^{\frac{1}{n}}\left(1 - \left(\frac{h}{0.5H}\right)^2\right)^{\frac{1}{n}}$$	*Eqn. 6.10*
Where:	
$u(w,h)$ =	Velocity at point *w* and *h* units far from the center
W and H =	The width and height of the rectangular section
u_{max}=	Maximum velocity (at the center)

The value of *n* depends on the Reynolds's number, *Re,* of the fluid, water in this case. Experimental values for different *r/R* and u/u_{max} values are plotted on half of the section, to give the profiles shown in Figure 6.3.

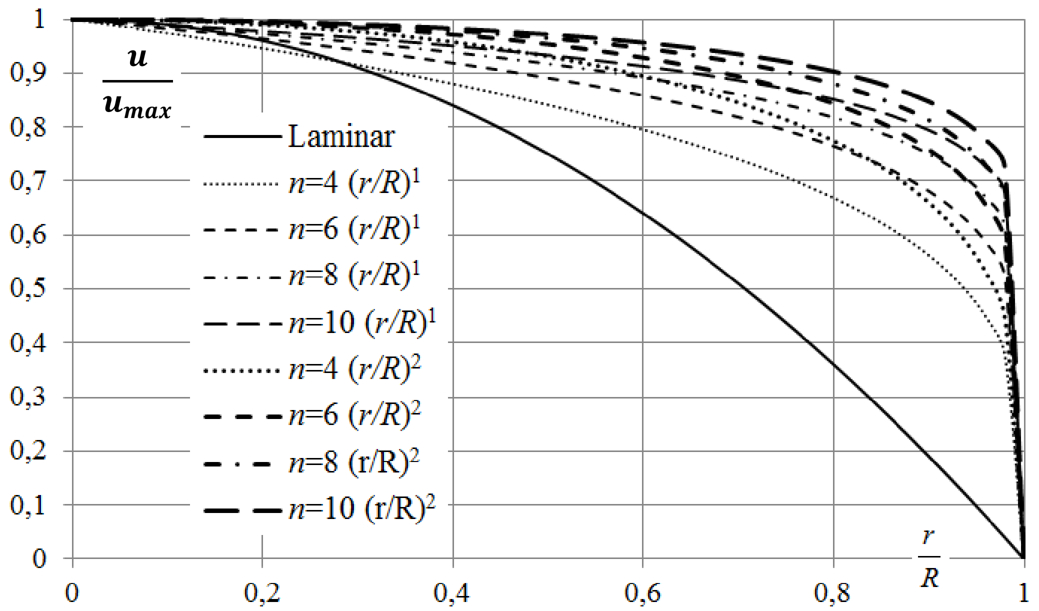

Figure 6.3: Velocity distribution for fully developed flow in circular pipe, for different values of n, and (r/R) exponent values of 1 and 2 [57].

From Figure 6.3, it is seen that as the n value increases, the profile gets flatter. With same n value, the profile is flatter for an r/R exponent value of 2, as compared to 1. Flatter profile is the characteristics of more developed turbulent flow. As the turbulence develops the profile gets flatter.

In Hydraulic Ram Pump, transition to and the flow conditions in the body of the pump are conducive for turbulence. Expansion at the inlet from the drive pipe to main body of the pump, cyclic rapid closure and opening of the Impulse Valve, cause rapid changes in velocity and makes the flow unsteady. The exit velocity increases as the Impulse Valve closes. Closure of the impulse valve causes the water to compress and generate a surge wave. This kind of transient, flow causes turbulence. However, the turbulence cannot be fully developed, as it does not get sufficient distance. The flow can, therefore, be considered as partially developed turbulent. The profile that is obtained by putting an n value of 4 and an exponent value for *r/R* of 2 is chosen to be a reasonable approximation. So, Equation 6.10 is used with an n value of 4 (Equation 6.11).

$u(w,h) = u_{max}\left(1-\left(\frac{w}{0.5W}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{h}{0.5H}\right)^2\right)^{\frac{1}{4}}$	*Eqn. 6.11*

The velocity we get from Equation 6.6 is average velocity. The velocity-profile-equation (Equation 6.10) is given in terms of the maximum velocity. Equation 6.11 is, therefore, to be written in terms of the average velocity. The average velocity is calculated by integrating

Equation 6.10 across sectional area of body of the pump and dividing it by same area (Equation 6.12).

$$u_{avg.} = \frac{\int_{-0.05}^{+0.05}\int_{-0.05}^{+0.05} u_{max}\left(1-\left(\frac{w}{0.5W}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{h}{0.5H}\right)^2\right)^{\frac{1}{4}} dwdh}{\int_{-0.05}^{0.05}\int_{-0.05}^{0.05} dwdh}$$	*Eqn. 6.12*

The results obtained are shown in Equation 6.13.

$u_{avg} = 0.76u_{max}$	*Eqn. 6.13*
or	
$u_{max} = 1.31u_{avg}$	

The Code used to calculate the maximum velocity in terms of the average velocity is given in Table 6.1.

Table 6.1: Python code used to compute the average velocity in terms of maximum velocity for a 100 by 100 mm square pipe.

```
# Code to write the maximum velocity in terms of the average velocity

import numpy as np

from scipy.integrate import dblquad

# Constants

W = 0.1

H = 0.1


# Define the integrand function

def integrand(h, w, u_max):

    return u_max * ((1 – (w / (0.5 * W))**2)**(1/4) * (1 – (h / (0.5 * H))**2)**(1/4))

# Define the limits of integration

w_lower = -0.05

w_upper = 0.05

h_lower = -0.05
```

```
h_upper = 0.05

# Function to calculate u_avg for any u_max

def calculate_u_avg(u_max):

    # Perform the double integration

    numerator, _ = dblquad(integrand, w_lower, w_upper, lambda w: h_lower, lambda w: h_upper,
args=(u_max,))

    # Calculate the denominator (area of the integration region)

    denominator = (w_upper – w_lower) * (h_upper – h_lower)

    # Calculate u_avg

    u_avg = numerator / denominator

    return u_avg

# Example usage

u_max_value = 10  # Replace this with any value of u_max

u_avg = calculate_u_avg(u_max_value)

print(f”For u_max = {u_max_value}, u_avg = {u_avg}”)
```

The velocity profile in terms average velocity is obtained by combining Equations 6.11 and Equation 6.13. The combination results in Equation 6.14

$$u(w,h) = 1.31u_{avg}\left(1-\left(\frac{w}{0.5W}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{h}{0.5H}\right)^2\right)^{\frac{1}{4}} \qquad \textit{Eqn. 6.14}$$

The velocity profile equation (Equation 6.14) is formulated by taking the origin at the center of the pipe. Such convention may have a problem of nullifying sign-sensitive Figures (such as moments), and giving erroneous results when integrations are computed as the limits of integration may range from negative to positive.

In order to avoid such problems, Equation 6.14 is re-written by transforming its origin to bottom-left corner. Such transformation yields Equation 6.15. Equation 6.15 is checked to obey all conditions obeyed by Equation 6.14 such as zero boundary and maximum central velocities.

$$u(w,h) = 1.31u_{avg}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}$$	*Eqn. 6.15*

The velocity profile plotted using Equation 6.15 for a square pipe of dimensions 10 cm by 10 cm (and for maximum velocity of 5 m/sec in the 50 mm diameter drive pipe) is shown in Figure 6.4. The Python code used to convert Equation 6.15 to plotting is depicted in Table 6.2 When the flow in the 50 mm diameter pipe enters the 100 by 100 mm square body of pump, its velocity is reduced proportional to the area ratio (0.196). This changes the constant 1.31 to 0.257 (Equation 6.16)

$$u(w,h) = 0.257u_{avg}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}$$	*Eqn. 6.16*

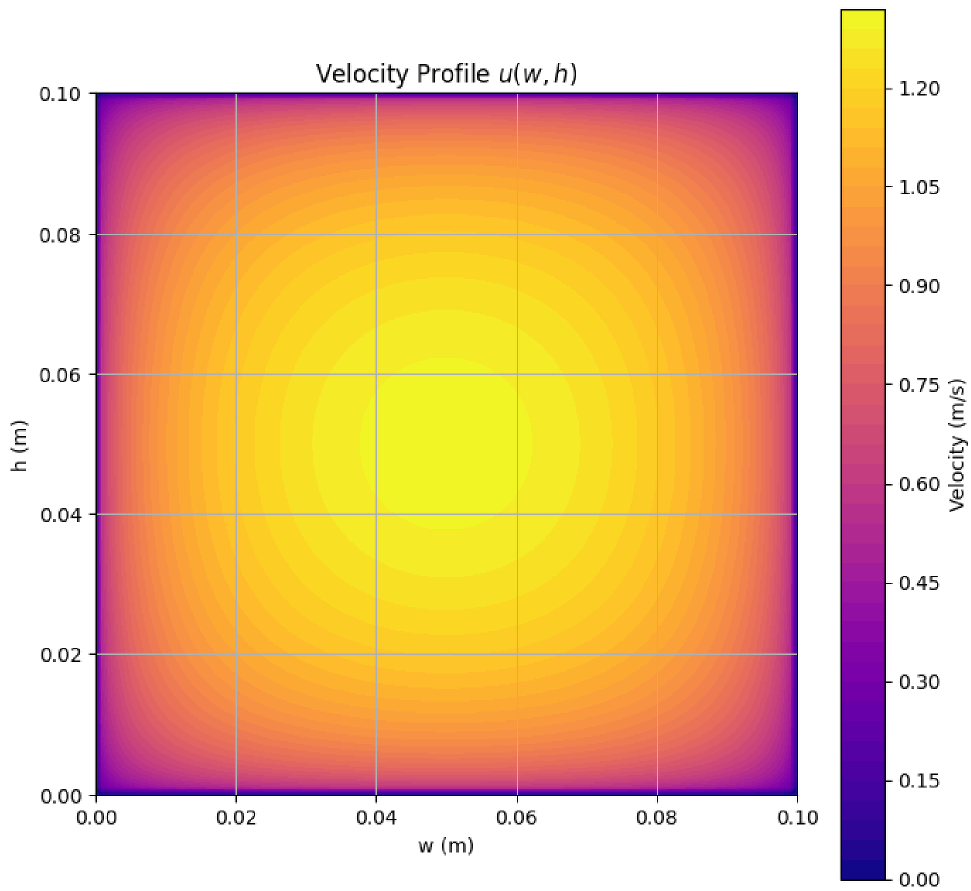

Figure 6.4: Water flow velocity profile in square pipe (100 by 100 mm)

Table 6.2: Python code for flow velocity profile plotting in square pipe (100 by 100 mm, connected to 50 mm diameter drive pipe.

```
# Velocity Profile with adjusted coordinate points and ^2

import numpy as np

import matplotlib.pyplot as plt

def velocity_profile(w, h, u_avg):

    “””Calculate the velocity based on the provided w and h.”””

    term_w = 1 – ((0.05 – w) / 0.05) ** 2

    term_h = 1 – ((0.05 – h) / 0.05) ** 2

    # Ensure that we don’t take the fourth root of negative numbers

    term_w = np.where(term_w < 0, 0, term_w)

    term_h = np.where(term_h < 0, 0, term_h)

    return 0.257 * u_avg * (term_w ** (1 / 4)) * (term_h ** (1 / 4)) #it was 1.31 before changed. To take care of
the expansion form 50 mm dm to 100 by 100

# Parameters

u_avg = 5.0  # Average velocity (you can adjust this as needed)

w_values = np.linspace(0, 0.1, 100)  # Range for w (0 to 0.1)

h_values = np.linspace(0, 0.1, 100)  # Range for h (0 to 0.1)

# Create a meshgrid for w and h values

W, H = np.meshgrid(w_values, h_values)

# Calculate velocity for each combination of w and h

U = velocity_profile(W, H, u_avg)

# Plotting

plt.figure(figsize=(8, 8))  # 8x8 to maintain a square aspect ratio

contour = plt.contourf(W, H, U, levels=50, cmap=’plasma’)  # Change cmap to ‘plasma’ for better contrast

plt.colorbar(contour, label=’Velocity (m/s)’)

plt.title(‘Velocity Profile $u(w,h)$’)

plt.xlabel(‘w (m)’)

plt.ylabel(‘h (m)’)

plt.xlim([0, 0.1])

plt.ylim([0, 0.1])

plt.gca().set_aspect(‘equal’, adjustable=’box’)  # Set equal aspect ratio

plt.grid(True)

plt.show()
```

The velocity profile across longitudinal section, at horizontal center of main body of the pump, for different maximum velocities can be plotted using Equation 6.15 by setting the values of both w and h to 0.05 (Figure. 6.5)

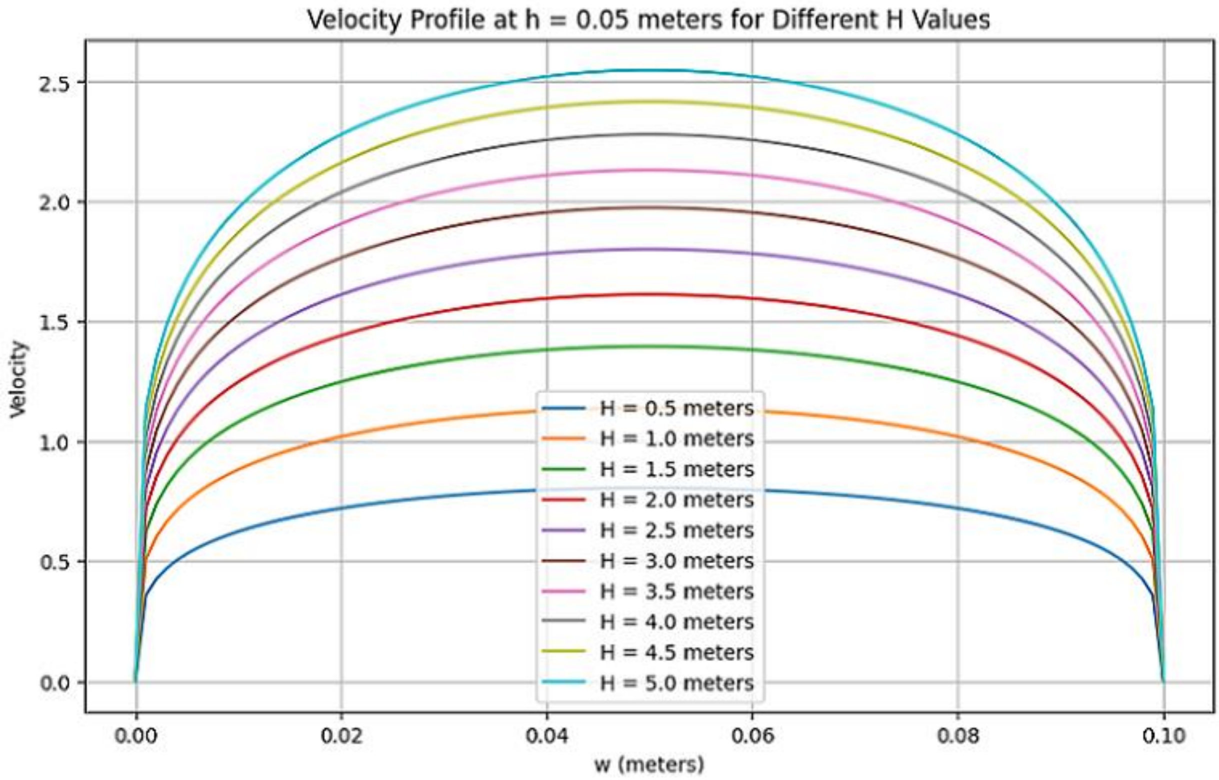

Figure 6.5: Free stream velocity profile along a longitudinal axis at the horizontal center of body of the pump for different values of H

The average velocity of flow u'_{avg} that acts on the vertically projected area of the Impulse Valve, which covers only partial sectional area of the body of the pump, is different from the average velocity for the full sectional area. u'_{avg} is computed by Equation 6.17. Equation 6.17 is formulated by summing up the velocities at every spot in the range of the vertically projected area and dividing it by area of the projection.

$$u'_{avg} = \frac{\int_0^{h\_max}\int_0^{0.1} 1.31u_{avg}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}} dwdh}{\int_0^{h\_max}\int_0^{0.1} dwdh}$$		*Eqn. 6.17*
Where:		
h_max=	The level in the main body of the pump where the vertical projection of the impulse valve reaches	

By: a) replacing $\sqrt{2gH}$ in place of u_{avg}; b) putting $0.1sin\theta$ in place of h_max; and c) introducing the factor of velocity reduction (0.19625) when flow enters from 50 mm diameter drive pipe to 100 by 100 mm square pump body, Equation 6.17 is rewritten as Equation 6.18.

$$u'_{avg} = \frac{\int_0^{0.1sin\theta} \int_0^{0.1} 1.139\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}} dwdh}{\int_0^{0.1sin\theta} \int_0^{0.1} dwdh} \quad \textit{Eqn. 6.18}$$

Table 6.3 compares the velocity for different fall heights and the partial average, V-avg.' (average velocity for the vertical projection of the impulse valve). Average velocity of the full sectional area is equal to the velocity obtained using Torriceli's Equation. The Table (Table 6.3) shows the comparison between velocity obtained from given fall heights and average of the velocity profile that matches with the vertical projection of the impulse valve.

Table 6.3: Comparisons between average velocities of flow across the full section versus projected area of the impulse valve (for flow that enter from 50 mm diameter drive pipe to 100 by 100 mm square pipe pump body)

Fall Height (m)	V-avg. = $\sqrt{2gH}$ (In drive pipe) (m/sec)	V-avg. in pump body (m/sec)	Angle (in degrees)				
			10	15	20	25	30
			h_max – vertical projection of the impulse valve for different angles (m)				
			0.0174	0.026	0.034	0.042	0.05
			V-avg.' (m/sec)	V-avg.' (m/sec)	V-avg.' (m/sec)	V-avg.' (m/sec)	V-avg.' (m/sec)
0.5	3.13	0.62	0.50	0.55	0.58	0.60	0.62
1	4.43	0.87	0.71	0.77	0.82	0.85	0.87
1.5	5.42	1.07	0.87	0.95	1.00	1.04	1.07
2.0	6.26	1.23	1.00	1.09	1.15	1.20	1.23
2.5	7.00	1.38	1.12	1.22	1.29	1.34	1.38
3.0	7.67	1.51	1.23	1.34	1.41	1.47	1.51
3.5	8.29	1.63	1.33	1.44	1.53	1.59	1.63
4.0	8.86	1.74	1.42	1.54	1.63	1.69	1.74
4.5	9.40	1.85	1.50	1.64	1.73	1.80	1.85
5.0	9.90	1.95	1.58	1.73	1.82	1.90	1.95

Note: The angle s are measured clockwise with the horizontal

The Code used for the computation is rendered in Table 6.4.

Table 6.4: Python Code used to compare average velocity on the impulse valve against average velocity across the section for different values of theta.

```
# Code to compute u_max, u_avg, u_avg_prime and plot same against H
import numpy as np

from scipy.integrate import dblquad

import matplotlib.pyplot as plt

# Constants

H_values = [0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5]  # Height values in meters

theta_values = [5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90]  # Angles in degrees

# Define the integrand function

def integrand(h, w, H):

    return 1.139 * np.sqrt(H) * ((1 – ((0.05 – w) / 0.05)**2)**(1/4)) * ((1 – ((0.05 – h) / 0.05)**2)**(1/4))

# Function to calculate velocity at specific w and h

def velocity_at_w_h(w, h, H):

    return 1.139 * np.sqrt(H) * ((1 – ((0.05 – w) / 0.05)**2)**(1/4)) * ((1 – ((0.05 – h) / 0.05)**2)**(1/4))

# Function to calculate u_avg

def calculate_u_avg(H):

    # Define the limits of integration

    w_lower = 0

    w_upper = 0.1

    h_lower = 0

    h_upper = 0.1

    # Perform the double integration

    numerator, _ = dblquad(integrand, w_lower, w_upper, lambda w: h_lower, lambda w: h_upper, args=(H,))

    # Calculate the denominator (area of the integration region)

    denominator = (w_upper – w_lower) * (h_upper – h_lower)

    # Calculate u_avg

    u_avg = numerator / denominator

    return u_avg
```

```
# Function to calculate u_avg_prime
def calculate_u_avg_prime(H, theta):
    # Convert theta from degrees to radians
    theta_rad = np.deg2rad(theta)
    # Define the limits of integration
    w_lower = 0
    w_upper = 0.1
    h_lower = 0
    h_upper = 0.1 * np.sin(theta_rad)
    # Perform the double integration
    numerator, _ = dblquad(integrand, w_lower, w_upper, lambda w: h_lower, lambda w: h_upper, args=(H,))
    # Calculate the denominator (area of the integration region)
    denominator = (w_upper – w_lower) * (h_upper – h_lower)
    # Calculate u_avg_prime
    u_avg_prime = numerator / denominator
    return u_avg_prime
# Task 1: Velocity at w = 0.05 and h = 0.05
w = 0.05
h = 0.05
u_max_values = []
for H in H_values:
    velocity = velocity_at_w_h(w, h, H)
    u_max_values.append(velocity)
    print(f"For H = {H} meters, velocity at w = 0.05 and h = 0.05 = {velocity}")
# Task 2: Compute u_avg for all H values
print("\nTask 2: u_avg for all H values")
u_avg_values = []
```

```
for H in H_values:
    u_avg = calculate_u_avg(H)
    u_avg_values.append(u_avg)
    print(f”For H = {H} meters, u_avg = {u_avg}”)

# Task 3: Compute u_avg_prime for all H and theta values
print(“\nTask 3: u_avg_prime for all H and theta values”)
results = {}
for H in H_values:
    results[H] = {}
    for theta in theta_values:
        u_avg_prime = calculate_u_avg_prime(H, theta)
        results[H][theta] = u_avg_prime
        print(f”For H = {H} meters and theta = {theta} degrees, u_avg_prime = {u_avg_prime}”)

# Plotting
plt.figure(figsize=(18, 6))

# Plot 1: H vs u_max
plt.subplot(1, 3, 1)
plt.plot(H_values, u_max_values, marker=’o’, linestyle=’-‘, color=’b’)
plt.xlabel(‘H (meters)’)
plt.ylabel(‘u_max’)
plt.title(‘H vs u_max’)
plt.grid()

# Plot 2: H vs u_avg
plt.subplot(1, 3, 2)
plt.plot(H_values, u_avg_values, marker=’o’, linestyle=’-‘, color=’r’)
plt.xlabel(‘H (meters)’)
plt.ylabel(‘u_avg’)
plt.title(‘H vs u_avg’)
```

```
plt.grid()

# Plot 3: H vs u_avg_prime for different theta values

plt.subplot(1, 3, 3)

for theta in theta_values:

    u_avg_prime_values = [results[H][theta] for H in H_values]

plt.plot(H_values, u_avg_prime_values, marker='o', linestyle='-', label=f'theta={theta}°')

plt.xlabel('H (meters)')

plt.ylabel('u_avg_prime')

plt.title('H vs u_avg_prime for different theta values')

plt.legend()

plt.grid()

plt.tight_layout()

plt.show()
```

From the Table (Table 6.3), it is seen that till the valve angle reaches 30°, V-avg.’ is less than V-avg. At 30°, V-avg. equals V-avg.’. This is because sine of 30° degree is 0.5 and the projected area of the impulse valve for that angle covers the bottom half of body of the pump, and from symmetry, the average for the lower half equals the average for the whole section. From 30° to 50°, V-avg.’ increases. Beyond 50°, V-avg.’ starts decreasing, but very slightly. At 90 degree (where the sine value is one), again V-avg. equals V-avg’. Figure 6.6 shows variation of V-avg.’ for an H value of 2 meters. From the Figure (6.6), it can be seen that V-avg’ equals V-avg at two angles (30° and 90°).

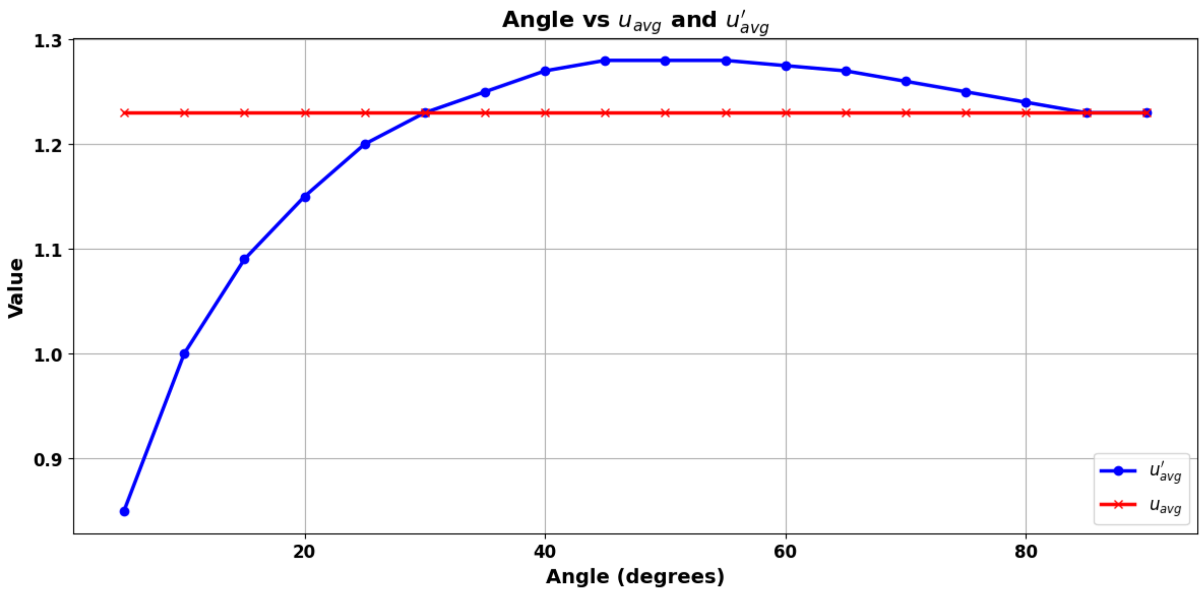

Figure 6.6: u-avg'and u-avg for *H*=2.0 meters

The pattern of variation of u_max (maximum velocity), u_avg (average velocity for the full section), and u_avg' (average velocity for the bottom partial sections that overlap with vertical projection of the impulse valve) are shown in Figures 6.7 to 6.9. From the Figures, it is seen that all velocities have similar pattern of variation

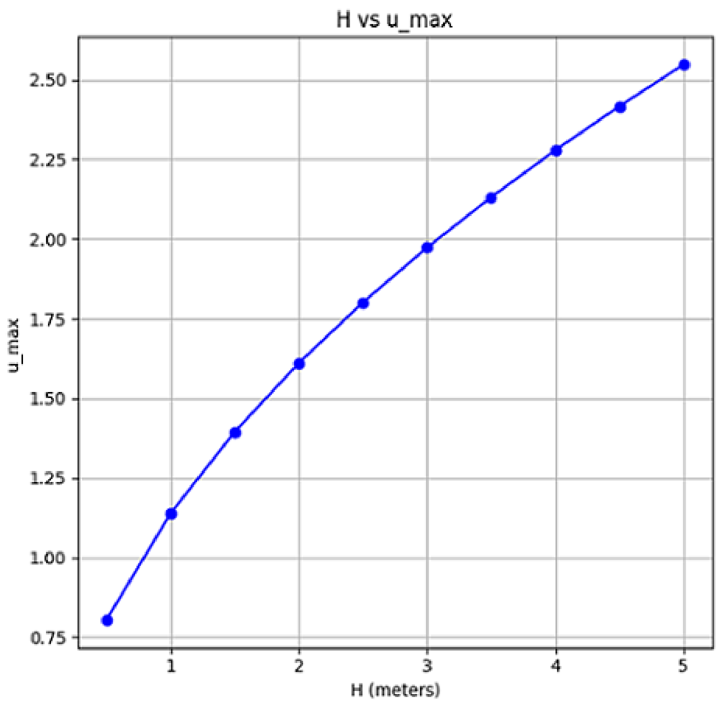

Figure 6.7: u_max (maximum velocity in the main body of the pump) versus *H* graph

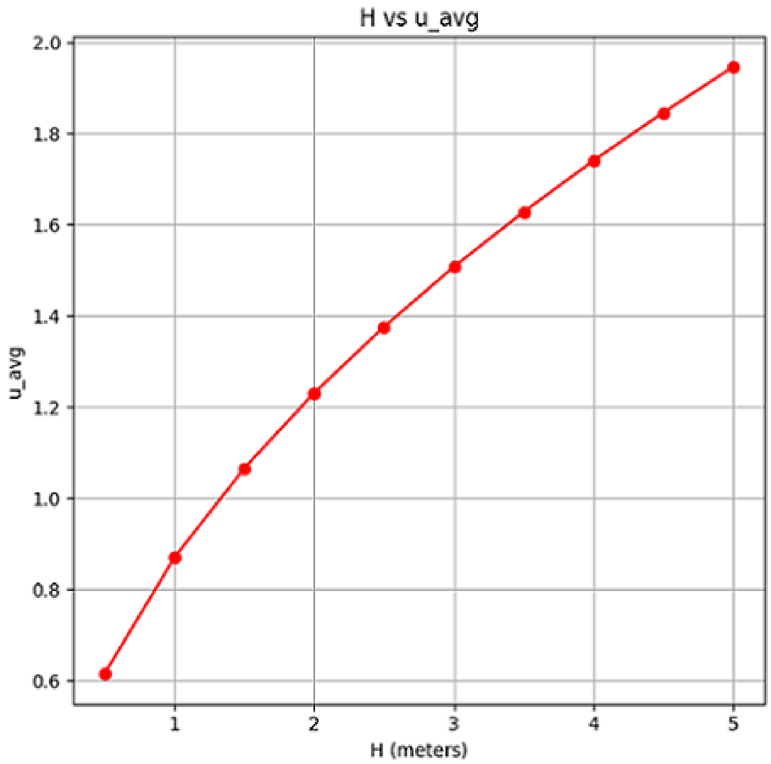

Figure 6.8: u_avg (average velocity in the main body of the pump) versus *H* graph

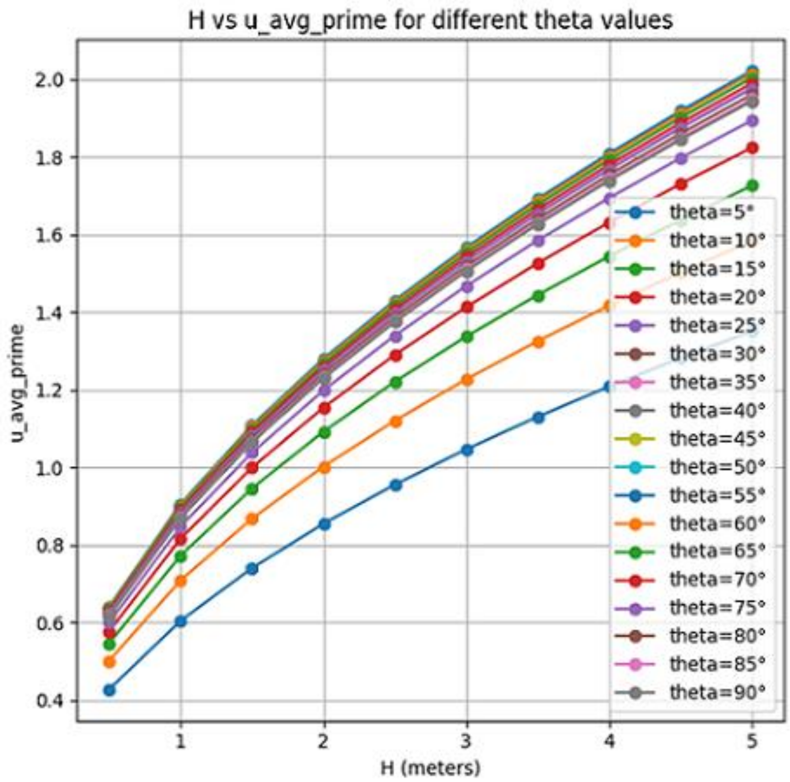

Figure 6.9: u_avg_prime (average velocity in the main body of the pump for the section that overlaps with vertical projection of the impulse valve) versus *H* graph

6.4 Frame of Comparison

When a hydraulic ram pump is viewed as a division of periods, the actions explained under chapter 3 (3.2.8) can be divided into three main periods: Acceleration period; delivery period; and recoil period. During the acceleration period, water moves from the source to the impulse valve by gravity. The flow in the drive pipe accelerates due to the net head. The acceleration may not be linear due to residual transients from previous pumping cycles propagating in opposite direction and friction resistance which increases with velocity.

The accelerating water reaches such velocity that the drag induced triggers closure of the impulse valve, overcoming its resistance. As the closure of the impulse progresses, the pressure in main body of the pump increases. Laboratory experiments and simulations results show that velocity of flow increases till the valve closes, and initially the pressure increase (in the main body of the pump) is very small, then becomes very high when the valve is fully closed [58]

The pressure rise is caused by conversion of the kinetic energy contained in the flowing water to pressure energy. The conversion is caused by restriction of passage due to closure. Closure of the impulse valve increases pressure in the main body of the pump while narrowing down the exit area which affects the free stream profile.

Following closure of the valve, a pressure wave develops at the surface of the valve and propagates upstream, with a velocity equal to that of sound wave in water (about 1400 meters per second for steel pipe). The pressure wave first reaches at the delivery valve, opens it and pushes water to the air chamber. The pressure continues propagating upstream countering the flow and increasing the pressure in the drive pipe till it reaches at the source (a surface exposed to the atmospheric pressure). Then a flow starts the opposite direction as the induced pressure is in the drive pipe is higher. This flow releases the pressure in the pipe. The release propagates back downstream and reaches the impulse valve. At this instant, the pressure normalizes. When the wave is reflected back upstream, it induces a flow away from the impulse valve. This flow (known as recoil) creates sub-atmospheric pressure that triggers opening of the impulse valve that ends the cycle. When the pressure in the main body of the pump parallels the pressure in the air chamber, the delivery valve closes. Flows and/or waves that move up and down stream may interfere with one another. Such interferences have high impact on performance of hydraulic ram pumps. The best performance is obtained through tests with varying parameters.

The aforementioned brief discussion hints that the flow in hydraulic ram pump is rather complex. On the other hand, the theory of drag (that is mainly used to study the performances of impulse and delivery valves) is weak and inadequate, except for flat plate (laid parallel to the flow direction). This is because of flow separation. Boundary layer theory can predict the separation point but cannot accurately estimate the (usually low) pressure distribution in the separated region. The difference between the high pressure in the front stagnation region and the low pressure in the rear separated region causes a large drag contribution called pressure drag. The knowledge of strong interaction between blunt-body viscous and inviscid layers is not also well developed [51]. Plate valve with rectangular vertically projected are is considered as blunt body.

For modeling, therefore, there comes a need to take simplifying assumptions without highly compromising results expected from comparisons. The following assumptions have been considered while working on the adaptation.

1. *Friction and other losses are disregarded*: It is hardly possible to model the different forms of friction for varying operation conditions of hydraulic ram pump. As comparisons are made between two exactly similar setups, except introduction of spring to dominantly replace weight of impulse valve, nullifying the effect of friction does not affect the result of comparison.

2. *Maintaining the free stream velocity distribution*: Investigation made on flow pattern in a hydraulic ram pump at various designs and settings of its waste valve [59] on a pump with circular, floating, gravity valve which fits concentrically to the vertically oriented circular main body/casing shows that the flow demonstrates even distribution of velocity near closed position. For the case at hand, when the valve approaches closed position, the outlets are restricted around the valve in three directions (the gaps on the left and right hand side and gap at the top). This has resemblance with the model being studied with two differences; the geometry of the pipe under consideration is square and has the openings only on three sides – left, right, and top. The velocity profile in the square pipe is approximated by the partially developed turbulent flow (Eqn. 6.11) which exhibits flatter central portion. Due to these similarities, the free stream velocity profile is maintained as basis of comparison.

3. *Drag force is the dominant closing force:* Contribution of the lift force for the closure is not considered. For the following two cases: a) As the bottom side of the valve plate is pinned, no flow is allowed under the valve; b) Near closed position, the valve almost assumes vertical position, with little or no vertical projection.

4. *The influence of confinement on drag force is not considered:* As the angle of the impulse valve with the horizontal increase, the valve covers majority of the cross sectional area of main body of the pump, and causes blockage. Due to this, pattern of the free stream velocity is altered. The flow passing through the valve is confined by the walls of the pump. Flow passes through the clearance between edge of the valve plate and wall of the pump. The situation, therefore, is not similar with the conditions in air tunnel [60]. The blockage effects are significant. However, when based on the velocity in the gap between plate and confining walls, rather than on free stream velocity, the value of C_d is practically constant [61]. As the blockage varies with

closure of the impulse valve, it is very difficult to assign varying drag coefficient. The influence of confinement on drag force is, therefore, not considered.

As all the assumptions are applied for all the comparisons, there will not be bias in the results. The figures obtained, however, may not be taken in the absolute sense. They should only be considered as relative comparison of the alternatives.

6.5 Introduction of Spring to Hydraulic Ram Pump

The working mechanism of a hydraulic ram pump is the automatic, and cyclic, closure and opening of its two valves: impulse valve and delivery valve. The two essentials of a delivery valve are its one way nature and bounded degree of movement. Impulse valve undergoes a number of hydro-mechanical performances that make it play more critical roles, with matching complexities.

One of the vital performances that determine efficiency of a hydraulic ram pump is closure time of its impulse valve. Closure time of impulse valve is considered as one area where the adaptation dwells. The adaptation on closure time is attained by introducing a spring to (a great extent) replace weight of the impulse valve. The process of closure of an impulse valve can be described as below.

1. *Development of water flow in the drive pipe*: When the impulse valve opens, water in the drive pipe accelerates due to gravity.
2. *Drag force on the impulse valve*: While the flow past the impulse valve develops, it exerts drag force on the impulse valve. The magnitude of drag force is proportional to square of flow velocity and drag coefficient of the impulse valve, which mainly depends on its geometry and orientation.
3. *Closure of the impulse valve*: When the drag force is big enough to trigger motion of the impulse valve, the valve starts closing.
4. *Motion triggering velocity*: If an impulse valve with lighter resistance is installed, it starts closing before the flow in the drive pipe develops fully. This means that the full potential of the site is not exploited. The resistance of an impulse valve should, therefore, be big enough to require the full velocity expected from a given fall height.

The aforementioned points reveal that a balanced resistance to closure by the impulse valve is very crucial for efficiency of hydraulic ram pump. The initial resistance is essential and is unavoidable as it is required to exploit full potential of a site (elevation). The effort to improve performance of ram pump, in relation to closure time, need, therefore, focus on manipulation of the resistance load once closure of the valve is triggered. Here it is good to note that, though short closure time considerably augments performance of hydraulic ram pump, the shortest closure time does not necessarily yield the most efficient performance.

To differentiate the two types of valves compared by the adaptation, the one that does not have a spring is named as *weight-only* valve, and the one with spring is called *spring-loaded* valve. The springs are assumed to obey Hook's law.

A few ram pump models have both valve opening and head adjustment provisions. The one in Figure 6.10 (dominantly available) is discussed as a show case.

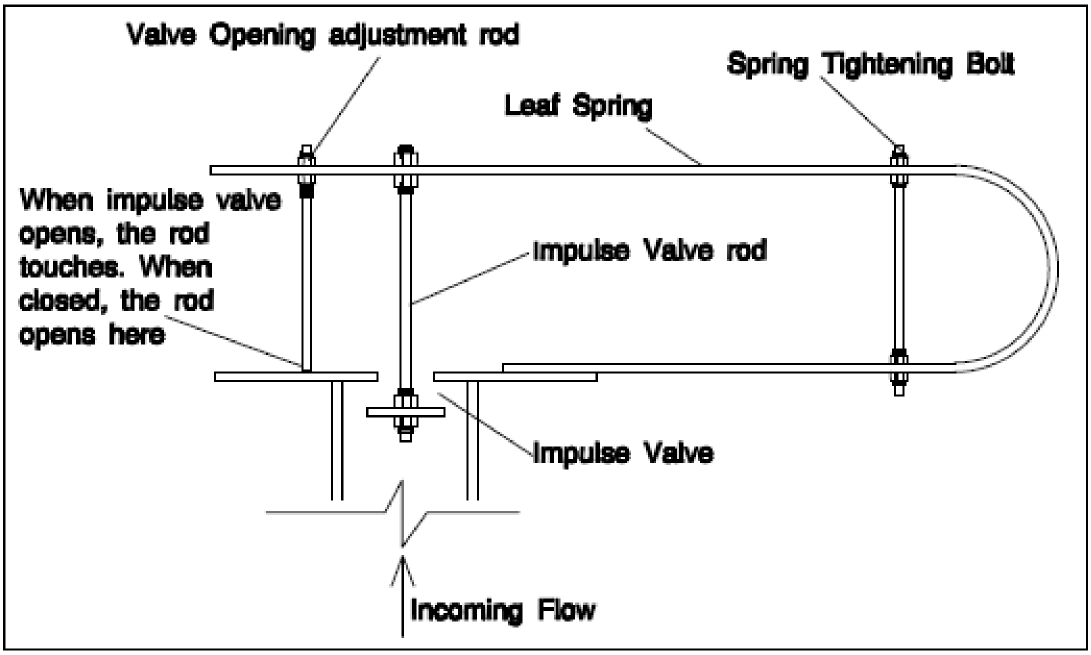

Figure 6.10: Adjustable impulse valve

In the valve opening arrangement of Figure 6.10, when it is required to increase opening of the impulse valve, to allow more flow through the pump, the Valve Opening Adjustment Rod need be shortened by tuning the nuts. When the valve opening adjustment rod is shortened, the impulse valve lowers and its opening widens. Though this arrangement imparts working discharge flexibility to the model, it has the following drawbacks.

a. To widen the opening, in addition to shortening the Valve Opening Adjustment Rod, screwing the Spring Tightening Bolt is required. This induces resistance at the Impulse Valve through the leaf spring, which persists for every position of the valve. The resistance even increases as the valve closes for the leaf spring is further strained. This causes loss of energy in the form of work done on the valve against the spring resistance. The lost energy would otherwise be used to increase the pumping head.
b. The increased valve opening, though makes the pump fit for increased flow conditions, it increases the time with which the valve closes, thereby reducing the magnitude of water hammer effect (pressure hike) in the pump.

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When the pump is to be used in an increased head, the load on the leaf spring is increased by tuning the Spring Tightening Bolt. This induces the required drag resistance to the Valve so that the impulse valve responds to the available pressure head, i.e., closure of the valve is triggered by the increased head. It has, however, the following adverse effects.

a. The induced resistance in this case as well persists at every position of the valve, and even increases as the valve closes due to increased strain in the spring. The increased and increasing resistance takes energy (in the form of work done, on the valve, against the spring resistance) that would otherwise be used to increase the pumping head; and
b. The induced resistance though makes the pump respond to the increased head, it lowers the speed with which the valve closes and hence increases the closure time of the Valve, thereby reducing the magnitude of water hammer effect (pressure hike) in the pump.

6.6 Introduction of Spring to the Model Pump

Though there are rooms to use once fixed impulse valve for different height and discharge conditions by tuning its opening angle that is not always possible. Only a range of angles are preferred to get overall increased efficiency.

Spring replaces weight of impulse valve for its ability to introduce resisting moment. Varying the resisting moment is possible by tuning either the strain in the spring, or the moment arm, or both. Figure 6.11 shows installation of a spring to the model pump. Figure 6.12 shows conceptual details of the spring installation with geometric variable that are used to develop relationships among the different dimensions. Figure 6.13 displays spring-loaded impulse valve details and its accessories. As required, in detail design, portion of the right face of the pump that is in alignment with the spring protrudes to house and allow free movement of the spring.

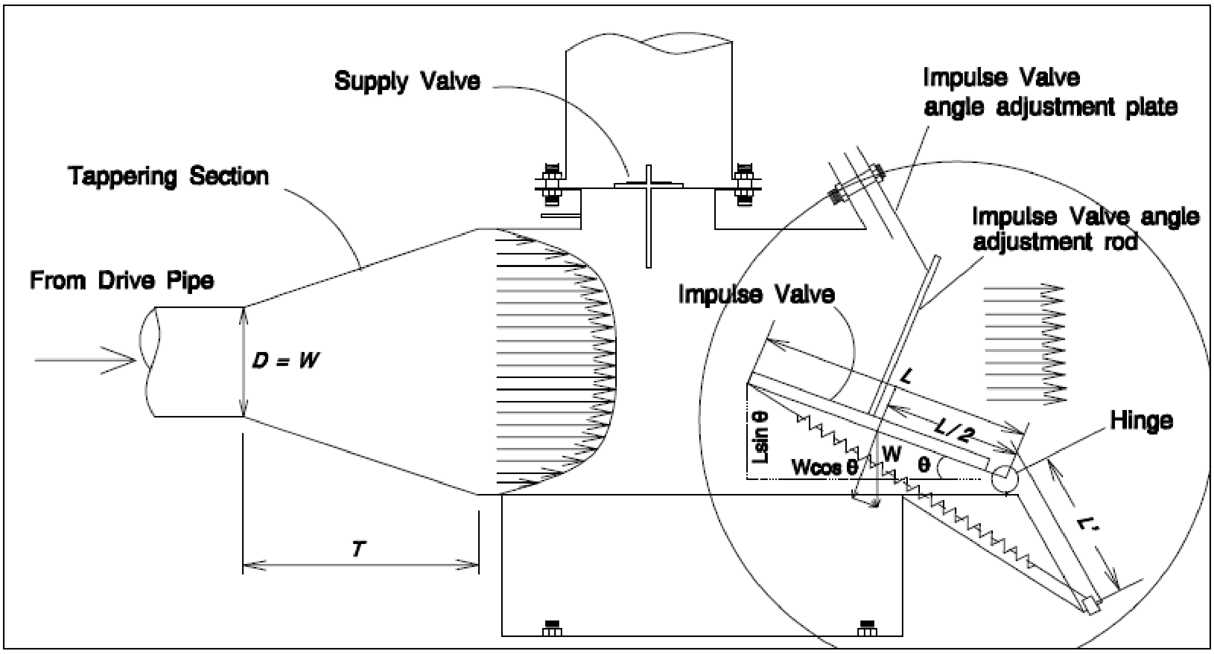

Figure 6.11: Introduction of a spring to replace valve weight: Pump section

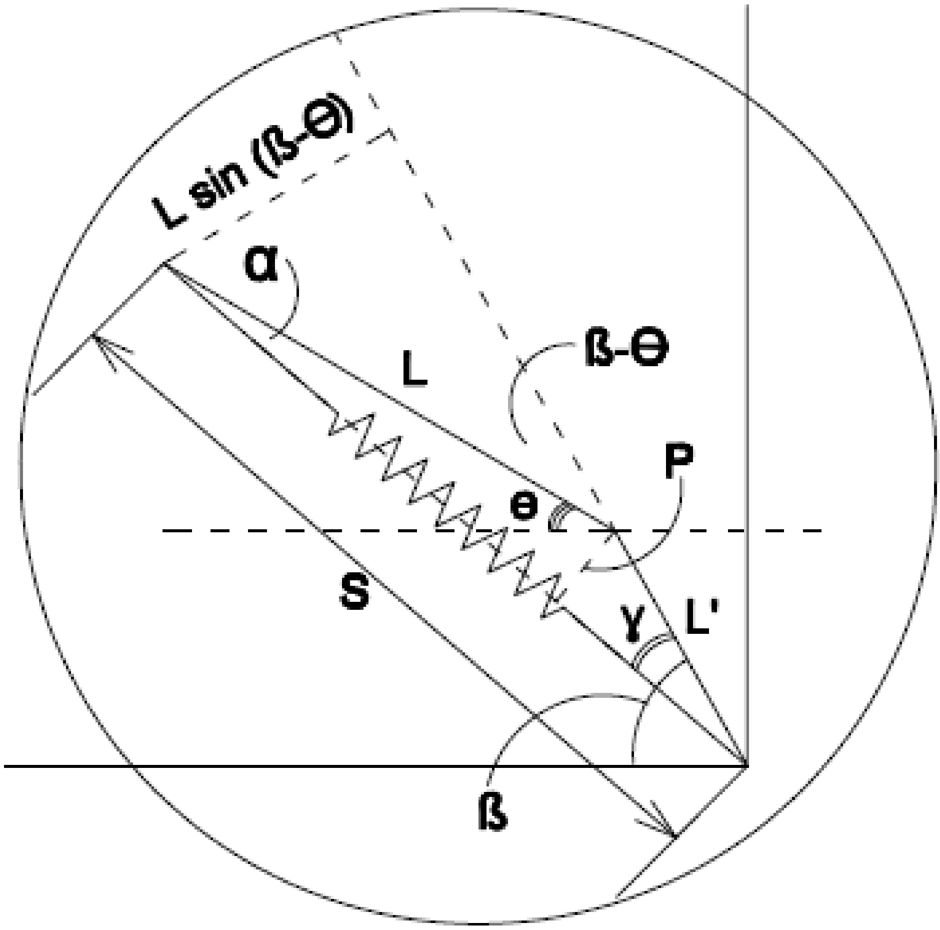

Figure 6.12: Introduction of a spring to replace valve weight: concept of spring installation

The axis (line of action) of the spring, (L') and (L) form a triangle. Referring Figure 6.12, and running a few geometric manipulations, yields the relationships in Equation 6.19.

$\propto = 180 - \gamma - (180 - (\beta - \theta))$	*Eqn. 6.19*
$\propto = \beta - \theta - \gamma$	
$\gamma = tan^{-1}\{(L * sin(\beta - \theta))/(L * cos(\beta - \theta) + L')\}$	
Where:	
$L' =$	length that protrudes out of the pump
$L =$	Length equal to vertical dimension of the chamber (main body of the pump)

$\beta =$	Angle (with the horizontal) of face of the pump that contains impulse valve
$\theta =$	Angle of the impulse valve at open position
$\gamma =$	Angle between axis of the spring and inclined face of the pump that contains impulse valve

Equations 6.19 relate the critical geometric elements with dimensions of parts of the pump given in Figure 6.12. The relationships are used to write different codes used to asses results of the adaptation.

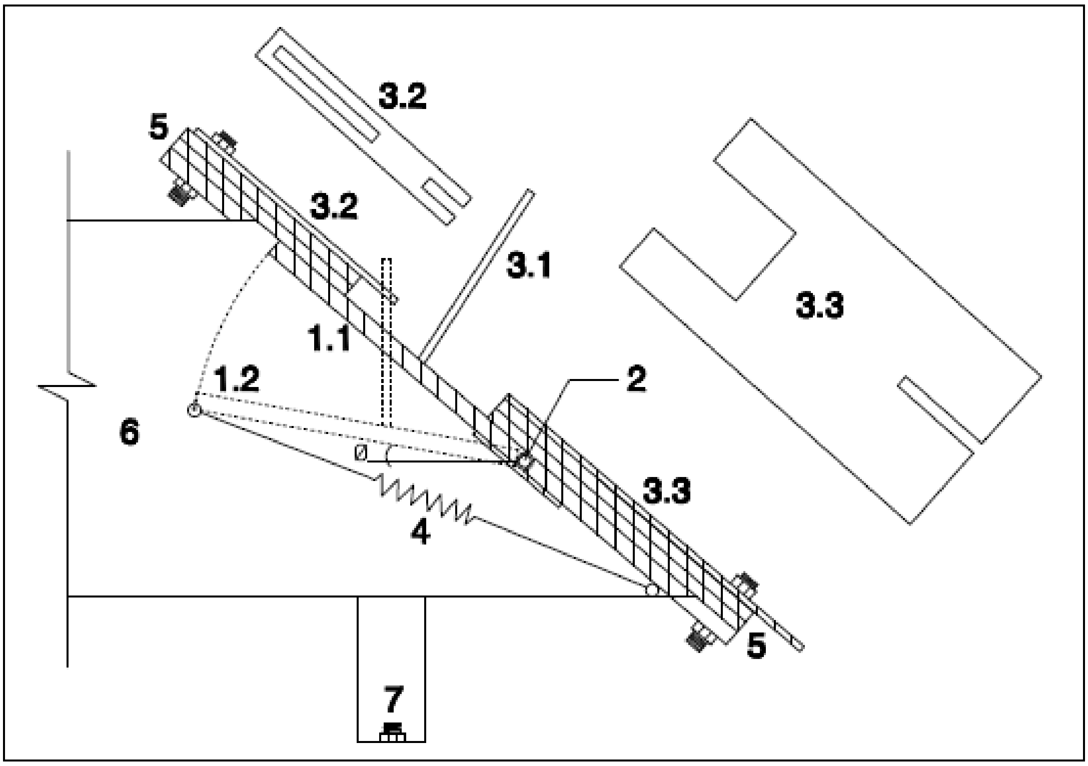

Figure 6.13: Spring-loaded impulse valve details and accessories

Names of the parts are given below

1. Impulse Valve
   1.1 closed position
   1.2 opened position
2. Hinge for the Impulse Valve
3. Impulse Valve Adjustment Triple
   3.1 rod (for angle adjustment)
   3.2 Plate (for angle adjustment)
   3.3 Plate (for opening adjustment)
4. Spring (to bring equivalent effect as weight of Impulse Valve)

5. Flange (that overlays valve opening to Impulse Valve)
6. Drive Pipe
7. Pump Stand

For the model Pump (Figures 6.11 and 6.12):

L'= 5 cm

L= 10 cm

β= 60°

θ = variable

For an arbitrarily picked θ value of 20°, the initial value of γ will be:

$$\gamma = tan^{-1}\{(0.1 * sin(40))/(0.1 * cos(40) + 0.05)\}$$

$$\gamma \approx 27°$$

From this, P, the moment arm for the spring will be:

$$P = L' \sin(27°) = 0.02m = 2cm$$

For impulse valve opening angle of 20°, impulse valve dimensions of 8 cm by 10 cm, weight of the impulse valve (in Newton) in terms of th (in mm) is:

$$W = 0.08 * 0.1 * \frac{th}{1000} * 7800 * 9.81$$

$$= 0.612 * th$$

The resisting moment due to weight of this impulse valve would be

$$M = 0.612th * 0.05 * \cos 20°$$

$$= 0.029 * th$$

The required tension in the spring, to effect same resisting moment, is given by Equation 6.20.

$T_S = \frac{0.029}{0.02} th = 1.44 * th$	*Eqn. 6.20*

The interpretation of Equation 6.20 is that the tension required in the spring to replace one mm of impulse valve thickness is 1.44 N. The required elongation in the spring, in turn, depends on the spring constant, K. As there must be an impulse valve of some thickness/weight, the counter-moment, the tension in the spring will be responsible to, is the difference between the moment due to drag force and that of the impulse valve.

6.6.1 Pump Closure Time and Pressure Surge Development

The main mechanics of operation of the Hydraulic Ram Pump family is water hammer. The amount of pressure developed in the pumps is inversely proportional to the closure time. As the pressure developed by the water hammer effect is partly used to strain the pump parts and the drive pipe, pumping height depends on rigidity of the pump and drive pipe materials as well. For an absolutely rigid pump and pipe material, the pressure hike created by bringing water with flow velocity of 1 meter/second to a halt in 'zero' time reaches 135 meters. This can be arrived at as follows.

For an absolutely rigid pipe that conveys incompressible liquid of mass density $\rho$with velocity V, the pressure developed in the pipe, when the flow comes to rest in time T , can be expressed employing Newton's Second Law of Motion, resulting in Equation 6.21[62].

$$P = \frac{\rho L V}{T}$$	*Eqn. 6.21*
Where:	
P=	The pressure developed in the pipe
ρ=	Density of the liquid
L =	Length of the pipe
V =	Velocity of flow
T =	Time required to bring the flow to a halt

Velocity of sound in liquid of bulk modulus of elasticity, K and mass density ρ, contained in a pipe, of diameter D, and wall thickness$e$, made of material with Modulus of Elasticity,E , is computed by Equation 6.22, Korteweg Equation [62]

$$C = \sqrt{\frac{1}{\rho(\frac{1}{K} + \frac{D}{eE})}}$$	*Eqn. 6.22*
Where:	
C=	The velocity of sound in the liquid
K=	Bulk modulus of elasticity of the liquid
ρ=	Mass density of the liquid
D=	Diameter of the pipe in which the liquid is flowing
E=	Elasticity of the pipe material
e=	Wall thickness of the pipe

For an ideal pipe material with an extremely high Evalue, Equation 6.22 is reduced to Equation 6.23.

$$C = \sqrt{\frac{K}{\rho}}$$	*Eqn. 6.23*

When water of bulk modulus of elasticity, K, flowing in an absolutely rigid pump body and rigid pipe of length L, and cross sectional area A, with velocity V, comes to a rest, the kinetic energy of the water will be converted into strain energy of water. The equivalence is expressed by Equation 6.24.

$$\frac{1}{2}\rho V^2 AL = \frac{1}{2}\frac{P^2}{K}AL$$	*Eqn. 6.24*
Where:	
ρ=	Mass density of water
V=	Velocity of water
A=	Area of the pipe
L=	Length of the pipe
P=	Pressure created in the pipe
K=	Bulk modulus of elasticity of water

The left hand side of Equation 6.24 is the kinetic energy of the flowing water and the right hand is the pressure energy. Rearranging and substituting equivalences, one gets Equation 6.25 [62]

$$P = C\rho V$$	*Eqn. 6.25*
Where:	
P=	Pressure in the pipe
C=	Velocity of sound (pressure wave) in water contained in pipe of material with Elasticity
ρ=	Mass density of water
V =	Velocity of water in the pipe before coming to rest

Substituting 1350 m/sec for velocity of pressure wave in water (contained in ductile iron pipe), 1000 kg/m^3 for mass density of water, and 1 m/sec for velocity of water, the resulting pressure will be 1,350,000 N/m^2, which is equivalent to 135 meters height of water. Equation 6.22 shows that propagation speed of pressure wave, also known as celerity (C) depends on bulk modulus of elasticity and density (of the fluid), and diameter, wall thickness to diameter ratio, and modulus of elasticity of the pipe material. Figure 6.14 gives the celerity values for different pipe materials.

Equation 6.25 shows that closure time and rigidity of pump and pipe materials have significant effect on the pressure development in the body of the pump, and hence, the pumping height. In the Equation (6.25), C is the only independent variable. Hence, for a given velocity, the pressure due to instantaneous closure solely depends on wave celerity.

From Figure 6.14, it is seen that the three properties of pipe materials are seen to cause C values that range from 200 m/s (for LPPE – low density polyethylene) to 1350 m/sec (for steel). The range indicates 675 percent variation in the C values. Relating Equations 6.21 and 6.25 hints that selection of drive pipe material alone has significant effect in the ram pump operation.

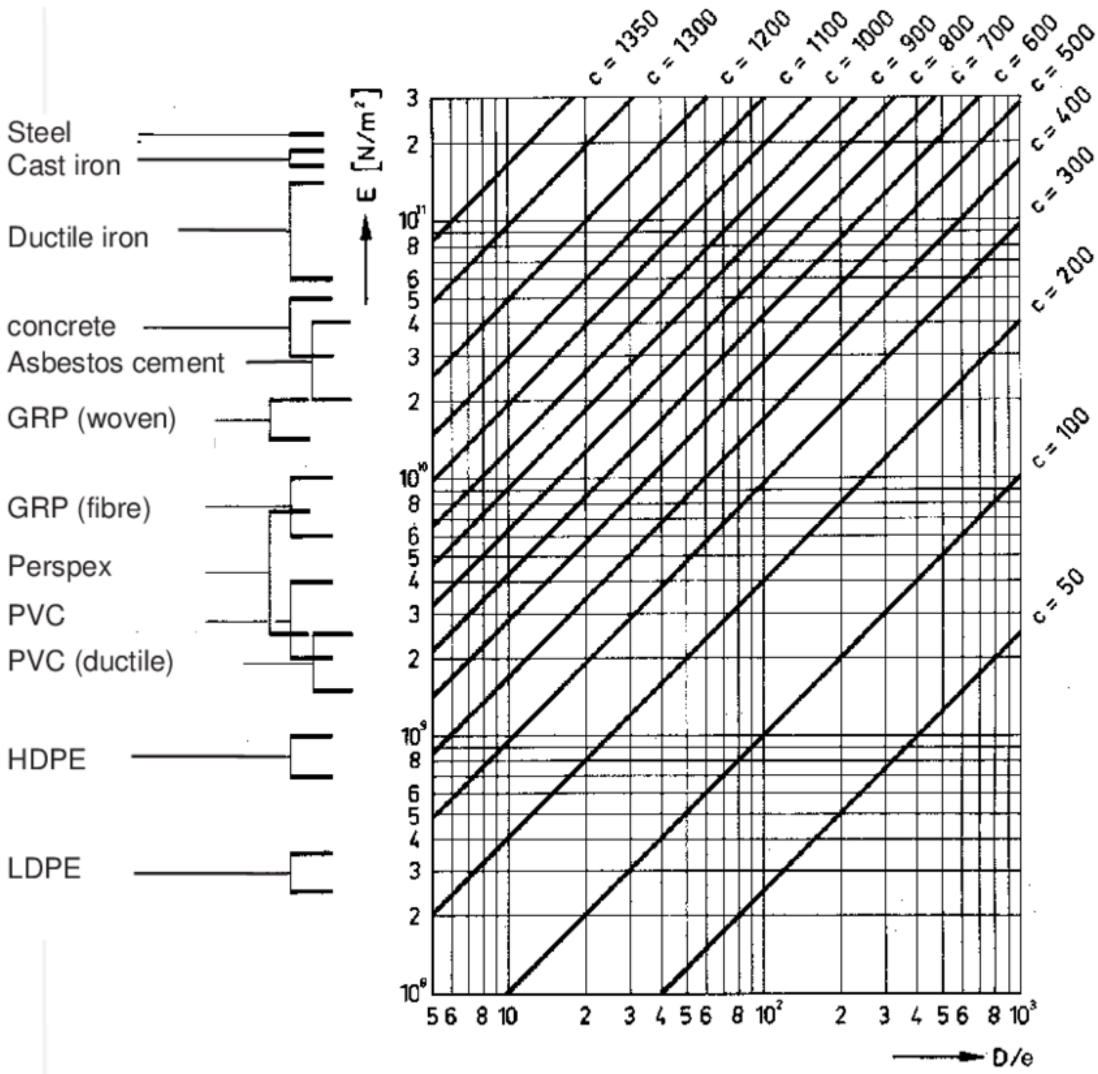

Figure 6.14: Wave propagation speed of water in pipes of different materials (source [63])

During closure of a valve, the flow in the pipe line exhibits different cyclic transient conditions which could mainly be divided into four phases. Before the valve was opened, the pressure in the pipe line is hydrostatic pressure that is equal to the water level of the reservoir / source. Figure 6.15 is used to explain the four phases that comprise a full cycle.

A] As the valve opens, water starts to flow past the valve. When the valve is suddenly closed, a pressure wave is created and propagates backward. The backward propagation of the pressure strains the pipe material as it travels, and brings the velocity to a halt progressively.

B] By the time the pressure surge reaches the inlet to the pipe, the pressure in the pipe becomes higher than the pressure in the reservoir / source. Due to this difference, backward flow (flow to the reservoir / source) starts and progresses back to the valve, releasing the developed pressure. The release continues towards the valve bringing the pressure in the pipe to static pressure, pressure before flow through the pipe starts.

C] The backward flow tends to continue even after the release of pressure from the full stretch of the pipe. This continuing flow starts to develop a negative pressure wave that propagates from the valve towards the source.

D] By the time the negative pressure reaches the source, the pressure difference at the inlet becomes the sum of hydrostatic pressure and the negative pressure. This pressure difference drives water back to the valve, and brings the pressure back to static pressure. This oscillation continues till pressure vanishes due to friction.

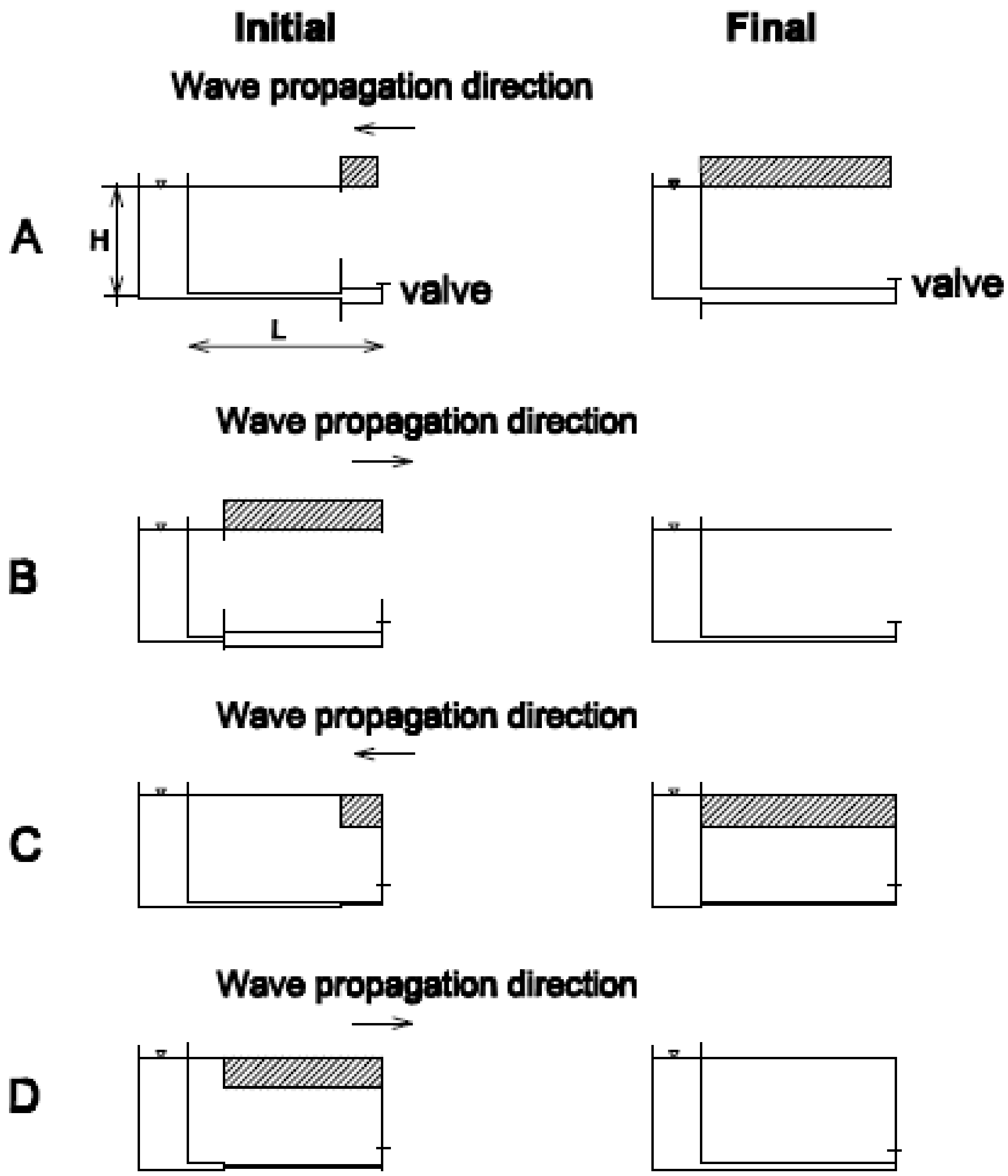

Figure 6.15: Wave propagation cycle following sudden closure of valve of a pipeline

The operation of hydraulic ram pump has similarity to these conditions. The difference with operation of the ram pump emanates from self-opening nature of its valve. Steps ‘A’ and ‘B’ take place after the rapid closure of impulse valve of the ram pump. Step ‘C’ cannot take place as the impulse valve opens following the trigger of negative pressure. Opening of the impulse valve (at the start of step ‘C’) interrupts the cycle and takes it back to phase ‘A’.

Rapidity of valve closure is determined by comparing the time of closure with the time the wave propagation requires to travel to the reservoir / source and be back to the valve. Such time is given by Equation 6.26.

$t = \frac{2L}{C}$		*Eqn. 6.26*
Where:		
$t =$	Round trip transit time	
$L =$	Length of the drive pipe	
$C =$	Wave speed	
If:		
$t_c < \frac{2L}{C}$,		then the valve closure is rapid
$t_c \geq \frac{2L}{C}$,		then valve closure is slow
Where:		
$t_c =$	Time of closure	

When the valve closure is rapid ($t_c < \frac{2L}{C}$), then full Joukowsky's pressure develops and hence Equation 6.25 (Joukowsky Equation) can be used to estimate the pressure surge. The following explanation shows how that is possible.

1. As the valve starts closing, pressure starts to develop and propagates back to the source (phase 'A' in Figure 6.15).
2. The celerity takes a time $\frac{2L}{C}$ to reflect back and arrive at the valve ('B' in Figure 6.15). The reflected wave is known to distract the pressure developed in the line during 'A'.
3. As the valve closure time is less than $\frac{2L}{C}$, the valve is fully closed before the reflected wave arrives at the valve. The developed surge following full closure of the valve travels back till it face the reflected wave. Based on by how much the closure time is less than $\frac{2L}{C}$, portion of the pipe upstream of the valve feels the fully developed pressure. As a critical condition, if the valve requires $\frac{2L}{C}$ to close, then by the time the reflected wave arrives at the valve, the valve is just fully closed. Such condition does not allow development of full pressure in any portion of the pipe.

If the valve closure is slow, $t_c \geq \frac{2L}{C}$, then Equation 6.25 (Joukowsky Equation) cannot be used (without modification) to estimate the pressure surge. The following explanation shows why that is so.

1. As the valve starts closing, pressure starts to develop and propagates back to the source (phase 'A' in Figure 6.15).
2. The celerity takes $\frac{2L}{C}$ to reflect back and arrive at the valve (phase 'B' in Figure 6.15). The reflected wave is known to distract the pressure developed in the line during phase 'A' ('B' in Figure 6.15).

3. As the valve closure time is greater than $\frac{2L}{C}$, the valve is not fully closed by the time the reflected wave arrives at the valve. In such a case, the magnitude of pressure depends on the portion closed.

The following two cases demonstrate the effect of closure time on the magnitude of pressure developed in the pipe line. As instantaneous closure is not possible, the two cases covered are:

I. When the time of closure is between zero and $\frac{L}{C}$;

II. When the time of closure is between $\frac{L}{C}$ and $\frac{2L}{C}$.

Case I. When the time of closure is between zero and $\frac{L}{c}$

$\frac{0.5L}{C}$, an arbitrary closure time between zero and $\frac{L}{c}$**,** is picked and the pressure development in the pipeline is traced.

Let the pressure caused by the instantaneous closure (full Joukowsky's head) be P. The valve is assumed to uniformly close in $\frac{0.5\mathrm{L}}{\mathrm{C}}$.

1. By the time the wave (triggered following the start of closure) reaches mid-way the reservoir / source and the valve, the valve is fully closed. The amount of pressure developed is P.
2. By the time the initial pressure surge reaches the reservoir / source, the surge from the fully developed pressure arrives at a point mid-way between the valve and the reservoir / source. This means the reflected wave and the wave from full closure of the valve meet around a point *0.75 L* from the valve. This shows that this portion (*0.75 L)* is subject to full Joukowsky's pressure.
3. Portion of the pipe line that experience full Joukowsky's pressure depends on how near the closure time is to instantaneous closure. The general formula to estimate portion the pipe line where full Joukowsky's pressure is developed is worked out give Equation 6.27.

$Length\ covered\ by\ Joukowsky\ pressure = L - x\frac{L}{2}$	*Eqn. 6.27*
Where:	
$L =$	Length of the pipeline
$x =$	Coefficient of $\frac{L}{C}$ when the closure time is expressed in terms of $\frac{L}{C}$. $(0 < x < 1)$

Case II. When the time of closure is between $\frac{L}{c}$ and $\frac{2L}{c}$

An arbitrary closure time between $\frac{\mathrm{L}}{\mathrm{C}}$ and $\frac{2\mathrm{L}}{\mathrm{C}}$ is picked and the pressure development in the pipeline is traced.

Let the pressure caused by the instantaneous closure (full Joukowsky's head) be P.

Let the valve closure time be $\frac{1.5L}{C}$. The valve is assumed to close uniformly in $\frac{1.5L}{C}$.

1. By the time the valve is fully closed, the wave (triggered following the start of closure) reaches the reservoir / source, reflected back and covers half of the pipe length.
2. The full pressure surge will cover quarter of the pipe length $\mathbf{L}$ before meeting the reflected wave.
3. So, full Joukowsky's head develops only in quarter ($0.25L$) length of the pipe. The general formula to estimate portion the pipe line where full Joukowsky's pressure is developed is worked out give Equation 6.28:

$Length\ covered\ by\ Joukowsky\ pressure = L - x\frac{L}{2}$	*Eqn. 6.28*
Where:	
$L =$	Length of the pipeline
$x =$	Coefficient of $\frac{L}{C}$when the closure time is expressed in terms of $\frac{L}{C}$. $(1 < x < 2)$

Case III. When the time of closure is greater than or equal to $\frac{2L}{C}$

An arbitrary closure time bigger than $\frac{2L}{C}$ is picked and the pressure development in the pipeline is traced.

Let the pressure caused by the instantaneous closure be P.

Let the valve closure time be $\frac{2.5L}{C}$. The valve is assumed to close uniformly in $\frac{2.5L}{C}$ seconds.

1. Before the valve is fully closed, the wave (triggered following the start of closure) completes round trip and reaches the valve. So full Joukowsky's pressure cannot develop in any portion of the pipe.
2. By the time the reflected wave reaches at the valve, the valve is closed by 4/5. This is a critical situation. The pressure in the pipe line does not increase once the reflected wave reaches the valve point. The maximum pressure expected from a closure time of $\frac{2.5L}{C}$ is $\frac{4P}{5}$. This shows that for a closure time longer than $\frac{2L}{C}$, the pressure in the pipe line is less than the full Joukowsky's pressure.
4. From this, it is possible to say that, if the valve closure time is greater than $\frac{2L}{C}$, the pressure developed along the pipe line is less than full Joukowsky's pressure computed employing Joukowsky equation. Magnitude of the pressure depends on portion of the valve closed at $t = \frac{2L}{C}$. The general formula to estimate magnitude of pressure when the closure time is longer than $\frac{2L}{C}$ is worked out give Equation 6.29:

$for\ time\ of\ closure > \frac{2L}{C}, Maximum\ pressure = \frac{2}{x}P$	*Eqn. 6.29*

Where:	
$P =$	full Joukowsky's pressure
$x =$	Coefficient of $\frac{L}{C}$when the closure time is expressed in terms of $\frac{L}{C}$. $(x > 2)$

Equation 6.29 is given in other expression (Equation 6.30) and called Michaud's formula. An experimental analysis made by A. Kodra [64] concludes that the commonly used Michaud's formula, which assumes linear velocity change, significantly underestimates pressure increase and hence should not be used.

$\Delta P = \frac{2\rho v_o L}{t_c}$	*Eqn. 6.30*

Where:	
$\Delta P =$	The pressure in the pipe due to closure
$\rho =$	Mass density of water
$v_o =$	Velocity before closure starts
$L =$	Length of the pipe
$t_c =$	Time of closure

Same experimental analysis concludes that the other method, known as Wood and Jones's method, also underestimates the pressure magnitude expected from uniform closure. Wood and Jones developed charts for different types of valves based on theoretical analysis of the most common types of valves. The charts express the relationship between dimensionless maximum transient pressure (Equation 6.31) and the dimensionless valve closure time (Equation 6.32). Both τ and t_{WJ} parameters are to be read from Wood and Jonse's chart (not provided here).

$\tau = \frac{g * h_L}{\Delta v * C}$	*Eqn. 6.31*

Where:	
$\tau =$	Dimensionless maximum transient pressure change
$h_L =$	The head drop under the initial steady flow conditions
$\Delta v =$	Change in velocity
$C =$	Wave speed

$$t_{WJ} = {T_C}\Big/{\frac{2L}{C}}$$		*Eqn. 6.32*
Where:		
$t_{WJ} =$	Dimensionless valve closure time	
$T_C =$	Time of valve closure	
$L =$	Length of the pipeline	
$C =$	Wave speed	

The value of the dimensionless maximum transient pressure change (to be read from chart) is related to the unknown maximum transient pressure change employing Equation 6.33.

$$\Delta p_m = \frac{\Delta p_{max}}{\Delta v * \rho * C}$$		*Eqn. 6.33*
Where:		
$\Delta p_m =$	Dimensionless maximum transient pressure head	
$\Delta p_{max} =$	Maximum transient pressure head	

Lorenzo Allievi, known Italian for his investigation on hydraulics developed charts which are also based on the assumption of uniform closing of gates. He included two additional assumptions: friction less and uniform diameter penstock [64]. Drive pipe of hydraulic ram pump is equivalent to Penstock in hydropower.

Allievi's charts have penstock parameter φ and valve operation parameter ϑ as X and Y axes respectively. The penstock parameter is expressed by Equation 6.34

$$\varphi = \frac{C * v_0}{2g * H_0}$$		*Eqn. 6.34*
Where:		
$C =$	Wave velocity	
$v_0 =$	Flow in penstock	
$g =$	Gravitational acceleration	
$H_0 =$	Steady state head	

The valve operation parameter is given by Equation 6.35

$$\vartheta = \frac{C * t_c}{2L}$$		*Eqn. 6.35*
Where:		
$C =$	Wave velocity	
$t_c =$	Valve closing time	
$L =$	Length of the penstock	

By entering the graph with the φ and ϑ values, Z^2 (pressure rise factors, $\frac{H_{max}}{H_0}$) are read. H_{max} is then calculated by equating Z^2 with $\frac{H_{max}}{H_0}$. Figures 6.16 to 6.18 are used for large, medium and small φ and ϑ values, respectively [65]. Figures 6.17 and 6.18 are enlargements of Figure 6.16. The curves numbered after 'S' in Figure 6.17 show the time in terms of μ (which equals $2\frac{L}{C}$) that elapses from start of closure to the moment of occurrence of maximum pressure [66]

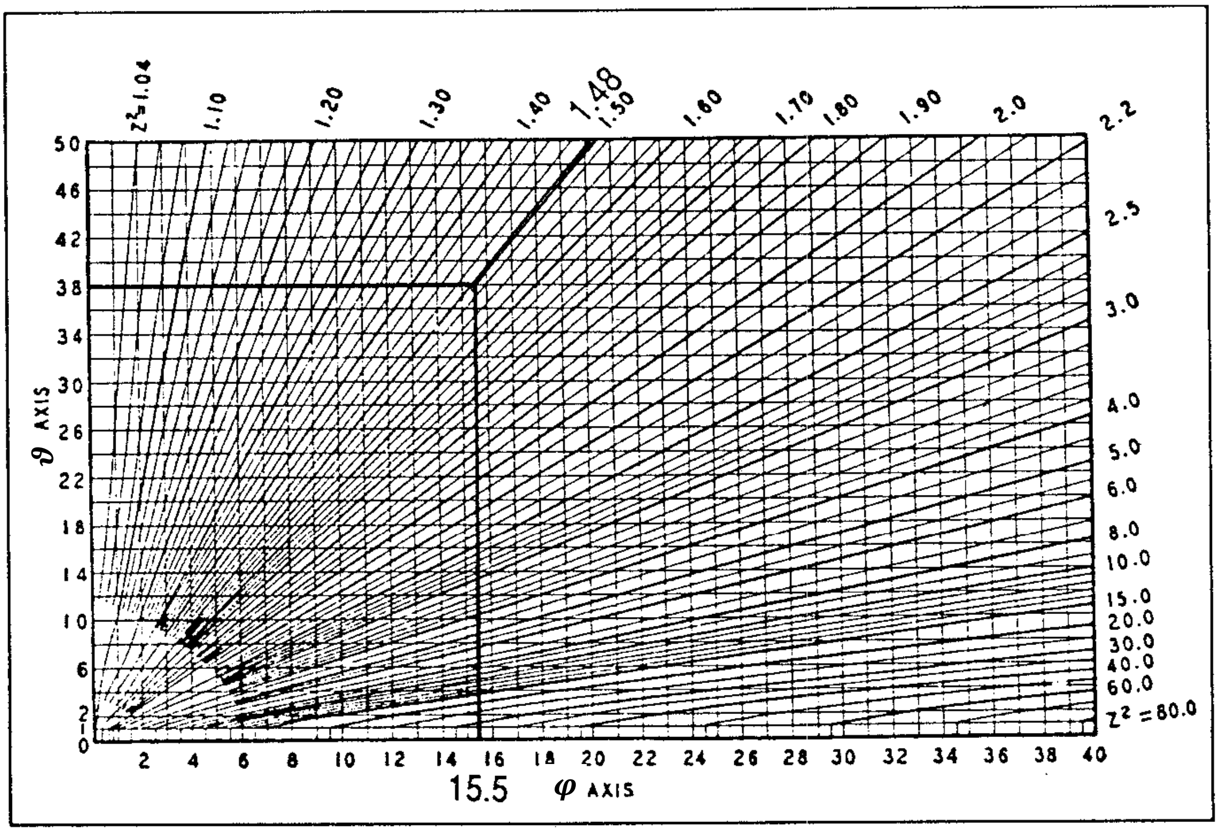

Figure 6.16: Allievi chart: pressure rise for uniform gate closure and simple conduits (to be used for large ϑ and φ values)

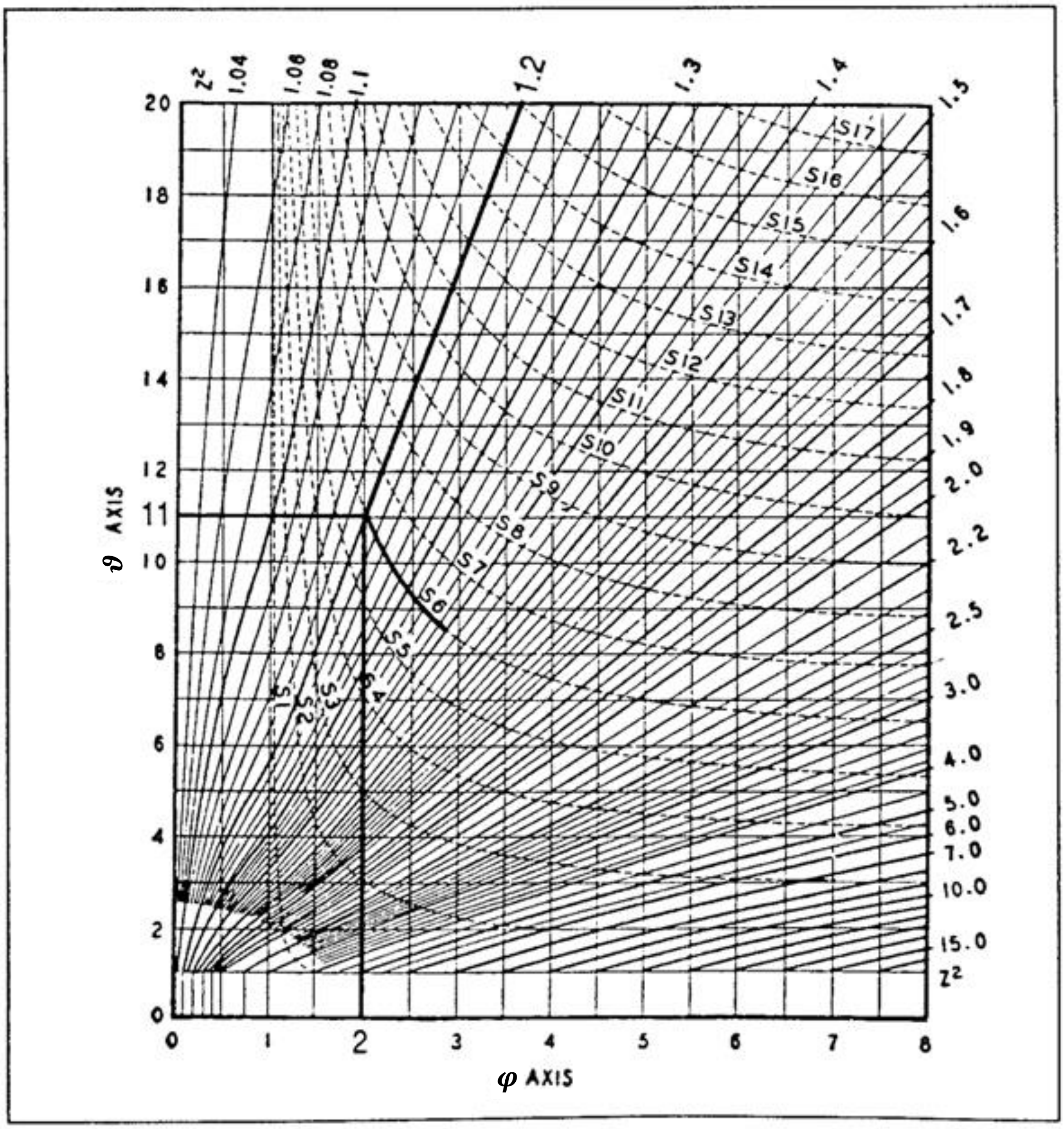

Figure 6.17: Allievi chart: Pressure rise for uniform gate closure and simple conduits (enlargement of part of Fig. 6.16 – for medium φ and ϑ.)

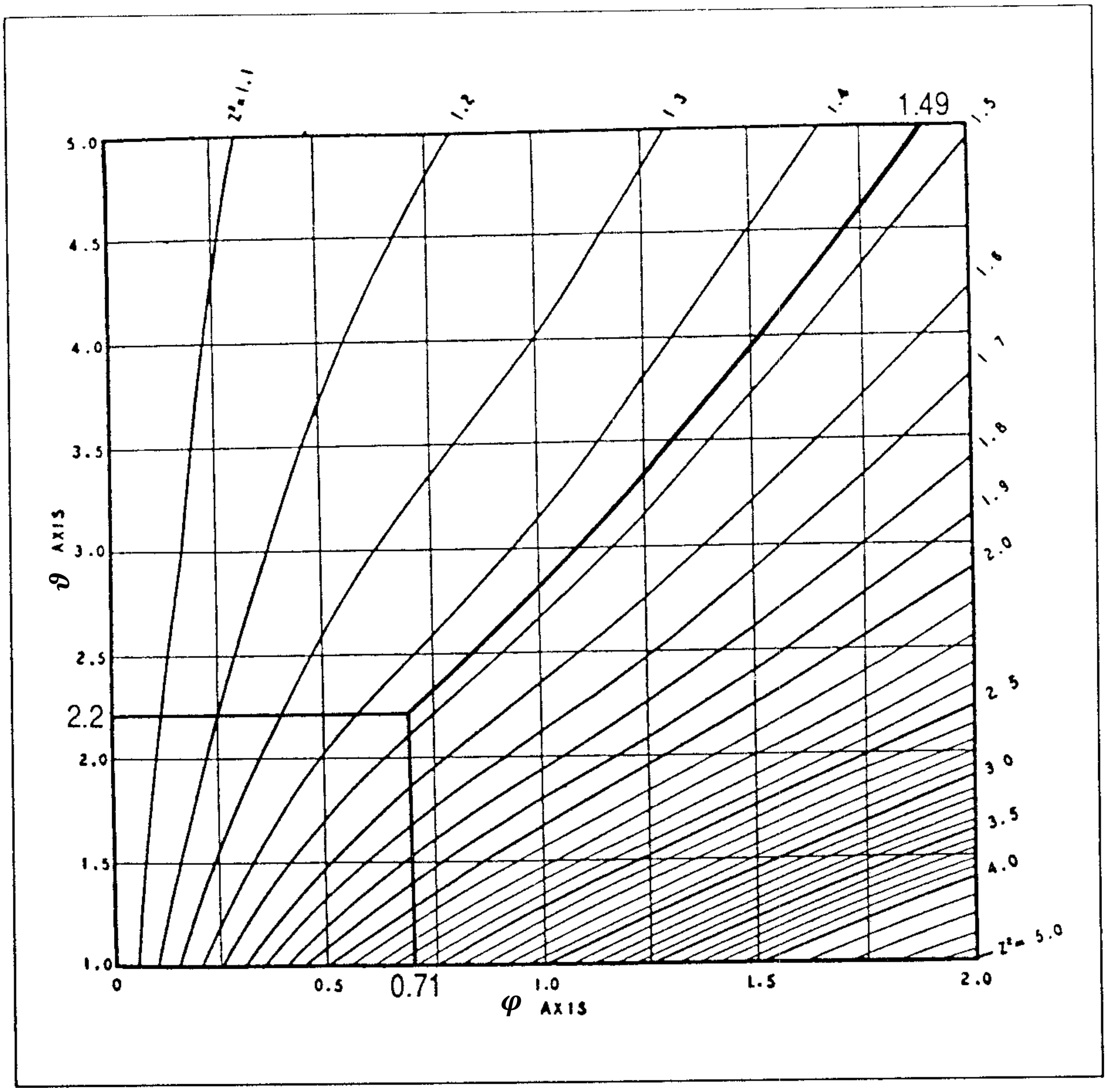

Figure 6.18: Allievi chart: Pressure rise for uniform gate closure and simple conduits (enlargement of part of Fig. 6.16 – for small φ and ϑ)

The above given extended explanations signifies the effect of speed of closure on productivity and efficiency of ram pump. To exploit the full Joukowsky's pressure from a site with a ram pump of 10 meters drive pipe, made of ductile iron, the closure time of the impulse valve need, at least, be less than 0.015 seconds.

For the model pump, the code to compute the closure time can be prepared using the outputs of the following discussions.

Newton's second law for rotational motion is expressed by Equation 6.36.

$\tau = rFsin\theta = I\alpha$	*Eqn. 6.36*

Where:	
$\tau=$	Net torque
$r=$	Distance between the axis of rotation and the point of action
$F=$	The force acting
$\theta =$	The angle between the force and the lever arm
$I =$	Mass moment of inertia (about the axis of rotation)
$\alpha =$	Angular acceleration = $\frac{d^2\theta}{dt^2}$

For the case at hand, the net torque is the difference between the moment (about the axis of rotation) caused by the drag force and the resistance moment due to the weight of the Impulse Valve.

When an object moves in a medium, it experiences resistance from the medium. This resistance is known as drag force. As velocity is relative, drag force occurs not only when an object moves in a medium, but also when a medium moves past a submerged object. In most of the cases, drag is something not desired. In hydraulic ram pump technology, however, drag is one of the main mechanisms that enable functioning of the pump.

Velocity that passes through body of the model pump induces drag force on the impulse valve. As the impulse valve is pinned at its bottom, the drag force is converted to moment (drag moment about the pinned bottom).

One of the fluid characteristics that influence drag force is viscosity. At very low speeds, and/or in fluids with high viscosity, and/or in very small dimensions, that is roughly below Re (Reynolds Number – the ratio of inertial force to viscous force) value of one, viscosity is the predominant parameter determining the drag of a body [67]. On the other hand, sharp edges always cause flow separation and high drag that is insensitive to Reynolds number. [51].

There are two types of drag force, friction drag and form drag. Form drag, also known as pressure drag, is strong on bluff body, and friction drag prevails on flat plates aligned with the flow direction.

The moment due to the drag force on the impulse valve is computed by:

a. considering the vertical projection of the Impulse Valve for a given angle (with the horizontal) at open position;
b. matching the velocity profile, of the flow through main body of the pump, that overlaps with the vertical projection of the Impulse Valve;
c. Integrating the drag force moments across the overlapping area.

Drag coefficients are defined by using a characteristic area A, which may differ on body shape: $C_D = {drag}\big/{\frac{1}{2}\rho v^2}$. Drag force is calculated using the drag force formula (Equation 6.37).

$Drag\ Force = \frac{1}{2}\rho_w v^2 C_D A$	*Eqn. 6.37*
Where:	
$\rho_w =$	Mass density of water
$v =$	Velocity of water
$C_D =$	Drag Coefficient (1.17 for rectangular plate)
$A =$	Area of the plate perpendicular to the flow direction

As the velocity varies from point to point in the main body of the pump, calculating the drag moment requires computation of the velocity at each point for the region where the drag force is to be worked out, by considering the velocity profile (Eqn. 6.16). Equation 6.38 computes the total drag moment by:

a. finding the velocities at every point in the vertically projected area of the impulse valve;
b. multiplying squares of the velocities by the corresponding infinitesimally small area around the point where the velocities are computed;
c. multiplying the result with the constant inputs of the formula (0.5, ρ_w, C_D) and the corresponding moment arms; and
d. summing up all the individual results across the region of integration.

$M_{drag} = \int_0^{0.1sin\theta}\int_{0.01}^{0.09}((\frac{1}{2}\rho_w C_D(1.139 * \sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}})^2\ dwdh) * h$	*Eqn.6.38*

In order for the pump to exploit the full potential, the impulse valve should barely resist the drag moment computed by Equation 6.38. For a steel impulse valve of width 0.08m, height 0.1m, and thickness th that has an open position of θ with the horizontal, the resisting moment is given by Equation 6.39.

$0.08 * 0.1 * th * 7800 * 9.81 * \frac{0.1}{2} * cos\theta = 30.61 * th * cos\theta = M_{drag}$	*Eqn. 6.39*
rearranging and including a factor 1,000 to get the result in mm yields	
$th = 1000 * \frac{M_{drag}}{30.61 * cos\theta}$	

The resisting moment due to weight of the Impulse Valve is straight forward (Equation 6.40). The mass moment of inertia about the axis of rotation of the Valve is computed using parallel axis theorem (Equation 6.41).

$$M_{valve} = b * d * th * \rho * g * \frac{l}{2} * cos\theta$$	*Eqn. 6.40*
$$I_{m(x)} = \frac{\rho * b * th * l^3}{3}$$	*Eqn. 6.41*

Where:	
$M_{valve} =$	Resisting moment of the valve
$I_{m(x)}$=	Mass moment of inertia about an axis that is parallel to the central axis and which passes through the point of rotation
ρ=	Mass density of the object (impulse valve in this case)
b=	Width of the valve
l=	Depth of the valve
$th =$	Thickness of the valve
$g =$	Gravitational acceleration
$\theta =$	Valve angle with the horizontal

Both moments (drag and valve moments) are functions of θ. Equation 6.36 can be rewritten as Equation 6.42.

$$\frac{M_{drag}(\theta) - M_{Valve}(\theta)}{I_{m(x)}} = \frac{d^2\theta}{dt^2}$$	*Eqn.6.42*

The complete equation (the expanded form of Equation 6.42) to compute the closure time of the valve can be written as Equation 6.43.

$$\frac{[\int_0^{0.1sin\theta} \int_{0.01}^{0.09}((\frac{1}{2}\rho_w C_D \left(1.139 * \sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dwdh) * h] - [b * l * t * \rho_s * g * (l/2)cos\theta]}{\frac{\rho_s * b * t * l^3}{3}} = \frac{d^2\theta}{dt^2}$$	*Eqn. 6.43*

As Equation 6.43 is complex, it requires numerical method to find the closure time given:

a. Initial angular velocity (zero in this case as the valve starts from rest at the beginning of every pumping cycle)
b. Initial angular position

c. Final angular position
d. Mass density of water
e. Mass density of steel (Impulse Valve material)
f. Geometrical dimensions of the valve (breadth – w, length –l, thickness –th)
g. Drag coefficient for the valve shape (1.17 for rectangular one)

Code is written to facilitate the numerical computation. The closure times of weight-only valve for different values of fall heights, valve thicknesses and initial angular position are rendered in Table 6.6 and 6.7. The prompt for the code writing that works out the computation is given in Table 6.5. The code is given in **Appendix III.**

Size of the drive pipe used in Table 6.6 is 50 millimeter. When size of the drive pipe is changed, the results change. Table 6.7 displays the parameters for an 80 millimeter drive pipe size. Same code is used by changing the velocity ratio factor from 1.137 to 2.917. Pattern of the required valve thickness for different initial valve opening angle and fall heights are shown in Figures 6.19 and 21 for drive pipe size of 50 and 80 millimeters respectively. Closure times of different initial opening angles and fall heights of weight-only valves for drive pipe size 50 and 80 millimeters are shown in Figures 6.20 and 22 respectively.

Table 6.5: Prompt to write code for valve thickness and closure time (weight-only valve)

1	$\gamma_{initial} = tan^{-1}\{(0.1 * sin(\beta - \theta_{initial}))/(0.1 * cos(\beta - \theta_{initial}) + 0.05)\}$
2	$M_{dragat\theta_{initial}} = \int_0^{0.1*sin\theta_{initial}} \int_{0.01}^{0.09} (\frac{1}{2}\rho_w * C_D \left(1.138 * \sqrt{H}\left(1-\left(\frac{0.05-x}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-y}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dxdy) * y$
3	$M_{valve_{at\theta_{initial}}} = 0.08 * 0.1 * th * \rho_s * g * \left(\frac{0.1}{2}\right) * cos\theta_{initial}$
4	$M_{springat\theta_{initial}} = K * \Delta S_{initial} * 0.05 * \sin(\gamma_{initial})$
5	$M_{drag} = \int_0^{0.1*sin\theta} \int_{0.01}^{0.09} (\frac{1}{2}\rho_w * C_D \left(1.138 * \sqrt{H}\left(1-\left(\frac{0.05-x}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-y}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dxdy) * y$
6	$\Delta S_{initial} = \Delta S_{t=0} = \Delta S_{\theta_{initial}}$
7	$\propto = \beta - \theta - \gamma$
8	$\theta_{final} = \beta$
9	$\gamma = tan^{-1}\{(0.1 * sin(\beta - \theta))/(0.1 * cos(\beta - \theta) + 0.05)\}$
10	$\theta_{initial} = \theta_{t=0}$
11	$\gamma_{initial} = \gamma_{t=0}$
12	$\propto_{initual} = \propto_{t=0}$
13	$S_{t=0} = 0.1 * cos(\propto_{t=0}) + 0.05 * cos(\gamma_{t=0}) - \Delta S_{t=0}$
14	$S = 0.1 * \cos(\alpha) + 0.05 * \cos(\gamma)$
15	$\Delta S = S - S_{t=0}$
16	$M_{valve} = 0.08 * 0.1 * th * \rho_s * g * \left(\frac{0.1}{2}\right) * cos\theta$

17	$M_{spring} = K * \Delta S * 0.05 * \sin(\gamma)$
18	$I_{valve} = \dfrac{\rho_s * 0.08 * th * 0.1^3}{3}$
19	$\dfrac{M_{drag} - M_{valve} - M_{spring}}{I_{valve}} = \dfrac{d^2\theta}{dt^2}$
20	Code: 1) find *th* such that $M_{dragat\theta_{initial}}$=$M_{valve}$ for H values of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 5.0 (all in meters); and $\theta_{initial}$ values of 10, 15, 20, 25, and 30 (all in degrees); 2) Compute valve closure times for $\theta_{initial}$ of 10, 15, 20, 25, and 30 (all in degrees), and H values of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 5.0 (all in meters). β is the final angle for all the cases, and initial angular velocity is zero rad/sec in all the cases. Note that the upper limit of the outer integral is 0.1*sinθ. The angles θ and β are measured clockwise with the horizontal. The valve closes when θ becomes equal to β.
21	For proof reading and debugging, results of the computation at each step are displayed.
22	Values to be given: $\beta(in\ degrees)$, $K(in\ N/m)$,ρ_w(in kg/m^3), $C_D(unit\ less)$, ρ_s(in kg/m^3), $g(in$ m/s^2), $\Delta S_{initial}(in\ meters)$

Table 6.6: Drag moments, impulse valve thicknesses, and closure times, tw (weight – only valve) for diameter of the drive pipe 50 mm and size of the main body of the pump 100 by 100 mm

Height H (m)	[Drag Moment (N-m)][Weight – only Impulse Valve Thickness (mm)] [Closure times: t_w, (sec)] for valve angles (with the horizontal) of:									
	10°	t_w	15°	t_w	20°	t_w	25°	t_w	30°	t_w
0.5	[0.0025] [0.083]	0.415	[0.007] [0.222]	0.509	[0.013] [0.440]	0.592	[0.021] [0.744]	0.669	[0.030] [1.136]	0.742
1	[0.005] [0.1666]	0.415	[0.013] [0.444]	0.509	[0.025] [0.881]	0.592	[0.041] [1.489]	0.669	[0.060] [2.273]	0.742
1.5	[0.008] [0.250]	0.415	[0.02] [0.665]	0.509	[0.038] [1.321]	0.592	[0.062] [2.233]	0.669	[0.090] [3.409]	0.742
2.0	[0.01] [0.333]	0.415	[0.026] [0.887]	0.509	[0.050] [1.762]	0.592	[0.082] [2.977]	0.669	[0.120] [4.546]	0.742
2.5	[0.013] [0.416]	0.415	[0.033] [1.109]	0.509	[0.063] [2.202]	0.592	[0.103] [3.721]	0.669	[0.151] [5.682]	0.742
3.0	[0.015] [0.499]	0.415	[0.039] [1.331]	0.509	[0.076] [2.642]	0.592	[0.123] [4.466]	0.669	[0.180] [6.819]	0.742
3.5	[0.018] [0.582]	0.415	[0.046] [1.553]	0.509	[0.089] [3.083]	0.592	[0.145] [5.210]	0.669	[0.211] [7.955]	0.742
4.0	[0.020] [0.665]	0.415	[0.052] [1.774]	0.509	[0.101] [3.523]	0.592	[0.165] [5.954]	0.669	[0.241] [9.092]	0.742
4.5	[0.023] [0.749]	0.415	[0.059] [1.996]	0.509	[0.114] [3.964]	0.592	[0.186] [6.698]	0.669	[0.271] [10.228]	0.742
5.0	[0.025] [0.832]	0.415	[0.066] [2.218]	0.509	[0.127] [4.404]	0.592	[0.206] [7.443]	0.669	[0.301] [11.365]	0.742

Note: 1. The angle is measured counter clockwise with the horizontal
2. The Drag Coefficient, C_D, is taken to be 1.17 .

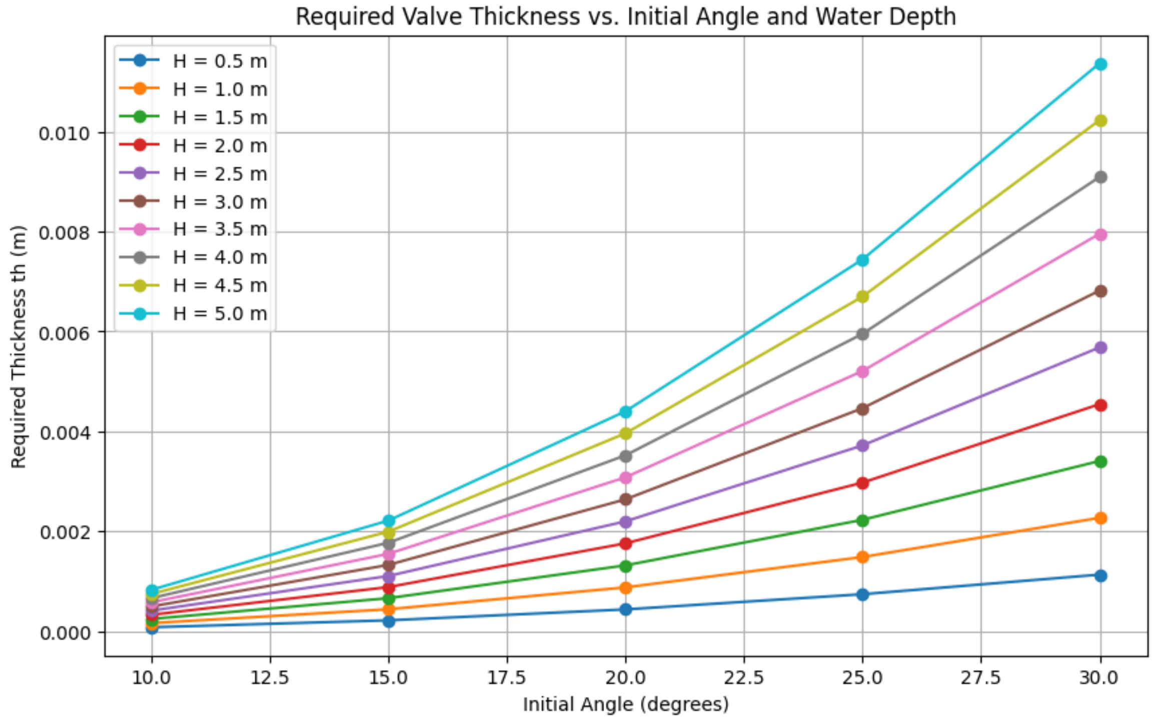

Figure 6.19: Required valve thickness for different initial valve opening angles and fall heights (drive pipe size 50 mm)

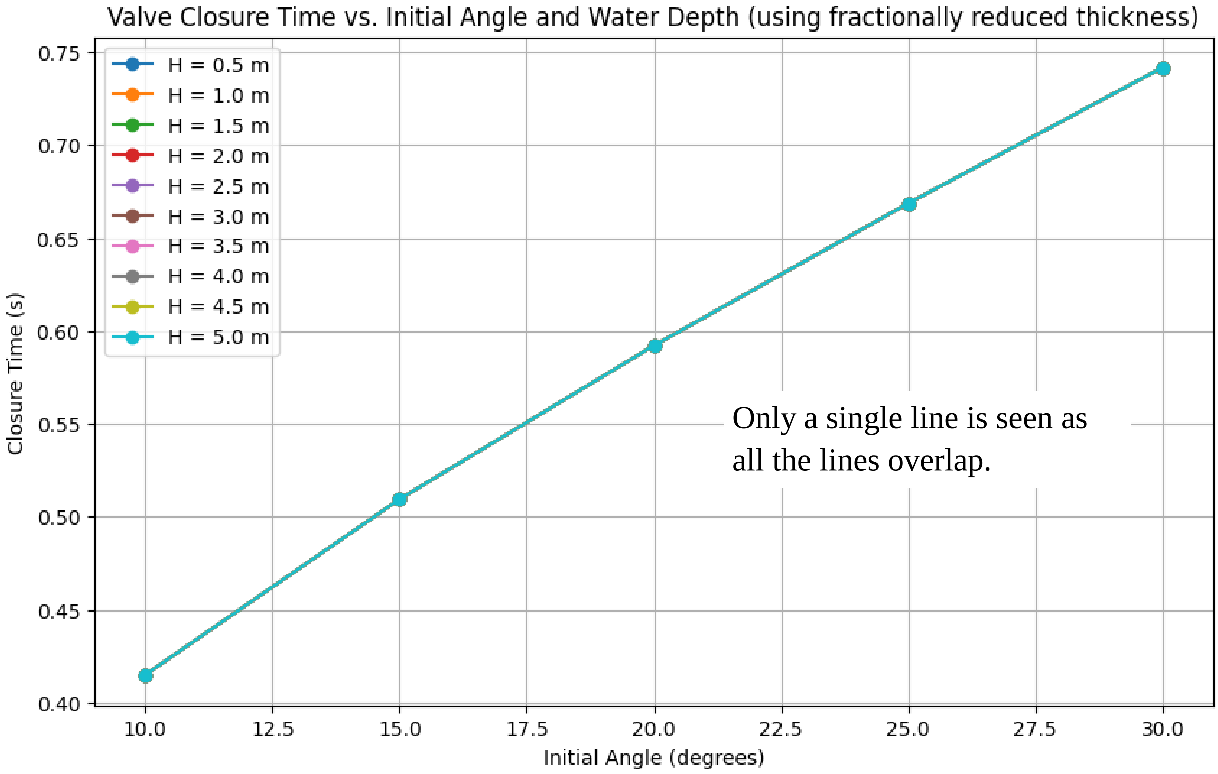

Figure 6.20: Valve closure time for different initial valve opening angles and fall heights (drive pipe size 50 mm)

Table 6.7: Drag moments, impulse valve thicknesses, and closure times, t_w (weight – only valve) for diameter of the drive pipe 80 mm and size of the main body of the pump 100 by 100 mm

Height H (m)	[Drag Moment (N-m)][Weight – only Impulse Valve Thickness (mm)] [Closure times: t_w, (sec)] for valve angles (with the horizontal) of:									
	10°	t_w	15°	t_w	20°	t_w	25°	t_w	30°	t_w
0.5	[0.0165] [0.547]	0.415	[0.043] [1.457]	0.509	[0.083] [2.894]	0.592	[0.136] [4.89]	0.669	[0.198] [7.467]	0.742
1	[0.033] [1.093]	0.415	[0.086] [2.915]	0.509	[0.166] [5.787]	0.592	[0.271] [9.78]	0.669	[0.396] [14.934]	0.742
1.5	[0.0494] [1.64]	0.415	[0.129] [4.372]	0.509	[0.25] [8.681]	0.592	[0.407] [14.67]	0.669	[0.594] [22.401]	0.742
2.0	[0.066] [2.186]	0.415	[0.172] [5.829]	0.509	[0.333] [11.57]	0.592	[0.543] [19.56]	0.669	[0.792] [29.868]	0.742
2.5	[0.082] [2.733]	0.415	[0.215] [7.286]	0.509	[0.416] [14.47]	0.592	[0.678] [24.45]	0.669	[0.99] [37.34]	0.742
3.0	[0.099] [3.279]	0.415	[0.258] [8.744]	0.509	[0.499] [17.36]	0.592	[0.814] [29.34]	0.669	[1.188] [44.80]	0.742
3.5	[0.115] [3.826]	0.415	[0.302] [10.20]	0.509	[0.583] [20.26]	0.592	[0.95] [34.23]	0.669	[1.385] [52.27]	0.742
4.0	[0.132] [4.372]	0.415	[0.345] [11.66]	0.509	[0.665] [23.15]	0.592	[1.085] [39.12]	0.669	[1.583] [59.735]	0.742
4.5	[0.148] [4.919]	0.415	[0.388] [13.12]	0.509	[0.749] [26.04]	0.592	[1.221] [44.01]	0.669	[1.781] [67.20]	0.742
5.0	[0.165] [5.465]	0.415	[0.431] [14.57]	0.509	[0.832] [28.94]	0.592	[1.356] [48.9]	0.669	[1.979] [74.67]	0.742

Note: 1. The angle is measured counter clockwise with the horizontal
2. The Drag Coefficient, C_D, is taken to be 1.17 .

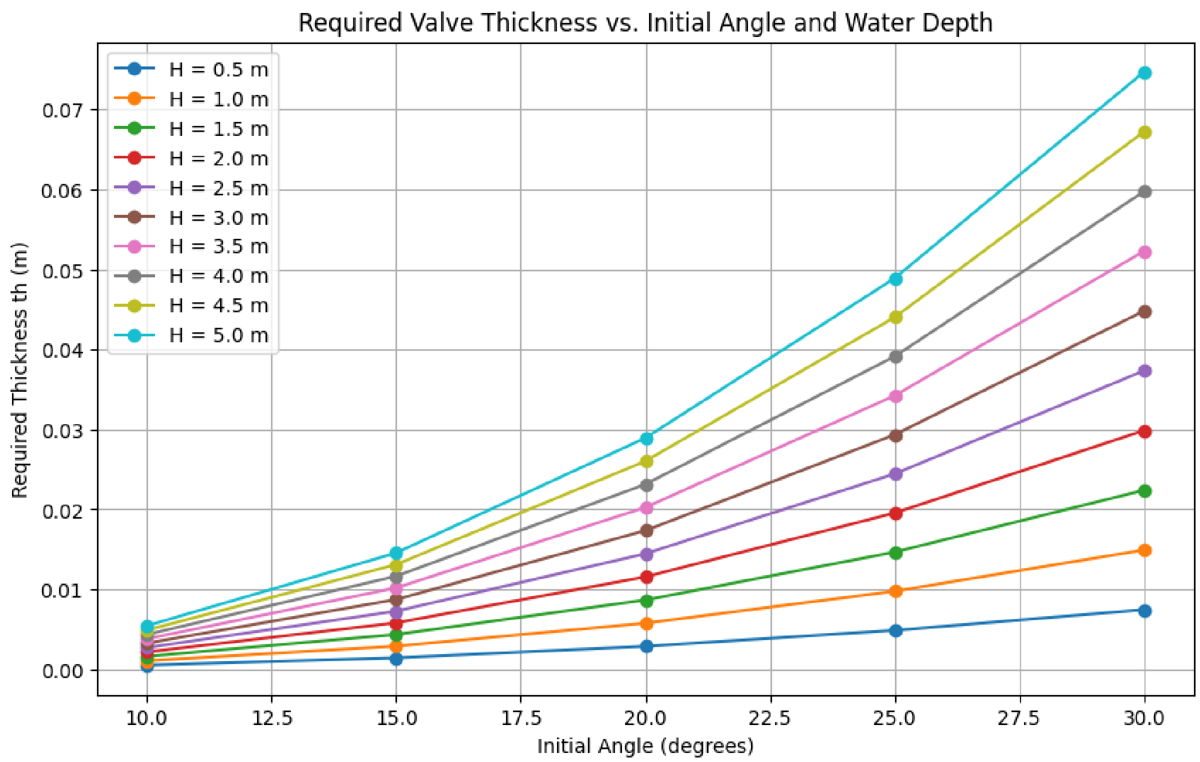

Figure 6.21: Required valve thickness for different initial valve opening angles and fall heights (drive pipe size 80 mm)

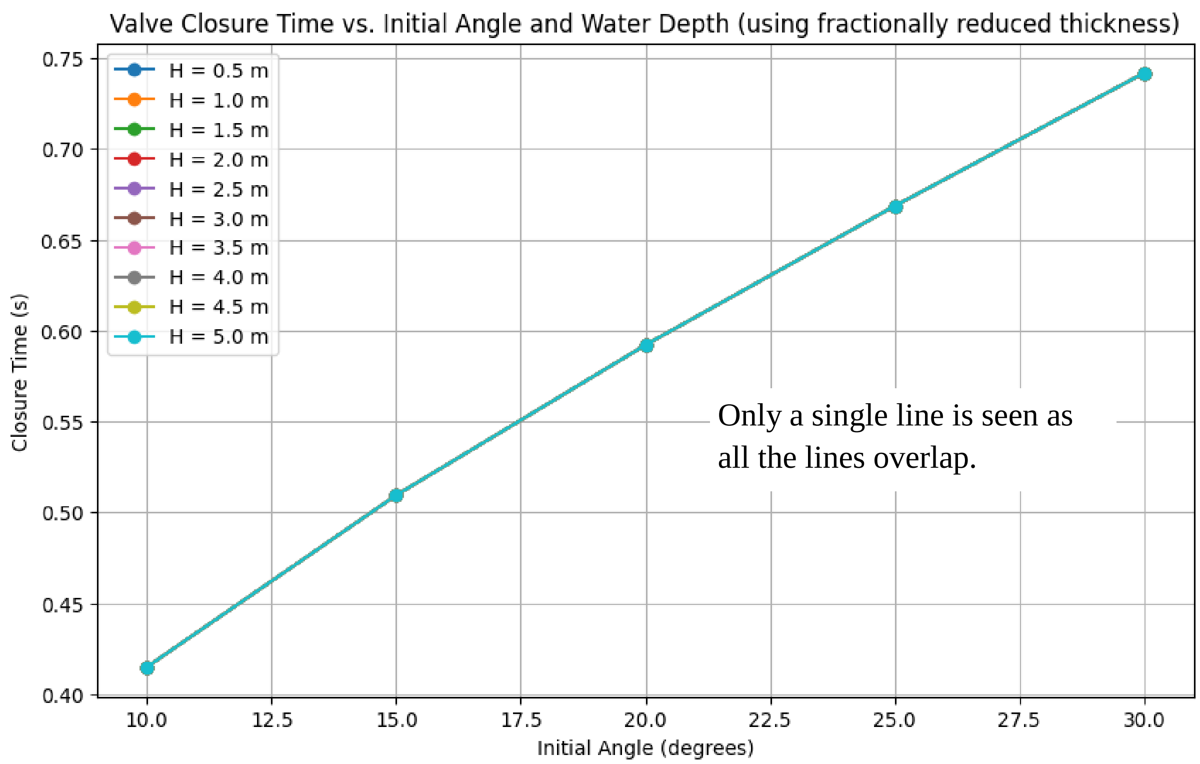

Figure 6.22: Valve closure time for different initial valve opening angles and fall heights (drive pipe size 80 mm.

In actual usage, height of water may fall between the discrete values given in Tables 6.6 and 6.7. A specific height requires tailored angle and valve thickness for optimum performance, but finding and installing the corresponding thickness is hardly possible. Changing the counter moment from weight of the valve to spring load introduces more flexibility. As the spring load can be adjusted by tuning its strain, making a given pump fit to different heights and discharge conditions is possible. Table 6.7 shows that the valve thickness can go as high as 75 mm which is not workable. Such physically impossible conditions signify the introduction of a spring to replace valve weight.

6.6.2 Resistance Moments versus Closure Time

Given a flow of water through the drive pipe, the speed with which the impulse valve closes depends on the rate at which the resistance moment decreases, and the intensity of pressure distribution increases with time. The resistance moment of the Impulse Valve is the sum of the moments due to weight of the valve and tensile force in the spring.

6.6.2.1 Resistance Moment due to Weight of the Valve

As weight of valve is fixed for a given thickness, the moment depends on its angle with the horizontal, as expressed through $cos\ \theta$. As the valve closes, the angle increase, and as the angle increases, the resistance moment decreases proportional to reduction of $cos\ \theta$. Figure 6.23 shows the rate at which the resistance moment of the valve decreases. When one uses spring to increase adaptability of the pump, the required valve thickness becomes thin and hence the resistance moment from the weight of the valve is not very significant.

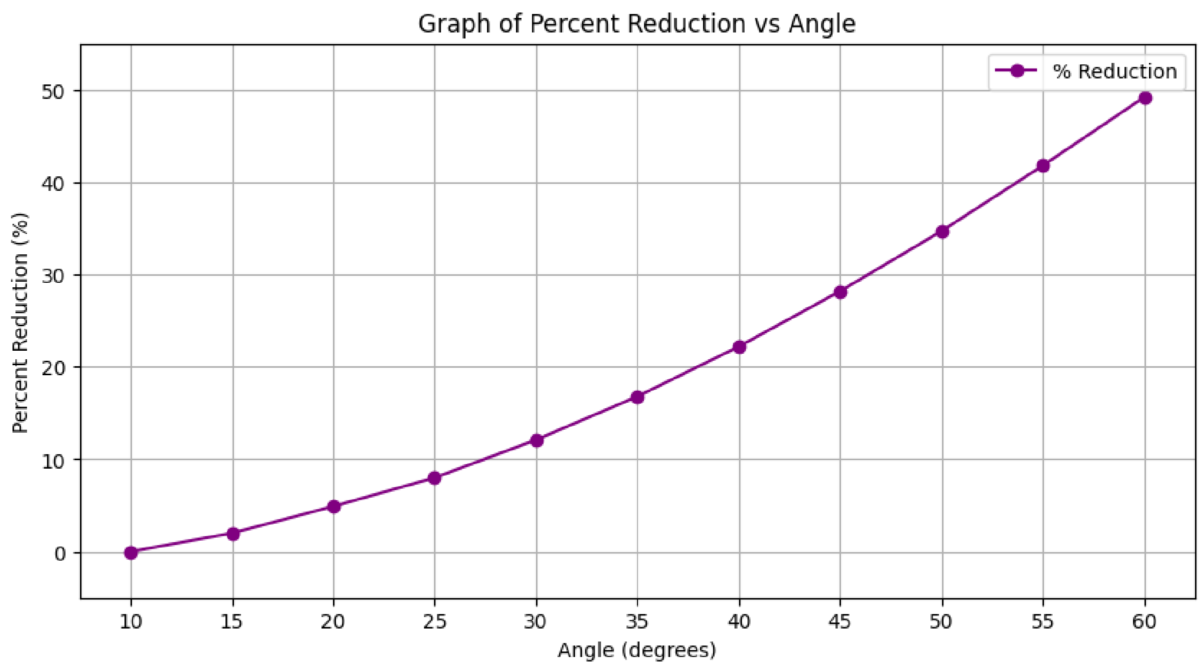

Figure 6.23: The rate at which the resistance moment of an impulse valve decreases as it closes (for weight-only valve and angle variation of 10 to 60)

6.6.2.2 Resistance Moment due to Spring

As the valve closes, the valve angle, θ, increases. Once the impulse valve starts closing, the spring length "S" increases and its moment arm, "P" decreases (Figure 6.12). While elongation of the spring increases the resistance moment of the valve, the reduction in moment arm of the spring decreases the resistance moment. The net effect depends on the difference between the two. In Figure 6.24, the red line (with point mark of x) shows the elongation of the spring, while blue line (with point mark of dot) represents the shortening of the moment arm. As seen from the Figure (6.24), for angle of the valve with the horizontal that ranges between 10 to 60 degrees, the spring elongates by 0.00742 units, while the moment arm shortens by 0.04764 units. In other words, the shortening of the moment arm is 6.42 times more as compared to elongation of the spring. As both elongation of the spring and shortening of the moment arm have parallel effect on the resistance moment, the net effect is that the resistance moment decreases very fast. The data for Figure 6.24 is generated by running Python code developed employing the steps depicted in Table 6.8.

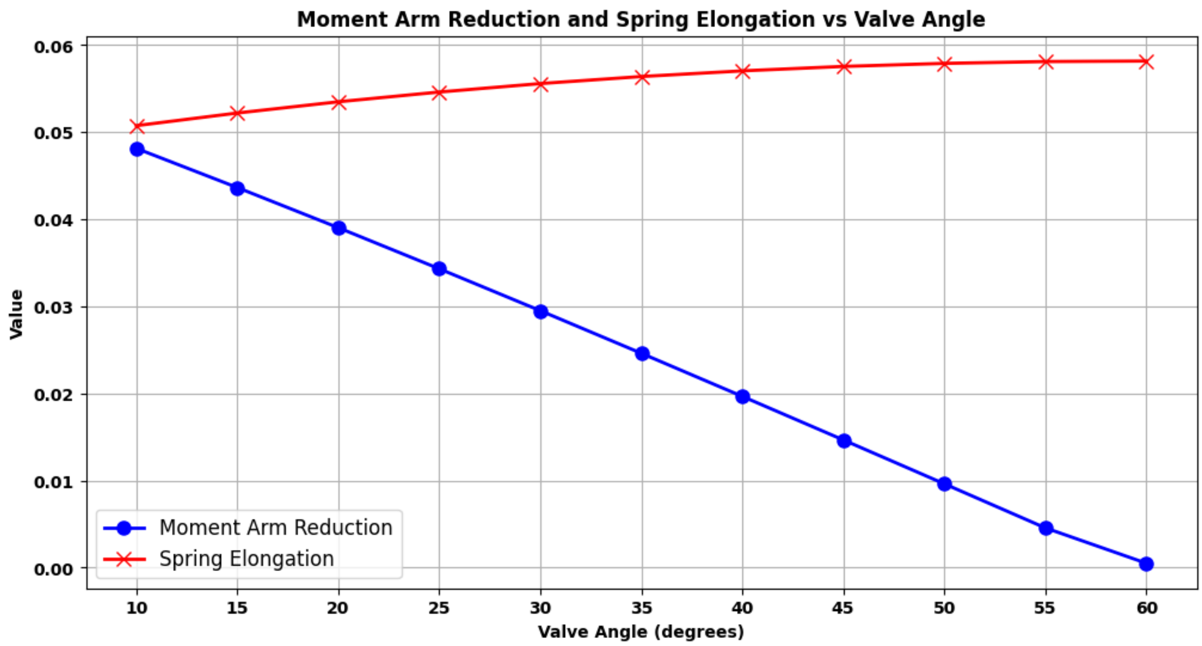

Figure 6.24: The rate at which the spring load increases and the moment arm decreases (for *spring-loaded* valve with angle variation of 10 to 60)

Table 6.8: Prompt to write code for examination of the effects of spring elongation and moment arm shortening

1	Refer to Figure 6.11
2	Given θ, β, L, and L'
3	Calculate $\gamma_1 = tan^{-1}\{(L * sin(\beta - \theta))/(L * cos(\beta - \theta) + L')\}$
4	Calculate $\propto_1 = \beta - \theta - \gamma_1$
5	Calculate $S_1 = L * cos \propto_1 + L' * cos\gamma_1$
6	Calculate $P_1 = L' * sin\gamma_1$

7	Increase θ by a small amount $d\theta$
8	Calculate $\gamma_2 = tan^{-1}\{(L * sin(\beta - (\theta + d\theta))/(L * cos(\beta - (\theta + d\theta)) + L')\}$
9	Calculate $\propto_2 = \beta - (\theta + d\theta) - \gamma_2$
10	Calculate $S_2 = L * cos \propto_2 + L' * cos\gamma_2$
11	Calculate $P_2 = L' * sin\gamma_2$
12	Write a code to compare $absolute\ value\ of\ (S_2 - S_1)$ and $absolute\ value\ of\ (P_2 - P_1)$ for different values of θ

The code so written is depicted in Table 6.9

Table 6.9: Python code to compare the effect of spring elongation and moment arm shortening on the resistance moment of the valve as it closes

```
import math
# Function to calculate gamma

def calculate_gamma(theta, beta, L, L_prime):

    numerator = L * math.sin(math.radians(beta – theta))
    denominator = L * math.cos(math.radians(beta – theta)) + L_prime
    gamma = math.degrees(math.atan2(numerator, denominator))
    return gamma

# Function to calculate alpha

def calculate_alpha(beta, theta, gamma):
    alpha = beta – theta – gamma
    return alpha

# Function to calculate S

def calculate_S(L, alpha, L_prime, gamma):
    S = L * math.cos(math.radians(alpha)) + L_prime * math.cos(math.radians(gamma))
    return S

# Function to calculate P

def calculate_P(L_prime, gamma):
    P = L_prime * math.sin(math.radians(gamma))
    return P

# Main function to compare absolute differences

def compare_absolute_differences(theta_start, theta_end, theta_step, beta, L, L_prime, dtheta):

    # Loop through θ values from θ_start to θ_end with step size theta_step

    theta = theta_start
    while theta <= theta_end:
```

```
print(f"\n--- θ = {theta} degrees ---")

# Step 2: Calculate γ1
gamma_1 = calculate_gamma(theta, beta, L, L_prime)

# Step 3: Calculate α1

alpha_1 = calculate_alpha(beta, theta, gamma_1)

# Step 4: Calculate S1

S_1 = calculate_S(L, alpha_1, L_prime, gamma_1)

# Step 5: Calculate P1

P_1 = calculate_P(L_prime, gamma_1)

# Step 6: Increase θ by dθ

theta_new = theta + dtheta

# Step 7: Calculate γ2

gamma_2 = calculate_gamma(theta_new, beta, L, L_prime)


# Step 8: Calculate α2

alpha_2 = calculate_alpha(beta, theta_new, gamma_2)

# Step 9: Calculate S2

S_2 = calculate_S(L, alpha_2, L_prime, gamma_2)

# Step 10: Calculate P2

P_2 = calculate_P(L_prime, gamma_2)

# Step 11: Compute absolute differences

abs_diff_S = abs(S_2 – S_1)

abs_diff_P = abs(P_2 – P_1)

print(f"Absolute value of S2 - S1 = {abs_diff_S}")

print(f"Absolute value of P2 - P1 = {abs_diff_P}")

if abs_diff_S > abs_diff_P:

    print("|S2 - S1| is larger than |P2 - P1|.")

elif abs_diff_S < abs_diff_P:

    print("|P2 - P1| is larger than |S2 - S1|.")
```

```
        else:

            print("|S₂ - S₁| and |P₂ - P₁| are equal.")

        # Update θ for the next iteration

        theta += theta_step

# Input values

theta_start = 10  # Initial θ in degrees
theta_end = 60    # Ending θ in degrees
theta_step = 1    # Step size for θ in degrees
beta = 60         # β in degrees

L = 10            # L
L_prime = 5       # L'

dtheta = 1        # dθ in degrees

# Compare absolute differences for different θ values

compare_absolute_differences(theta_start, theta_end, theta_step, beta, L, L_prime, dtheta)
```

Sample output of the comparison

```
--- θ = 10 degrees ---
Absolute value of  S₂ - S₁ = 0.048
Absolute value of  P₂ - P₁ = 0.051
|P₂ - P₁| is larger than |S₂ - S₁|.

--- θ = 11 degrees ---
Absolute value of  S₂ - S₁ = 0.047
Absolute value of  P₂ - P₁ = 0.051
|P₂ - P₁| is larger than |S₂ - S₁|.

--- θ = 12 degrees ---
Absolute value of  S₂ - S₁ = 0.046
Absolute value of  P₂ - P₁ = 0.051
|P₂ - P₁| is larger than |S₂ - S₁|.

--- θ = 13 degrees ---
Absolute value of  S₂ - S₁ = 0.045
Absolute value of  P₂ - P₁ = 0.051
|P₂ - P₁| is larger than |S₂ - S₁|.

--- θ = 14 degrees ---
Absolute value of  S₂ - S₁ = 0.045
Absolute value of  P₂ - P₁ = 0.052
|P₂ - P₁| is larger than |S₂ - S₁|.

--- θ = 15 degrees ---
Absolute value of  S₂ - S₁ = 0.044
Absolute value of  P₂ - P₁ = 0.052
|P₂ - P₁| is larger than |S₂ - S₁|.
```

6.6.3 Comparison of Closure Times (valve weight against spring)

To see the closure time impact of replacing valve weight with spring, the following steps are employed.

1. *Computation of closure times by putting spring-loaded valve*: Though, ideally, it is possible to convert any valve weight to the equivalent spring load, a physical valve of the lightest possible weight is mandatory to be used with the spring in order to get the effect of a valve opening and closing. So, lightest weight spring loaded valve is used. The spring thickness may be determined by the wear and tear it experiences.

2. *Computation of closure times by replacing the spring load with equivalent valve weight:* To effect this step, influence of the spring is nullified by putting zero in place of stiffness (K) value in the code written for closure time computation.
3. *Comparing the two*: The comparison between closure times of the above two steps show the difference.

Same code given in **Appendix III** is used for the comparison. The general formula used for the comparison and its expanded form is given in Equation 6.44.

<table>
<tr><td colspan="3">$$\frac{M_{drag}(\theta) - M_{valve}(\theta) - M_{spring}(\theta)}{I_{m(x)}} = \frac{d^2\theta}{dt^2}$$</td><td rowspan="9">Eqn. 6.44</td></tr>
<tr><td colspan="3">$$M_{drag}(\theta) = \int_0^{0.1sin\theta}\int_{0.01}^{0.09}((\frac{1}{2}\rho_w C_D\left(1.139*\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dwdh)*h$$</td></tr>
<tr><td colspan="3">$$M_{valve}(\theta) = b*l*t*\rho_s*g*\left(\frac{l}{2}\right)cos\theta$$</td></tr>
<tr><td rowspan="2">$M_{spring}(\theta) = K(Lcos\alpha + L'cos\gamma - L_{initial})*(L'sin\gamma)$</td><td>$K$=</td><td>spring stiffness</td></tr>
<tr><td>ρ_s=</td><td>mass density of valve</td></tr>
<tr><td rowspan="2">$\gamma = tan^{-1}\{L*sin(\beta-\theta))/(L*cos(\beta-\theta)+L'\}$</td><td>$b$=</td><td>width of valve</td></tr>
<tr><td>l=</td><td>length of valve</td></tr>
<tr><td rowspan="2">$I_{m(x)}$=$\rho_s*b*th*l^3/3$</td><td>th=</td><td>thickness of valve</td></tr>
<tr><td colspan="2">refer Fig. 6.12 and Eqn. 6.19 for details</td></tr>
</table>

Table 6.10: [Impulse Valve Thicknesses], [K], [$\Delta S_{initial}$] and [closure times, ts] for *spring – loaded* valve, for 80 mm diameter drive pipe and size of the main body of the pump 100 by 100 mm

Height H (m)	[Impulse valve thickness (mm)][Spring constant, K (N/m)] [Initial spring extension (mm)], Closure times: t_s(sec)] for valve angles (with the horizontal) of:									
	10°	t_s	15°	t_s	20°	t_s	25°	t_s	30°	t_s
0.5	[0.1][100] [4.8]	0.223	[0.1][150] [10.6]	0.164	[0.1][350] [10.1]	0.142	[0.1][900] [7.4]	0.134	[0.1][1500] [7.6]	0.119
1	[0.1][100] [10.8]	0.149	[0.1][150] [21.9]	0.113	[0.1][350] [20.6]	0.096	[0.1][900] [15.0]	0.087	[0.1][1500] [15.3]	0.077
1.5	[0.1][100] [16.7]	0.121	[0.1][150] [33.3]	0.092	[0.1][350] [31.2]	0.078	[0.1][900] [22.5]	0.070	[0.1][1500] [22.9]	0.062
2.0	[0.1][100] [22.6]	0.105	[0.1][200] [33.5]	0.081	[0.1][350] [41.7]	0.068	[0.1][900] [30.1]	0.060	[0.1][1500] [30.6]	0.054
2.5	[0.1][100] [28.5]	0.094	[0.1][200] [42.0]	0.073	[0.1][500] [36.5]	0.062	[0.1][900] [37.6]	0.054	[0.1][1500] [38.3]	0.048
3.0	[0.1][150] [22.9]	0.087	[0.1][300 [33.7]	0.068	[0.1][500 [43.9]	0.057	[0.1][900 [45.2]	0.05	[0.1][1500 [46.2]	0.044
3.5	[0.1][150] [26.9]	0.081	[0.1][300] [39.4]	0.063	[0.1][600] [42.7]	0.053	[0.1][1500] [31.7]	0.047	[0.1][2000] [40.2]	0.041
4.0	[0.1][150] [30.8]	0.076	[0.1][300] [45.1]	0.059	[0.1][600] [48.8]	0.496	[0.1][1500] [36.2]	0.044	[0.1][2000] [46.0]	0.039
4.5	[0.1][150] [34.8]	0.072	[0.1][350] [43.5]	0.056	[0.1][800] [41.2]	0.047	[0.1][1500] [40.7]	0.042	[0.1][2500] [41.4]	0.037
5.0	[0.1][150] [38.7]	0.068	[0.1][350] [48.4]	0.053	[0.1][800] [45.8]	0.045	[0.1][1500] [45.3]	0.04	[0.1][2500] [46.0]	0.035

Note: 1. The angle is measured clockwise with the horizontal
2. The Drag Coefficient, C_D, is taken to be 1.17

Table 6.11: Relative valve closure times for impulse valve weight, for equivalent spring and percentage difference

Height H (m)	Angle														
	10°			15°			20°			25°			30°		
	Closure Time		%	Closure Time		%	Closure Time		%	Closure Time		%	Closure Time		%
	t_w	t_s		t_w	t_s		t_w	t_s		t_w	t_s		t_w	t_s	
0.5	0.415	0.223	46	0.509	0.164	68	0.592	0.142	76	0.669	0.134	80	0.742	0.119	84
1	0.415	0.149	64	0.509	0.113	78	0.592	0.096	84	0.669	0.087	87	0.742	0.077	90
1.5	0.415	0.121	71	0.509	0.092	82	0.592	0.078	87	0.669	0.070	90	0.742	0.062	92
2.0	0.415	0.105	75	0.509	0.081	84	0.592	0.068	89	0.669	0.060	91	0.742	0.054	93
2.5	0.415	0.094	77	0.509	0.073	86	0.592	0.062	90	0.669	0.054	92	0.742	0.048	94
3.0	0.415	0.087	79	0.509	0.068	87	0.592	0.057	90	0.669	0.05	93	0.742	0.044	94
3.5	0.415	0.081	80	0.509	0.063	88	0.592	0.053	91	0.669	0.047	93	0.742	0.041	94
4.0	0.415	0.076	82	0.509	0.059	88	0.592	0.496	16	0.669	0.044	93	0.742	0.039	95
4.5	0.415	0.072	83	0.509	0.056	89	0.592	0.047	92	0.669	0.042	94	0.742	0.037	95
5.0	0.415	0.068	84	0.509	0.053	90	0.592	0.045	92	0.669	0.04	94	0.742	0.035	95

Note: 1. The angle is measured clockwise with the horizontal

2. The Drag Coefficient, C_D, is taken to be 1.17

3. Diameter of the drive pipe is 80 mm and size of the chamber is 100 by 100 mm.

t_w= time of closure due to valve weight

t_s= time of closure due to spring force

For a given $\theta, \beta, H, K, \rho_{w,}C_D, \rho_s, g$ values, the code computes $\Delta_{s\_initial}$ and valve closure time.

6.6.4 Observations and their Explanations

The following are observed from the simulations the results of which are depicted in Tables 6.6 and 6.7.

1. For the heights and valve angles considered, the use of spring results in very significant reduction of relative time of closure.

   The reasons for such reductions are the following.

   a. In case of the *weight-only* valve, the net torque is the difference between the torque caused by drag force less the resistance torque by weight of the valve. This net torque is expected to bring angular acceleration on the valve of greater mass moment of inertia. In case of spring-loaded valve, on the other hand, though the net torque is same, that net torque acts on a valve with smaller mass moment of inertia. In other words, the spring contributes to the resistance moment, but does not contribute to the mass moment of inertia. The lesser the mass moment of inertia, the higher the angular acceleration is, and hence the faster the closure time. By how much weight of the valve is replaced with spring, by so much the closure time is shortened. This reason holds true for the rest of the observations as well.

   b. The resistance from the spring vanishes as the *spring-loaded* valve attains closed position. For weight valve, however, till the valve is closed, and even at closed position, there is a residual counter moment as the angle with the horizontal is 60°, not 90°. Initially the valves in both cases have equal counter moment. Once closure starts, however, the rate at which the resistance from *weight-only* valve decreases is less than that of the spring-loaded valve. Referring Figure 6.25 the shaded area represents the additional energy consumed by the *weight-only* valve as compared to *spring-loaded* one.

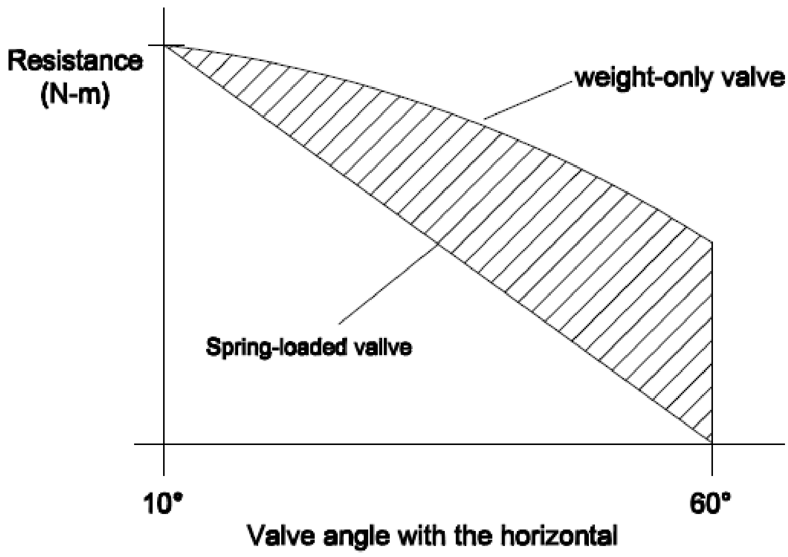

Figure 6.25: Valve resistances at different positions (spring-loaded and weight-only valves)

c. The other measure which enables exploitation of the available head is reducing the angle of opening (as measured clockwise with the horizontal), or, in other words, widening the opening of the valve as the head increases. This setup results in reduction of closure time, as compared to the closure time obtained by keeping the angle and increasing the valve thickness. This is because of the outweighing retardation effect of the increase in mass required to balance the drag moment, following the increased vertical projection, of the valve, with increased valve angle. Same is empirically observed from Tables 6.6 and 6.7.

2. Equations 6.42 and 6.43 show that the angular acceleration approaches infinity as the thickness of the valve approaches zero. Though this is theoretically possible (by making the full resistance to be induced by the spring), it is constrained by the following two conditions.
   a. Velocity of the valve, at any instant, cannot be faster than the velocity of water flowing through the main body of the pump (near the valve), which is finite for a given setups. Velocity faster than the velocity of water implies separation between the water and the valve. Such phenomenon, if happens, creates partial vacuum which retards the flow and regulates the velocity to equilibrium.
   b. As thickness of the valve approaches zero its strength diminishes and cannot withstand the pressure, wear and tear caused by the pumping mechanisms.

   The velocity in the drive pipe which equals $\sqrt{2gH}$ (for friction less condition) is reduced by the area ratios of the cross sections of the drive pipe and main body of the pump while flowing through main body of the pump. As the valve closes, however, area of the valve opening decreases and this increases the exit velocity.

3. For a given opening angle of impulse valve, the valve closure time is independent of height H and independent of the area ratio of drive pipe to main body of the pump. This observation is mathematically proved as follows.

   Proof.

   a) Computation of closure times follows the following steps:
      i. The valve thicknesses (that balance the drag moment with the valve moments) are computed. Drag moment is worked out using Equation 6.38, and the valve moment is obtained from Equation 6.40. These conditions do not give any closure times as rotation of the valve is not triggered because of the equilibrium between the driving (drag) and resisting (valve) moments.
      ii. Thickness of the valve is reduced by infinitesimally small amount. This reduction triggers rotation of the valve and hence results in closure times (Equation 6.43).

b) The velocity distribution in a square pipe is given by Equation *P-A*. Equation *P-A* is a modified form of Equation 6.11. It is obtained by shifting the origin of the coordinates from center of the square pipe to bottom left corner.

$u(w,h) = u_{max}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}$	*Eqn. P-A*

c) In Equation *P-A*, the velocity used is the maximum velocity while the velocity computed by $\sqrt{2gH}$ is the average velocity, not the maximum velocity.

d) Equations 6.13 relate the maximum and average velocity. When Equation *P-A*, that takes the maximum velocity, is rewritten in terms the average velocity, it gives Equation *P-B*

$u(w,h) = 1.31u_{avg}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}$	*Eqn. P-B*

e) Replacing $\sqrt{2gH}$ in place of $u_{avg}$and putting the g value results in Equation *P-C*

$u(w,h) = 5.803\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}$	*Eqn. P-C*

f) When the water enters from a drive pipe of area A_D to main body of the pump of area A_P, The average velocity is reduced by the ratio $^{A_D}/_{A_P}$ and Equation *P-C* takes the form Equation *P-D* in main body of the pump

$u(w,h) = \frac{A_D}{A_P}5.803\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}$	*Eqn. P-D*

g) Equating the drag moment with the valve moment for equilibrium yields Equation *P-E*.

$$[\int_0^{0.1sin\theta}\int_{0.01}^{0.09}((\frac{1}{2}\rho_w C_D\left(\frac{A_D}{A_P}5.803\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dwdh)*h] = [b*l*(th)*\rho_s*g*(l/2)cos\theta]$$	*Eqn. P-E*

h) Equation 6.43 (the equation used to compute closure time of the impulse valve can now be written as Equation *P-F*.

$$\frac{\{[\int_0^{0.1sin\theta}\int_{0.01}^{0.09}((\frac{1}{2}\rho_w C_D\left(\frac{A_D}{A_P}5.803\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dwdh)*h]-[b*l*(th)*\rho_s*g*(l/2)cos\theta]\}}{\{\frac{\rho_s*b*(th)*l^3}{3}\}}=\frac{d^2\theta}{dt^2}$$	*Eqn. P-F*

i) If the area ratio $\frac{A_D}{A_P}$ and the height H are altered by factors η and ξ respectively, then the left hand side of Equation *P-E*, is factored by

$$\eta^2 * \xi$$

j) As adjustment is possible only through varying the thickness of the right hand side of Equation, for equilibrium, thickness of the valve th should also be factored by same $\eta^2 * \xi$. Equation *P-F* then becomes

$$\frac{\{(\eta^2*\xi)[\int_0^{0.1sin\theta}\int_{0.01}^{0.09}((\frac{1}{2}\rho_w C_D\left(\frac{A_D}{A_P}5.803\sqrt{H}\left(1-\left(\frac{0.05-w}{0.05}\right)^2\right)^{\frac{1}{4}}\left(1-\left(\frac{0.05-h}{0.05}\right)^2\right)^{\frac{1}{4}}\right)^2 dwdh)*h]-[b*l*((\eta^2*\xi)*th)*\rho_s*g*(l/2)cos\theta]\}}{(\eta^2*\xi)*\{\frac{\rho_s*b*(th)*l^3}{3}\}}=\frac{d^2\theta}{dt^2}$$	*Eqn. P-G*

k) Factoring out $(\eta^2 * \xi)$ from all expressions in both numerator and denominator and canceling yields back Equation *P-F* and this proves that the closure time is independent of height (*H*) and area ratio ($\frac{A_D}{A_P}$) alterations

l) As the decrease in valve thickness to trigger closure of the valve is infinitesimally small (only 1/10,000,000 of the equilibrium thickness) it does not alter the above conclusion.

4. When weight is replaced with spring load, the closing time decreases significantly as the fall height increases.

   This is because of the following reasons

   a. As the weight of the *weight-only* valve increases, following increase in height, the residual counter-moments at every spot increase.
   b. Once closure starts, the rate at which the resistance from *weight-only* valve decreases is less than that of the *spring-loaded* valve. At every position the resistance from the weight-only valve is greater than that of the *spring-loaded* valve, and this decreases the net force acting on the valve.

5. For a given fall height, the closing time increases with increase of initial open position valve angle (for weight-only valve), and the contrary happens for *spring-loaded* valve.

   This is because of the fact that bigger mass is required for equilibrium as the initial open position angle increases (for weight-only valve) and bigger mass means higher moment of inertia. For *spring-loaded* valve, on the other hand, the balance is created by increasing the tension in the spring which has no effect on mass moment of inertia. Reduction of rotation angle (for *spring-loaded* valve) decreases the closure time.

6. For a given initial opening angle and for *spring-loaded* valve, the closure time deceases as the fall height increases

   The reason for such shortening of closure time is that the drag moment increases as the height increases. For *spring-loaded* valve, there is no need to increase the mass. The balance is gained by stretching the spring. Increased drag moment with constant mass moment of inertia results in shorter closure time.

6.7 Adaptation on Working Heads

6.7.1 Thickness and Opening of Impulse Valve

Tables 6.6 and 6.7 show the thicknesses of steel impulse valve required to fully exploit different heads for varying angles of the valves (at open positions) and for drive pipe sizes of 50 and 80 mm respectively.

By full exploitation of a given head, it is meant that the drag force generated from the flow caused by the head is just enough to trigger closure of the valve. If the head required to trigger closure of the valve is bigger than the available, the valve does not close and the pump does not start functioning. What happens if the available head exceeds the amount required to trigger closure?

When the available head exceeds the amount required to trigger closure; which means when the velocity required to exert closure-triggering drag force, given the vertically projected area of the valve exposed to the flow, is less than the final velocity expected from the full height, the trigger starts earlier. From Equation 6.6, it can be seen that this earlier time gives a height less than the full height available, which implies that only portion of the potential is used.

With fixed weight of impulse valve, and fixed valve angle, it is hardly possible to make a pump fit to varying heads and discharges. One valve weight with one valve angle is fit to a unique potential. From Table 6.6, it is read that for a valve angle of 15 degrees, the valve thickness required to tap a potential of 3.5 meter is 1.6 mm. This is when a 50 mm drive pipe feeds a 100 by 100 mm square chamber of the pump. For a given pump size, as the diameter of drive pipe increases, the Impulse valve thickness, required for a given height, increases. As seen from Table 6.7, when the size of the drive pipe increases to 80 mm, then the impulse valve thickness required for same 3.5 meters of height would be 10.2 mm. As the angle increases, the valve thickness required increases as well. For similar height of 3.5 meters and valve angle of 25 degrees, the required valve thickness increases to 5.2 and 34.2 mm (for 50 mm and 80 mm drive pipe sizes, respectively). The relationship between valve angle and valve thickness for a given height is quadratic.

Though the possibility of varying valve angle imparts considerable flexibility to ram pumps, pumps do not perform with equal efficiency at all valve angles. Generally, efficiency of a pump is measured by looking at the ratio of output to input. For the case of hydraulic ram pump, the input is product of head and flow in drive pipe and output is the product of head and flow in delivery pipe [68].

Efficiency of hydraulic ram pump depends, among others, on: weight and stroke of the impulse valve [69]; the size ratios of impulse valve to delivery valve [70]; and ratio of sectional area of main body of the pump to opening of impulse valve. One area of the adaptation is making area of the impulse valve opening adjustable by introducing sliding plate.

6.8 Parallel Adaptation

6.8.1 Delivery Pipe

Introduction of a spring is shown to have two main advantages. One is fast closure of the impulse valve and the other is imparting adjustable drag resistance to the impulse valve. To exploit this versatility, main body of the pump can be made bigger and size of the drive pipe can be selected based on the available and/or the required flow.

Empirically size of the supply pipe is recommended to be half of the drive pipe [71]. Flexibility of using varying drive pipe sizes requires matching sizes of the supply pipe. In order to accommodate the varying diameters of delivery pipes, the opening at the pressure chamber shall be designed for the maximum delivery pipe size. For the model pump chosen, the calculated opening at the pressure chamber is a square of side 70 mm (half the area of main body of the pump). For smaller drive pipe sizes, the matching size of delivery pipe is less than the maximum opening availed. A transition zone is, therefore, provided in order to make sure that no vena contracta is formed.

Vena contracta is formed when sudden contraction is experienced by a flow. If the maximum delivery pipe is directly connected to the pressure chamber, it is likely that vena contracta is formed, depending on the size of the pressure chamber and magnitude of the velocity. To avoid the formation of vena contracta, the opening at the pressure chamber (for the delivery pipe) is made bigger than the maximum size of the delivery pipe. How bigger should it be?

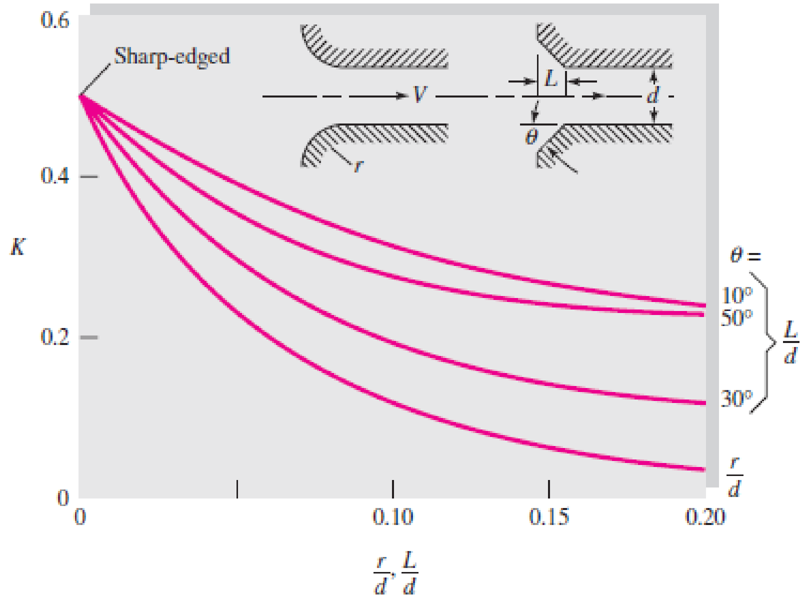

Figure 6.26: Rounded and beveled inlet coefficients

Figure 6.26 shows loss coefficients, K, for beveled and rounded exits. When $r = 0.2d,$ the entrance is well rounded and the loss coefficient is practically negligible. Same figure shows that a beveled exit with beveling angle of 30° shows lower K value of 0.15 next to a well rounded exit for an L/d ratio of 0.2 (which gives an L value of 35 mm). From this, it can be seen that, an opening with 20 mm (35$*$ tan30°) extra for each side is required. This makes the total opening 110 mm (70+20+20). The pressure chamber needs, therefore, to have a minimum of 110 mm. The nearest available commercial size may be chosen.

The convergence angle, required to avoid vena contracta due to sudden contraction, is generally bigger than the divergence angle, required to avoid formation of vortex due to sudden expansion. This is the reason why convergent entrance transition zone of a Venturi meter is shorter than its divergent outlet transition. Though the purpose of Venturi meter is to measure the flow in a pipe, its hydraulic and geometric requirements (such as nominal head loss) are also required and hence can be adapted to the relevant sections of hydraulic ram pump.

American Society of Mechanical Engineers recommends the following for a Venturi meter:

a. Length of section before tapering $L_1 \geq$ diameter of the pipe (D);
b. Length between flange and start of convergence, $Z \leq {}^{D}/_{2} \pm {}^{D}/_{4}$ (for 100 mm $\leq D \leq 150\ mm$)
c. ${}^{D}/_{4} \leq Z \leq {}^{D}/_{2}$ (for $150\ mm \leq D \leq 810mm$)
d. Included angle of the convergence section to be $21° \pm 1°$.

For the model pump, the delivery pipe connection details will be as shown in Figure 6.27.

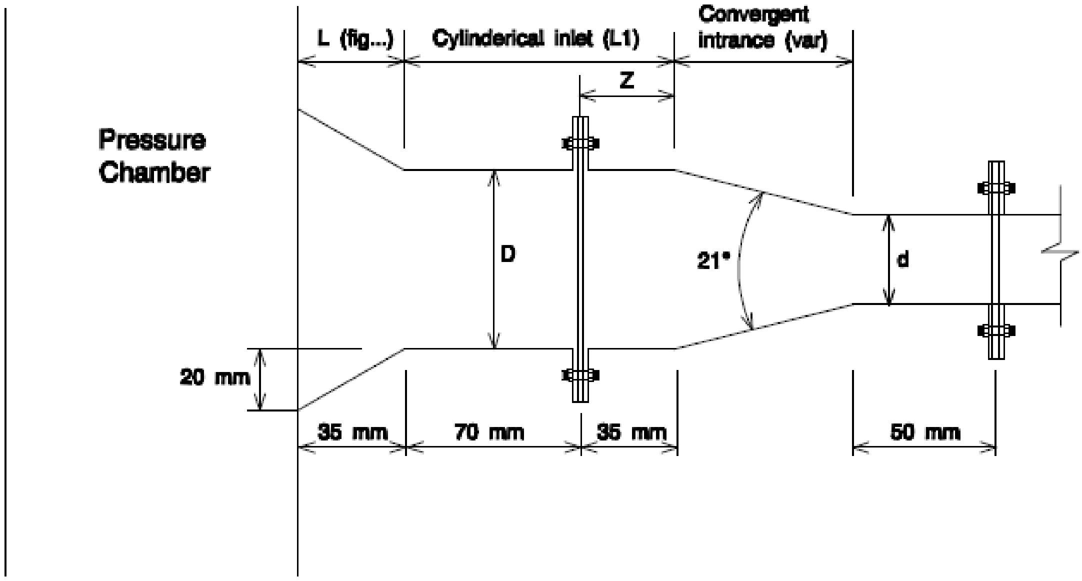

Figure 6.27: Pressure chamber - delivery pipe connection detail

The adapters (flanges) introduced have the following additional advantages as well

a. enable production of the Pump by parts
b. give access to the internal parts of the Pump and
c. make the product suitable for packing, assembling and disassembling

6.8.2 Application of Design Charts

Most of the design norms and tables of hydraulic ram pump are prepared for circular sections. This may be seen as a challenge in using square (rectangular) sections in place of circular sections. It is possible, however, to make design of pumps employing the available provision for circular sections by computing the equivalent circular sections for the square (rectangular) ones, employing Equation 6.45. The equivalent diameter is the diameter of a circular duct or pipe that for equal flow gives the same pressure loss or resistance as an equivalent duct or pipe [72].

$$D_e = \frac{1.30\ (ab)^{0.625}}{(a+b)^{0.25}} \qquad \textit{Eqn. 6.45}$$

Where:

$D_e =$	Equivalent Diameter
$a =$	One side dimension of the rectangular (square) section
$b =$	The other side dimension of the rectangular (square) section

For square sections, "a" and "b" take same values.

6.8.3 The Pump after Adaptation

Vertical section of the pump with its generic parts and parts included by the adaptation are given in Figure 6.28. Isometric view of same is displayed in Figure 6.29. Name of the parts are depicted in table 6.12.

Table 6.12: Names of hydraulic ram pump parts

No.	Part Name	No.	Part Name
1	Drive Pipe	14	Supply Valve (rod)
2	Adapter / tapering section (from pump size to Drive Pipe size)	15	Supply Valve (sliding tube)
3	Main Body of Pump	16	Supply Valve (sliding tube bracing)
4	Impulse Valve opened position	17	Supply Valve (movement control and opening adjustment bolt)
5	Impulse Valve closed position	18	Supply Valve Holder (where Snifter is also installed)
6	Hinge for the Impulse Valve	19	Snifter (to suck and replenish dissolving air)
7	Impulse Valve Angle Adjustment Rod	20	Flange (that connects Supply Valve Holder and Pressure Chamber)
8	Spring	21	Pressure Chamber
9	Impulse Valve Opening Adjustment Plate	22	Supply Pipe (plate)
10	Flange (that fixes valve opening to Impulse Valve)	23	Pressure Gauge
11	Adapter Flanges (that connect tapering sections)	24	Bolt and Nut (for pump fixing)
12	Adapter Flanges (that connect tapering sections)	25	Pump Fixing Frame
13	Supply Valve	26	Spring-Valve Connection

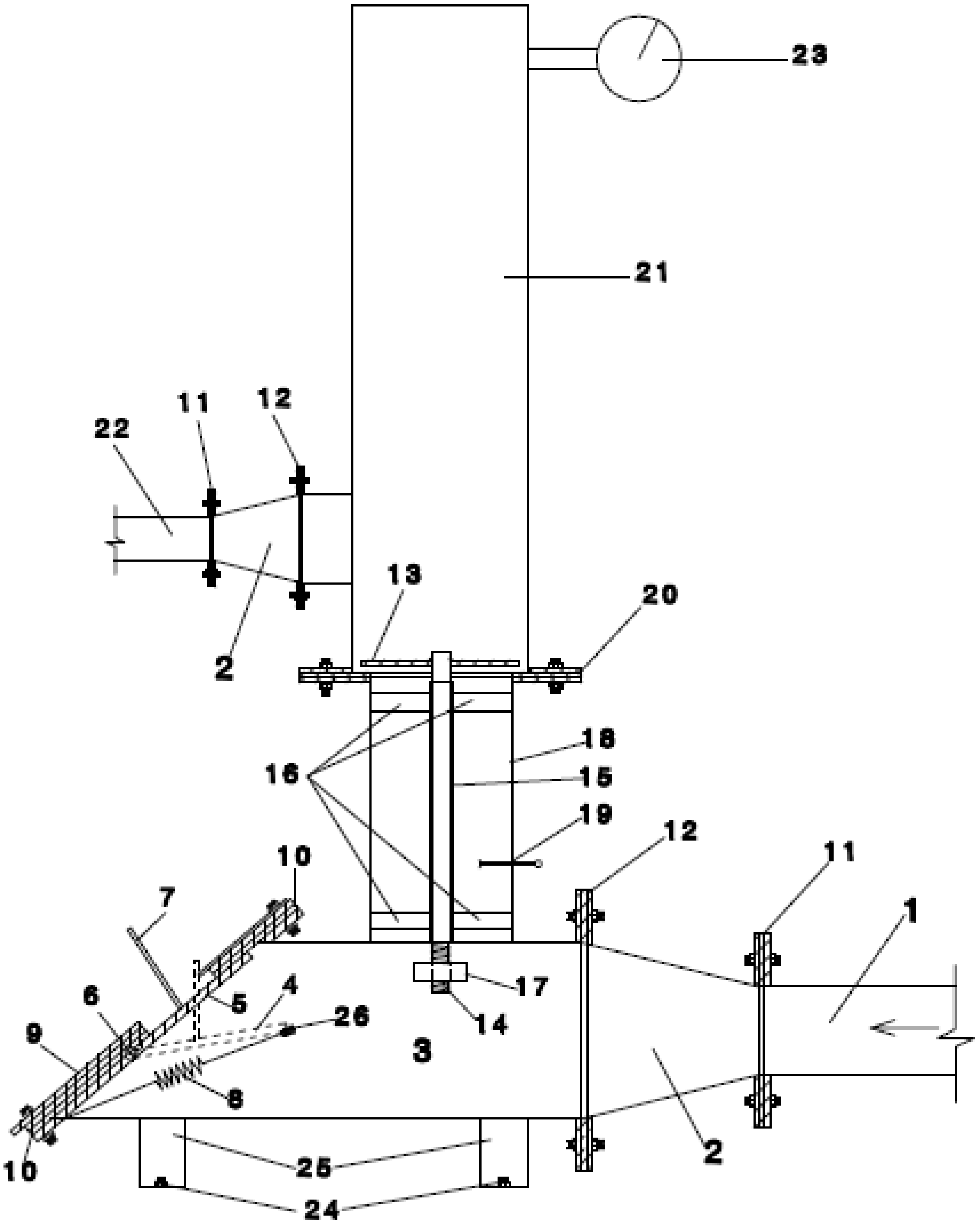

Figure 6.28: Vertical section of the pump with its generic and adopted parts

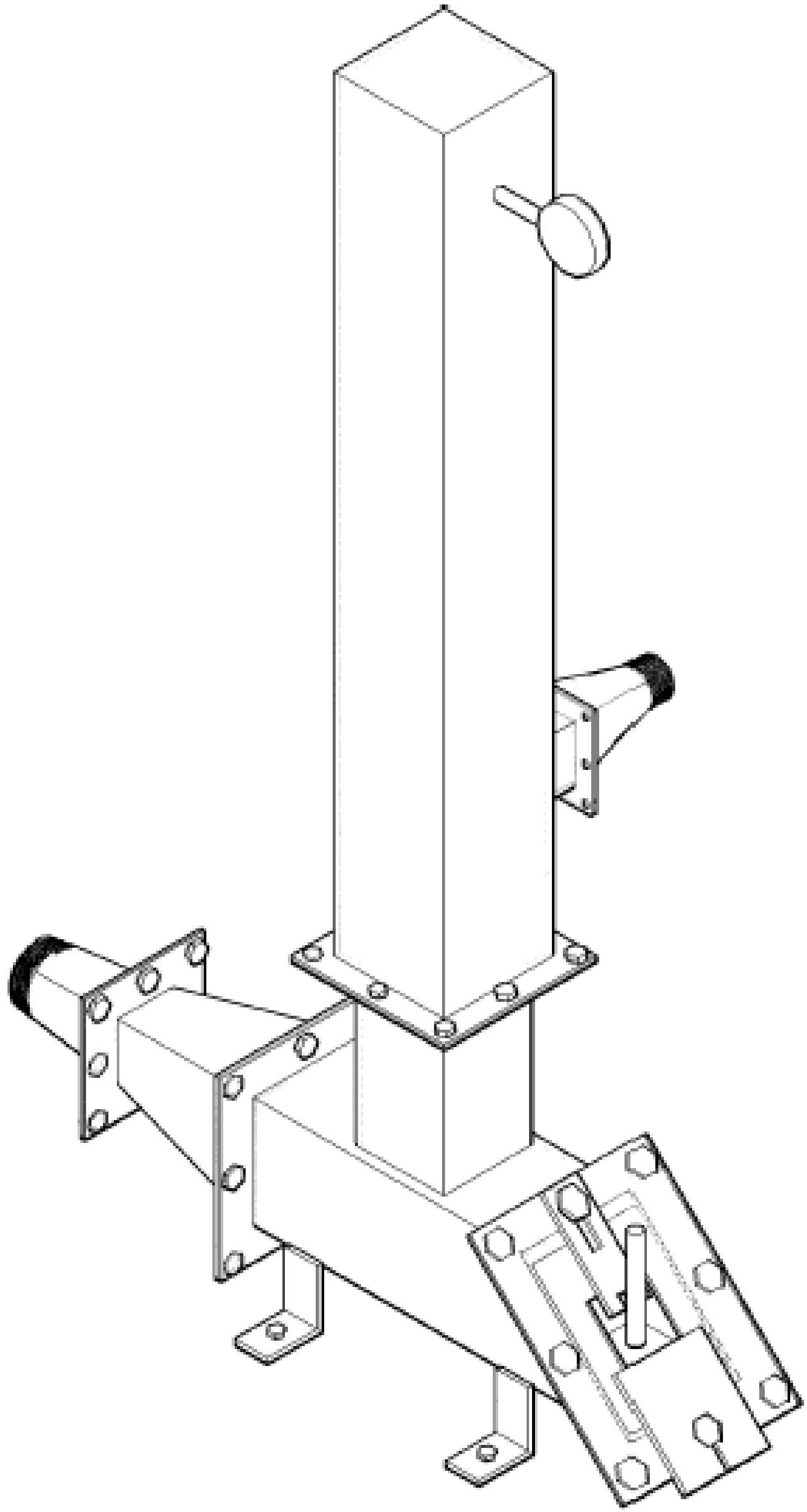

Figure 6.29: Isometric view of the adapted pump

CHAPTER 7

7. Conclusion

Hydro-powered water pumping technologies are pumping technologies that use the energy contained in flowing water to pump portion of it to a level higher than the fall height. The general mechanics of operation can be divided into five categories: manomeric; potential to pressure; sealed tank confinement; water hammer and turbine action.

The comparative analysis identified and addressed thirty-three hydro-powered water pumping technologies with the aim of prioritizing them based on their appropriateness to the major target groups, who are smallholder farmers in Ethiopia, with low level of economy and technical capacity, living in scattered settlement with poor infrastructure, including power. The prequalifying criteria used to filter the candidates, mainly ease of manufacturing and simplicity of operation, has solely taken into account the target groups.

When there is more than one criterion to compare alternatives, multi-criteria comparison techniques are used. The Strength, Weakness, and Suitability evaluation made on the five important considerations; Problem type, Criteria structure, Decision maker involvement, Data availability and quality, and Method complexity and performance; while choosing multi-criteria analysis method implied the most appropriateness of Analytical Hierarchy Process (AHP). The provisions to measure consistency, in undergoing the pair-wise comparisons, and sensitivity; of the ranking to the criteria weights, and measures of performance; are the other equally significant advantages Analytical Hierarchy Process has over the other methods. The sensitivity analyses have involved a total of 3822 pairs for criteria weight and measure of performance.

To nullify the influence of variation in magnitudes (scales) of variables in pair-wise comparison, or to obtain comparable unit, normalization is used. For uniformity, beneficial grading has been employed in all cases, and Linear Normalization (by Sum) is chosen for its transparency.

There are two models used to determine the final Preference / Ranking of the Technologies. Weighted Sum Model and Weighted Product Model. Analytical Hierarchy Process employs Weighted Sum Model.

The rigorous comparative analysis using fourteen criteria of comparison on the fourteen prequalified technologies brought up Hydraulic Ram Pump as the most preferred hydro-powered water pumping technology for flows in rugged terrains ranging from small cricks to large streams. Venturi and Glockmann pumps that stand 2nd and 3rd also belong to the recent generations of ram pump family, with appreciable improvements yet parallel complexity and increased cost. Spiral and Coil pumps are equally preferred for low lands with rolling terrains, characterized by slow but voluminous flow.

Results of the comparative analyses have been examined for consistency of the pair-wise comparisons, the basis for the analysis, and have yielded figures well below the low upper limit set (10 percent). Consistency Ratio – CR of the pair-wise comparisons among criteria during assignment of relative weight to each criterion has been found to be 2.2 percent and that of the comparison of each technology against all the criteria has resulted in an average value of 4.67 percent, all individual values being less than 10 percent. For comparison among increased number of alternatives and parallel number of criteria (similar to the case at hand),where the tolerable consistency limit may go as high as 20 percent, the results found show very high consistency in both cases.

Robustness of the rankings has been revealed through their low sensitivity to alteration on Criteria Weight. The minimum relative increments (in %) required by the criteria weights to swap rank of the first-standing technology in Group ‘A’ (T10) with the remaining, is 31 percent. For Group B, the percent alteration required for swap is 1961.

Sensitivity analysis for Group ‘A’ on measure of performance resulted in a minimum criticality degree of 41 percent which shows high robustness. For Group ‘B’, the minimum criticality degree (6.5 percent) is not that high, but the technologies with such criticality degree are those that rank 5th and above. Hence, the ranking can be considered robust for the top four technologies.

Hydraulic Ram Pump has ample rooms for improvement that emanate from its sensitive and thoroughly interconnected mechanics of operation. The significant improvements revealed by the recent generations of hydraulic ram pump show those possibilities. Results of the adaptation made in this research also strengthen this same fact. The hydro-powered water pumping technologies suitable for low land areas are generally less sophisticated.

Adapting the Hydraulic Ram Pump, keeping its simplicity of production, ease of operation and long service life, and, at the same time, matching the attractive futures of Venturi Pump was the challenge entered into. The two typical advantages of a Venturi Pump, fast closure time due to venturi (where the name of the pump comes from) action and functionality in varying flows are approached from different angles.

Introduction of spring to the selected model of hydraulic ram pump, to (significantly) replace valve weight, has been simulated to result in tremendous relative reduction of closure times (as compared to a model with *weight-only* valve) that range from as low as 46 percent to as high as 95 percent for the given setups used in the simulation. The reductions in closure times emanate from the characteristics of coil spring to impart resistance moment to the impulse valve, with no addition to the mass moment of inertia, a quantity that appears at the denominator in the formula for angular acceleration, and hence extensively influences closure time of an impulse valve. Given the fact that water hammer pressure is inversely proportional to closure time of the valve, the relative reductions registered promise very significant improvement to pumping height.

The simulations have also shown that, given a fixed valve opening angle, increasing the valve thickness to counter the drag moment, expected from varying fall heights, results in same closure time. The other measure which enables exploitation of the available head is reducing the angle of opening (with the horizontal), or, in other words, widening the opening of the valve. This setup has an effect of increasing closure time as it widens the angle of swing of the valve, and, at the same time, has an effect of reducing the closure time due to the increased pressure from the increased height.

Comparison of values (Tables 6.6 and 6.7) show that though the angle of swing increases with adverse effect of increasing time of closure, the pressure increase outweighs, and the closure times tend to decrease. In other words, the reduction in closure time gained from reduced closing angle (by increasing thickness/weight of the impulse valve) is less than the retarding effect introduced due to increased valve thickness/weight. This shows that adaptation to increased height by reducing the valve angle (with the horizontal) at open position is preferred to keeping the angle of opening and increasing thickness/weight of impulse valve.

Close observations into outputs of the extensive analysis of options revealed the following two hypotheses that are later proved mathematically under Chapter 6.6.4.

1. Given an initial angle of opening, and given the thickness of *weight-only* valve is adjusted for initial equilibrium, between drag and resisting moments, closure time does not vary with fall height H.
2. Given an initial angle of opening, and given the thickness of *weight-only* valve is adjusted for initial equilibrium, between drag and resisting moments, closure time is independent of area ratio of drive pipe to main body of the pump.

This being the case, however, adjusting the valve thickness enables exploitation of the available head by making the velocity of water in the pump, required to trigger closure of the impulse valve, close to the maximum velocity that can be obtained from the given head. The velocity of water that closes the valve has significant influence on the magnitude of surge to be developed in the body of the pump.

The study introduced flexibility to the selected model of ram pump by improving the interface between drive pipe and main body of the pump; and pressure chamber and supply pipe, through introduction of adapters. The adaptors make a sizable body of ram pump fit to varying drive pipe sizes and supply pipes.

Hydro-powered Water Pumping Technologies are candidate water supply options for smallholder farmers. During the past two years alone, the period during which this research has been conducted, price of fuel, on average increased by more than 53 percent. The rise in price continues as Government subsidies diminish. Such price escalation, coupled with very low hydropower grid coverage, particularly in the rural area, additionally signifies the use of hydro-powered water pumping technologies in Ethiopia. This research (with the following major knowledge contributions) serves as an excellent spring board for any effort that aims at introducing such eco friendly technologies in Ethiopia and triggers other research topics around the Hydro-powered water pumping Technologies. Conducting experiments on the absolute reduction in time of closure under different setups and examining the associated effects on efficiency and pumping height will be one of the research areas to follow.

1. Comprehensive introduction of the technologies to Ethiopia
2. Categorizing the technologies based on their appropriateness for the different terrains characteristics of Ethiopia and Ranking of the technologies based on the categorization.
3. Adaptation
   - 3.1 Replacement of valve weight with spring significantly reduces valve closure time. This: a) substantially improves pumping heights; b) made the use of pump possible in high fall areas; c) reduces material consumption
   - 3.2 Makes the pump *one big size fits all* by changing only the adaptors at interface between drive pipe and main body of the pump and pressure chamber and supply pipe.
4. Proven Hypotheses from Observations: For a given opening angle of impulse valve, the valve closure time is independent of height *H* and independent of the area ratio of drive pipe to main body of the pump.

Though the research is conducted with particular attention to Ethiopian context, it could as well be used by other countries with similar background.

Appendix I

Proof of Theorem 1[3]

Theorem 1: When Analytical Hierarchy Process method is used, the quantity $\delta'_{k,i,j}$ $(1 \le i < j \le M \ and \ 1 \le k \le N)$ by which the current weight W_k of criterion C_k needs to be modified (after normalization) so that the ranking of the Alternatives A_i and A_j will be reversed is given by Equation 4.5.

$\delta'_{k,i,j} < \frac{P_j - P_i}{a_{jk} - a_{ik}}(\frac{100}{W_k}), if \ (a_{jk} > a_{ik})$ or	*Eqn. 4.5*
$\delta'_{k,i,j} > \frac{P_j - P_i}{a_{jk} - a_{ik}}(\frac{100}{W_k}), if \ (a_{jk} < a_{ik})$	

Furthermore, the condition in Equation 4.6 should be satisfied for the value $\delta'_{k,i,j}$ to be feasible.

$\frac{P_j - P_i}{a_{jk} - a_{ik}} \le W_k$	*Eqn. 4.6*

Proof: Let $\delta'_{1,1,2}$ be the minimum change on Weight (W_1) of Criteria (C_1) required to swap the ranking between two alternatives *A*$_1$ and *A*$_2$.

The altered weight (W_1^*) of criterion C_1 will then be as given in Equation *A-1*.

$W_1^* = W_1 - \delta'_{1,1,2}$	*Eqn. A-1*

As this change disturbs the summation (the criteria weights do not sum up unity), the new criteria weights with the new (altered) criterion need to be renormalized to bring sum of the criteria weight to one. The normalized weights of each criterion can be computed as below.

$W_1' = \frac{W_1^*}{W_1^* + W_2 + \cdots + W_n} = \frac{W_1^*}{W_1^* + \sum_{j=2}^{n} W_j}$	*(a)*	*Eqn. A-2*

[3]The author took the proof from the reference document [49] and elaborated it, as required, to increase its understandability.

$W_2' = \frac{W_2}{W_1^*+W_2+\cdots+W_n} = \frac{W_2}{W_1^*+\sum_{j=2}^{n} W_j}$	*(b)*	
$W_n' = \frac{W_n}{W_1^*+W_2+\cdots+W_n} = \frac{W_N}{W_1^*+\sum_{j=2}^{n} W_j}$	*(c)*	

Where:

$W_1', W_2', \ldots, W_n' =$	Renormalized weights of the Criteria
$W_1^* =$	The altered weight of Criterion 1
$W_2 + \cdots + W_n =$	The unaltered weights of the rest of criteria

Let P_1' and P_2' be the new total points of alternatives A_1 and A_2.

Before the alteration, $P_1 > P_2$ (where P_1 and P_2 are the total points won by the technologies / Alternatives) one and two, respectively. P_1 is the Alternative the weight of which is altered, and P_2 is the Alternative the rank of which swaps with P_1. The swap to occur, the total points won by the Alternatives should change in such a way that $P_1' < P_2'$. P_1' to be less than P_2', the sum of the products that result in P_1' and P_2' should fulfill the following inequality.

$\sum_{j=1}^{n}(W_j' \, a_{1j}) < \sum_{j=1}^{n}(W_j' \, a_{2j})$	*Eqn. A-3*

Separating the first terms of the summation inequality (Equation *A-3*) and using the equivalence for W_j' in Equation *A-2* , Equation *A-3* can be written as:

$\frac{W_1^*}{W_1^*+\sum_{j=2}^{N} W_j} a_{11} + \frac{\sum_{j=2}^{N} W_j}{W_1^*+\sum_{j=2}^{N} W_j} a_{1j} < \frac{W_1^*}{W_1^*+\sum_{j=2}^{N} W_j} a_{21} + \frac{\sum_{j=2}^{N} W_j}{W_1^*+\sum_{j=2}^{N} W_j} a_{2j}$	*Eqn. A-4*

Multiplying both sides by the denominator, results in Equation *A-5*. Equation *A-5* separates the altered Criteria Weight and brings the Criteria Weights in the summation to the values before renormalization.

$W_1^* a_{11} + \sum_{j=2}^{n} W_j\, a_{1j} < W_1^* a_{21} + \sum_{j=2}^{n} W_j\, a_{2j}$	*Eqn. A-5*

Bringing the equivalence for W_1^* from Equation *A-1* and putting it in Equation *A-5* and rearranging yields Equations *A-6*.

$(W_1 - \delta'_{1,1,2})a_{11} + \sum_{j=2}^{n} W_j\, a_{1j} < (W_1 - \delta'_{1,1,2})a_{21} + \sum_{j=2}^{n} W_j\, a_{2j}$ (a)	*Eqn. A-6*
$W_1 a_{11} - \delta'_{1,1,2} a_{11} + \sum_{j=2}^{n} W_j\, a_{1j} < W_1 a_{21} - \delta'_{1,1,2} a_{21} + \sum_{j=2}^{n} W_j\, a_{2j}$ (b)	
$W_1 a_{11} + \sum_{j=2}^{n} W_j\, a_{1j} - \delta'_{1,1,2} a_{11} < W_1 a_{21} + \sum_{j=2}^{n} W_j\, a_{2j} - \delta'_{1,1,2} a_{21}$ (c)	

The first two expressions of the left and right hand sides of the inequalities in (*Eqn. A-6 (c)*) are P_1 and P_2, respectively. Replacing the corresponding terms with P_1 and P_2 into Equations *A-6* and rearranging gives Equation *A-7*, and that proves Theorem 1.

$P_1 - \delta'_{1,1,2} a_{11} < P_2 - \delta'_{1,1,2} a_{21}$	(a)	*Eqn. A-7*
$P_1 - P_2 < \delta'_{1,1,2}(a_{11} - a_{21})$	(b)	
$\dfrac{P_1 - P_2}{a_{11} - a_{21}} > \delta'_{1,1,2}$	(c)	
$\delta'_{1,1,2} < \frac{(P_2 - P_1)}{a_{21} - a_{11}}$ for $a_{21} > a_{11}$	(d)	
$\dfrac{P_1 - P_2}{a_{11} - a_{21}} < \delta'_{1,1,2}$	(e)	
$\delta'_{1,1,2} > \frac{(P_2 - P_1)}{a_{21} - a_{11}}$ for $a_{21} < a_{11}$	(f)	

Due to their ranking, P_1 is greater than P_2 and hence $P_1 - P_2$ is always positive and.$P_2 - P_1$ negative. In Equation *A-7* (b), if $a_{21} > a_{11}$, dividing both sides by $(a_{11} - a_{21})$, which is negative, changes the sign and gives the Equation in *A-7*(c). Exchanging the positions of P_1 and P_2 (at the numerator) and $a_{11}$and a_{21} (at the denominator) keeps sign of the quotient same and results in *A-7*(d).

If, on the other hand, $a_{21} < a_{11}$, dividing both sides of *A-7*(b) by $(a_{11} - a_{21})$, which is positive, does not change the sign and gives the Equation in *A-7*(e). Exchanging the positions of P_1 and P_2 (at the numerator) and $a_{11}$and a_{21} (at the denominator) keeps sign of the quotient same and results in *A-7*(f).

As Criteria Weight cannot be negative, the maximum value $\delta'_{k,i,j}$can assume is W_k. Therefore, $\delta'_{k,i,j}$to be feasible Equation 4.6 should hold true.

Appendix II

Proof of Theorem 2[4]

Theorem 2: When the AHP method is used, the threshold value $'_{i,j,k}$ (in %) by which the measure of performance of alternative A_i in terms of criterion C_i needs to be modified so that the ranking of Alternatives $A_i$and $A_k$will change, is given by Equation 4.8.

$$'_{i,j,k} = \frac{P_i - P_k}{[P_i - P_k + W_j(a_{kj} - a_{ij} + 1)]} * \frac{100}{a_{ij}}$$ *Eqn. 4.8*

For the threshold value to be feasible, the condition in Equation 4.9 should also be satisfied.

$$'_{i,j,k} \leq 100$$ *Eqn. 4.9*

Proof: Assume that $A_i$and A_k are the two Alternatives to swap. The threshold value $'_{i,j,k}$ ($i \neq k$, $1 \leq i, k \leq$ M, and 1≤ $j \leq$ N) is the minimum change in the current value of the a_{ij} measure performance.

Let a_{ij}^* in Equation *A-8* be the perturbed (altered) measure of performance of a_{ij}

$$a_{ij}^* = a_{ij} - '_{i,j,k}$$ *Eqn. A-8*

For ease of understanding, let us consider swap between Alternatives A2 and A3 (where $P_2 \geq P_3$) by altering measure of performance of $\boldsymbol{a_{34}}$. The point is to look for $'_{3,4,2}$ that swaps the new values of P_2 and P_3, that is $P_2' < P_3'$. The perturbed measure of performance $\boldsymbol{a_{34}}$ is given by Equation *A-9*.

$$a_{34}^* = a_{34} - '_{3,4,2}$$ *Eqn. A-9*

In Analytical Hierarchy Process the final sum of the measures of performance under the criteria of comparison should add up to unity. As the perturbation disturbs this condition, the column where the measure of performance is found need be renormalized. As the perturbed

[4]The author took the proof from the reference document [49] and elaborated it, as required, to increase its understandability.

measure of performance is found in 4th column, the figures in that column are to be renormalized as follows.

$a'_{14} = \dfrac{a_{14}}{a_{14} + a_{24} + a^*_{34} + \cdots + a_{M4}}$	*Eqn. A-10*
$a'_{24} = \dfrac{a_{24}}{a_{14} + a_{24} + a^*_{34} + \cdots + a_{M4}}$	
$a'_{34} = \dfrac{a_{34}}{a_{14} + a_{24} + a^*_{34} + \cdots + a_{M4}}$	
$\vdots$	
$a'_{M4} = \dfrac{a_{M4}}{a_{14} + a_{24} + a^*_{34} + \cdots + a_{M4}}$	

Replacing $a_{34} - {}'_{3,4,2}$ by $a^*_{3,4}$ (using Equation *A-9*) in the denominator of and *A-10* the denominator becomes

$a_{14} + a_{24} + a_{34} - {}'_{3,4,2} + \ldots + a_{44} + a_{M4}$	*Eqn. A-11*
$a_{14} + a_{24} + a_{34} + \cdots + a_{44} + a_{M4} - {}'_{3,4,2}$	

As $a_{14} + a_{24} + a_{34} + \cdots + a_{44} + a_{M4} = 1$, Equation *A-11* can be simplified to give

$1 - {}'_{3,4,2}$	*Eqn. A-12*

Equation *A-10* can then be written as follows

$a'_{14} = \dfrac{a_{14}}{1 - {}'_{3,4,2}}$	*(a)*	*Eqn. A-13*

$a'_{24} = \dfrac{a_{24}}{1 - {}'_{3,4,2}}$	(b)	
$a'_{34} = \dfrac{a^*_{34}}{1 - {}'_{3,4,2}} = \dfrac{a_{34} - {}'_{3,4,2}}{1 - {}'_{3,4,2}}$	(c)	
⋮	(d)	
$a'_{M4} = \dfrac{a_{M4}}{1 - {}'_{3,4,2}}$	(e)	

Points (measures of performance) obtained for each Technology under each criterion are multiplied by the weight of the corresponding criteria and the products are summed up (along the row of the Alternatives) to get the final point for each Alternative. As this determines the ranking, and the swap is between A_2 and A_3, the following inequality for same should hold true.

$a_{21}W_1 + \cdots + a'_{24}W_4 + \cdots + a_{2N}W_N < a_{31}W_1 + \cdots + a'_{34}W_4 + \cdots + a_{3N}W_N$	*Eqn. A-14*

Let us add $(a_{24} - a_{24})W_4$ and $(a_{34} - a_{34})W_4$ to the left and right hand side of Equation *A-14*. As both the terms are zero, they do not affect the inequality.

$$a_{21}W_1 + \cdots + a'_{24}W_4 + (a_{24} - a_{24})W_4 \ldots + a_{2N}W_N < a_{31}W_1 + \cdots + a'_{34}W_4 + (a_{34} - a_{34})W_4 \ldots + a_{3N}W_N$$

$$a_{21}W_1 + \cdots + a'_{24}W_4 + a_{24}W_4 - a_{24}W_4 \ldots + a_{2N}W_N < a_{31}W_1 + \cdots + a'_{34}W_4 + a_{34}W_4 - a_{34}W_4 \ldots + a_{3N}W_N$$

$a_{21}W_1 + \ldots a_{24}W_4 + \ldots + a_{2N}W_N = P_2$ and $a_{31}W_1 + \ldots + a_{34}W_4 + \ldots a_{3N}W_N = P_3$

$a'_{24}W_4 - a_{24}W_4 + P_2 < a'_{34}W_4 - a_{34}W_4 + P_3$	*Eqn. A-15*

Substituting the equivalent for a'_{24} and a'_{34} from Equation *A-13* results in,

$$\frac{a_{24}}{1-{}'_{3,4,2}}W_4 - a_{24}W_4 + P_2 < \frac{a_{34}-{}'_{3,4,2}}{1-{}'_{3,4,2}}W_4 - a_{34}W_4 + P_3 \qquad \textit{Eqn. A-16}$$

Collecting similar terms gives

$$\frac{a_{24}W_4}{1-{}'_{3,4,2}} - \frac{(a_{34}-{}'_{3,4,2})W_4}{1-{}'_{3,4,2}} < P_3 - P_2 + a_{24}W_4 - a_{34}W_4 \qquad \textit{Eqn. A-17}$$

Adding up the left side yields

$$\frac{a_{24}W_4 - a_{34}W_4 + a_{34} + W_4({}'_{3,4,2})}{1-{}'_{3,4,2}} < P_3 - P_2 + a_{24}W_4 - a_{34}W_4 \qquad \textit{Eqn. A-18}$$

Multiplying both sides by $1-{}'_{3,4,2}$ gives

$$a_{24}W_4 - a_{34}W_4 + W_4\left({}'_{3,4,2}\right) < (1-{}'_{3,4,2})(P_3 - P_2 + a_{24}W_4 - a_{34}W_4) \qquad \textit{Eqn. A- 19}$$

Multiplying terms in the brackets gives

$$a_{24}W_4 - a_{34}W_4 + W_4\,({}'_{3,4,2}) < P_3 - P_2 + a_{24}W_4 - a_{34}W_4 - P_3({}'_{3,4,2}) + P_2({}'_{3,4,2}) - a_{24}W_4({}'_{3,4,2}) + a_{34}W_4({}'_{3,4,2}) \qquad \textit{Eqn. A- 20}$$

Eliminating like terms with similar signs from both sides of the inequality

$$W_4({}'_{3,4,2}) < P_3 - P_2 - P_3({}'_{3,4,2}) + P_2({}'_{3,4,2}) - a_{24}W_4({}'_{3,4,2}) + a_{34}W_4({}'_{3,4,2}) \qquad \textit{Eqn. A- 21}$$

Factoring out ${}'_{3,4,2}$ for the right hand side give Equation *A-22*

$$W_4({}'_{3,4,2}) < P_3 - P_2 - (P_3 - P_2 + a_{24}W_4 - a_{34}W_4)\,({}'_{3,4,2}) \qquad \textit{Eqn. A-22}$$

Collecting the terms that bear ${}'_{3,4,2}$ to one side

$P_3 - P_2 > W_4('_{3,4,2}) + (P_3 - P_2 + a_{24}W_4 - a_{34}W_4)('_{3,4,2})$	*Eqn. A-23*

Factoring out $'_{3,4,2}$

$P_3 - P_2 > '_{3,4,2}(W_4 + P_3 - P_2 + a_{24}W_4 - a_{34}W_4)$	*Eqn. A-24*

Extracting $'_{3,4,2}$

$'_{3,4,2} < \dfrac{P_3 - P_2}{P_3 - P_2 + W_4 + a_{24}W_4 - a_{34}W_4}$	*Eqn. A-25*

Factoring out W_4 in the denominator gives Equation *A-26* and that proves the Theorem.

$'_{3,4,2} < \dfrac{P_3 - P_2}{[P_3 - P_2 + W_4(1 + a_{24} - a_{34})}$	*Eqn. A-26*

As the performance measurements sum up to unity the value of a'_{34}can at most assume a value of 1, and its value cannot be negative. The unlikely minimum it can take is zero.

Hence, for the case at hand,

$0 \leq a'_{34} \leq 1$	*Eqn. A-27*

Bringing the equivalence of a'_{34} from Equation *A-13* (c) and putting it in Equation *A-27* gives Equations *A-28.*

$0 \leq \dfrac{a_{34} - '_{3,4,2}}{1 - '_{3,4,2}} \leq 1$	(a)	
$0 \leq a_{34} - '_{3,4,2} \leq 1 - '_{3,4,2}$	(b)	*Eqn. A-28*
$'_{3,4,2} \leq a_{34} \leq 1$	(c)	

From Equation *A-28*(b), as the minimum cannot be less than zero, the minimum for $a_{34} - {}'_{3,4,2}$ is zero. Hence, for such a case, ${}'_{3,4,2} = a_{34}$

In case if the alteration is reduction, this is fine because, as the new value of a_{34} becomes zero, the zero value does not change after normalization as well.

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Appendix III

Python code to compute closure times for different initial opening angles of impulse valves, both for *spring-loaded* and *weight-only* valve options

```
import numpy as np

from scipy.integrate import dblquad, solve_ivp

from scipy.optimize import fsolve

import matplotlib.pyplot as plt

import traceback # Import traceback for detailed error printing

# --- Placeholder Values (REPLACE WITH YOUR ACTUAL VALUES) --

# These are crucial for the calculations.

beta_deg = 60          # β in degrees  <-- REPLACE THIS

K = 0               # K in N/m      <-- REPLACE THIS

rho_w = 1000          # ρ_w in kg/m³  <-- REPLACE THIS

C_D = 1.17             # C_D (unitless) <-- REPLACE THIS

rho_s = 7800          # ρ_s in kg/m³ (density of steel, for example) <--
REPLACE THIS

g = 9.81              # g in m/s²     <-- REPLACE THIS

delta_S_initial = 0.00 # ΔS_initial in meters <-- REPLACE THIS

# Define the fractional thickness reduction value for closure time
calculation

THICKNESS_REDUCTION_FRACTION = 1 / 10000000 # 1/10,000,000th of the
calculated thickness

# Convert beta to radians

beta_rad = np.deg2rad(beta_deg)

# Ranges for H and theta_initial

H_values = [0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0]  # H in
meters <-- ADJUST IF NEEDED

theta_initial_values_deg = [10, 15, 20, 25, 30]  # θ_initial in degrees
<-- ADJUST IF NEEDED

# Store results
th_results = {H: {} for H in H_values}
```

```
closure_times = {H: {} for H in H_values}

# --- Helper Functions based on your equations ---

# Equation 9: gamma = tan⁻¹(...)

def calculate_gamma(theta_rad, beta_rad):
    numerator = 0.1 * np.sin(beta_rad - theta_rad)
    denominator = 0.1 * np.cos(beta_rad - theta_rad) + 0.05
    if abs(denominator) < 1e-9:
         return np.pi / 2 * np.sign(numerator) if abs(numerator) > 1e-9
else 0
    arg = numerator / denominator

    return np.arctan(arg)

# Equation 7: alpha = beta - theta - gamma

def calculate_alpha(theta_rad, beta_rad, gamma_rad):

    return beta_rad - theta_rad - gamma_rad

# Equation 14: S = 0.1*cos(alpha) + 0.05*cos(gamma)

def calculate_S(alpha_rad, gamma_rad):

    return 0.1 * np.cos(alpha_rad) + 0.05 * np.cos(gamma_rad)

# Equation 15: Delta S = S - S_t0

def calculate_delta_S(S, S_t0):

    return S - S_t0

# Equation 13 (Interpretation): S_t0 = S_initial - Delta S_initial
def calculate_S_t0(theta_initial_rad, beta_rad, delta_S_initial):
    gamma_initial_rad = calculate_gamma(theta_initial_rad, beta_rad)
    alpha_initial_rad = calculate_alpha(theta_initial_rad, beta_rad,
gamma_initial_rad)
    S_initial = calculate_S(alpha_initial_rad, gamma_initial_rad)
    S_t0 = S_initial - delta_S_initial
    return S_t0

# Velocity profile function (Equation 2 & 5) - Used in M_drag

def velocity_profile(x, y, H):

    # See detailed notes in the previous response regarding
```

```
interpretation.

    # Assume x is width (0.01 to 0.09), y is vertical height from pivot
(0 to 0.1*sin(theta)).

    term_x_arg_sq = ((0.05 - x) / 0.05)**2
    term_x_arg_sq = min(term_x_arg_sq, 1.0) # Clamp to avoid issues near
1
    term_x = (1 - term_x_arg_sq)**(1/4)


    term_y_arg_sq = ((0.05 - y) / 0.05)**2
    term_y_arg_sq = min(term_y_arg_sq, 1.0) # Clamp to avoid issues near
1
    term_y = (1 - term_y_arg_sq)**(1/4)


    # Ensure terms are not NaN or negative due to precision
    term_x = np.nan_to_num(term_x, nan=0.0)
    term_y = np.nan_to_num(term_y, nan=0.0)
    term_x = max(term_x, 0.0)
    term_y = max(term_y, 0.0)


    v = 2.917 * np.sqrt(H) * term_x * term_y # For diameter 50 drive pipe
1.138, For 80 it is 2.917

    return v

# Function to calculate M_drag (Equation 2 & 5) - depends on theta and H

def M_drag(theta_rad, H):

    y_upper = 0.1 * np.sin(theta_rad)

    if y_upper <= 1e-9:

        return 0.0

    def integrand(y, x):

        v = velocity_profile(x, y, H)

        force_per_area = 0.5 * rho_w * C_D * v**2

        moment_per_area = force_per_area * y # y is the lever arm

        return np.nan_to_num(moment_per_area, nan=0.0, posinf=1e18,
neginf=-1e18)
```

```
    x_lower = 0.01

    x_upper = 0.09

    y_lower = 0.0

    try:
        result, error = dblquad(integrand, x_lower, x_upper, y_lower,
y_upper, epsabs=1e-6, epsrel=1e-6)
        result = np.nan_to_num(result, nan=0.0, posinf=1e18, neginf=-
1e18)
        return result

    except Exception as e:

        print(f"  Warning: Error during M_drag integration at
theta={np.rad2deg(theta_rad):.2f}°, H={H}: {e}")

        # traceback.print_exc() # Uncomment for detailed error

        return 0.0

# Function to calculate M_valve (Equation 3 & 16) - depends on theta and
th

def M_valve(theta_rad, th):

    # Magnitude is Mass * g * lever_arm.

    magnitude = (0.08 * 0.1 * th * rho_s) * g * (0.1 / 2) *
np.cos(theta_rad)

    return magnitude

# Function to calculate M_spring (Equation 4 & 17) - depends on Delta S
and gamma

def M_spring(delta_S, gamma_rad):

    magnitude_with_sign = K * delta_S * 0.05 * np.sin(gamma_rad)

    return magnitude_with_sign

# Function to calculate Moment of Inertia (Equation 18) - depends on th

def calculate_I_valve(th):

    return (rho_s * 0.08 * th * (0.1)**3) / 3

# --- Part 1: Computing required thickness (th) ---

print("--- Part 1: Computing required thickness (th) ---")

# The target function for finding th (based on M_drag - M_valve -
M_spring = 0)
```

```
def find_th_target(th, theta_initial_rad, H, S_t0_for_this_case,
beta_rad):

     if th <= 0 or not np.isfinite(th):

         return 1e9

     gamma_initial_rad = calculate_gamma(theta_initial_rad, beta_rad)

     alpha_initial_rad = calculate_alpha(theta_initial_rad, beta_rad,
gamma_initial_rad)

     S_initial = calculate_S(alpha_initial_rad, gamma_initial_rad)

     delta_S_initial_current = calculate_delta_S(S_initial,
S_t0_for_this_case)

     m_drag_initial = M_drag(theta_initial_rad, H)

     m_valve_initial = M_valve(theta_initial_rad, th)

     m_spring_initial = M_spring(delta_S_initial_current,
gamma_initial_rad)

     residual = m_drag_initial - m_valve_initial - m_spring_initial

     return residual

# Use root finding to find th for each combination of H and theta_initial

for H in H_values:

    print(f"\n--- Finding th for H = {H} m ---")

    for theta_initial_deg in theta_initial_values_deg:

        theta_initial_rad = np.deg2rad(theta_initial_deg)

        print(f"  θ_initial = {theta_initial_deg}°
({theta_initial_rad:.4f} rad)")

        S_t0_for_this_case = calculate_S_t0(theta_initial_rad, beta_rad,
delta_S_initial)

        # Compute M_drag and M_spring at the initial angle to estimate th

        m_drag_at_initial = M_drag(theta_initial_rad, H)

        gamma_initial_rad = calculate_gamma(theta_initial_rad, beta_rad)

        alpha_initial_rad = calculate_alpha(theta_initial_rad, beta_rad,
gamma_initial_rad)

        S_initial = calculate_S(alpha_initial_rad, gamma_initial_rad)

        delta_S_initial_actual = calculate_delta_S(S_initial,
```

```
S_t0_for_this_case)

        m_spring_at_initial = M_spring(delta_S_initial_actual,
gamma_initial_rad)

        target_m_valve = m_drag_at_initial - m_spring_at_initial

        denominator_for_th = (0.08 * 0.1 * rho_s * g * 0.05 *
np.cos(theta_initial_rad))

        initial_guess_th = 0.005 # Default guess

        if abs(denominator_for_th) > 1e-9:

             predicted_th = target_m_valve / denominator_for_th

             if predicted_th > 0 and predicted_th < 0.1:

                 initial_guess_th = predicted_th

        try:

            th_solution, info, ier, msg = fsolve(

                find_th_target,

                initial_guess_th,

                args=(theta_initial_rad, H, S_t0_for_this_case,
beta_rad),

                full_output=True,

                xtol=1e-9

            )

            if ier == 1 and th_solution[0] is not None and th_solution[0]
> 1e-6 and np.isfinite(th_solution[0]):

                 th_results[H][theta_initial_deg] = th_solution[0]

                 print(f"    Calculated S_t0 = {S_t0_for_this_case:.6f}
m")

                 print(f"    M_drag at θ_initial =
{m_drag_at_initial:.6f} Nm")

                 print(f"    M_spring at θ_initial =
{m_spring_at_initial:.6f} Nm")

                 print(f"    Target M_valve at θ_initial (M_drag -
M_spring) = {target_m_valve:.6f} Nm")

                 if abs(denominator_for_th) > 1e-9:

                     print(f"    Predicted th = {predicted_th:.6f} m
```

```
(used as guess if positive)")
                 else:
                     print("    Denominator for predicted th is near 
zero.")
                 print(f"    fsolve successful: Required th = 
{th_solution[0]:.6f} m")
            else:
                th_results[H][theta_initial_deg] = np.nan
                print(f"    fsolve failed: Could not find a valid 
positive th. ier={ier}, msg={msg}, solution={th_solution[0]}")
        except Exception as e:
            th_results[H][theta_initial_deg] = np.nan
            print(f"    Error during fsolve: {e}")
            # traceback.print_exc()
# Print the calculated thicknesses
print("\n--- Calculated Thicknesses (th in meters) ---")
for H in H_values:
    print(f"H = {H} m:")
    for theta_initial_deg in theta_initial_values_deg:
        th_val = th_results[H].get(theta_initial_deg, np.nan)
        print(f"  θ_initial = {theta_initial_deg}°: {th_val:.6f}" if not 
np.isnan(th_val) else f"  θ_initial = {theta_initial_deg}°: N/A")
# --- Part 2: Computing Valve Closure Times ---
print("\n--- Part 2: Computing Valve Closure Times ---")
# Define the ODE system (dθ/dt, d²θ/dt²) based on Equation 19
def valve_ode(t, state, H, th_current, S_t0, beta_rad):
    theta_rad = state[0]
    dtheta_dt = state[1]
    gamma_rad = calculate_gamma(theta_rad, beta_rad)
    alpha_rad = calculate_alpha(theta_rad, beta_rad, gamma_rad)
```

```
    S = calculate_S(alpha_rad, gamma_rad)

    delta_S = calculate_delta_S(S, S_t0)

    m_drag = M_drag(theta_rad, H)

    m_valve = M_valve(theta_rad, th_current) # Use the slightly reduced
thickness

    m_spring = M_spring(delta_S, gamma_rad)

    i_valve_current = calculate_I_valve(th_current) # Use the slightly
reduced thickness for I

    net_moment = m_drag - m_valve - m_spring

    if i_valve_current <= 1e-12:

        angular_acceleration = 0.0

    else:

        angular_acceleration = net_moment / i_valve_current

    angular_acceleration = np.nan_to_num(angular_acceleration, nan=0.0,
posinf=1e18, neginf=-1e18)

    return [dtheta_dt, angular_acceleration]

# Compute closure times for each combination

for H in H_values:

    print(f"\n--- Computing Closure Times for H = {H} m ---")

    for theta_initial_deg in theta_initial_values_deg:

        theta_initial_rad = np.deg2rad(theta_initial_deg)

        th_calculated = th_results[H].get(theta_initial_deg)

        if th_calculated is None or np.isnan(th_calculated) or
th_calculated <= 1e-6:

            print(f"  θ_initial = {theta_initial_deg}°: Skipping due to
invalid or non-positive calculated th.")

            closure_times[H][theta_initial_deg] = np.nan

            continue

        # --- Apply the fractional thickness reduction for closure time
simulation

        thickness_reduction_amount = th_calculated *
```

```
THICKNESS_REDUCTION_FRACTION

        th_for_ode = th_calculated - thickness_reduction_amount

        # Ensure thickness remains positive after reduction

        if th_for_ode <= 0:

             print(f"  θ_initial = {theta_initial_deg}°: Skipping as
reduced th ({th_for_ode:.6f}) is non-positive.")

             closure_times[H][theta_initial_deg] = np.nan

             continue

        print(f"  θ_initial = {theta_initial_deg}°
({theta_initial_rad:.4f} rad)")

        print(f"    Calculated th = {th_calculated:.6f} m")

        print(f"    Reduction amount = {thickness_reduction_amount:.9f}
m")

        print(f"    Using reduced th for ODE = {th_for_ode:.6f} m")

        S_t0_for_this_case = calculate_S_t0(theta_initial_rad, beta_rad,
delta_S_initial)

        print(f"    Using S_t0 = {S_t0_for_this_case:.6f} m")

        initial_state = [theta_initial_rad, 0.0]

        print(f"    Initial state: θ = {np.rad2deg(initial_state[0]):.4f}
°, dθ/dt = {initial_state[1]:.4f} rad/s")


        t_span = [0, 500]

        def valve_closure_event(t, state, H, th_current, S_t0, beta_rad):

            # The event occurs when theta reaches beta (or slightly
beyond, due to floating point)

            return state[0] - beta_rad

        valve_closure_event.terminal = True

        valve_closure_event.direction = 1 # Trigger when the value is
increasing

        print("    Solving ODE...")

        try:

            solution = solve_ivp(
```

```
                valve_ode,
                t_span,
                initial_state,
                args=(H, th_for_ode, S_t0_for_this_case, beta_rad),
                events=valve_closure_event,
                dense_output=True,
                rtol=1e-6,
                atol=1e-9
            )
            if solution.t_events is not None and
len(solution.t_events[0]) > 0:
                closure_time = solution.t_events[0][0]
                closure_times[H][theta_initial_deg] = closure_time
                print(f"    Valve closed successfully at time t =
{closure_time:.6f} s")
            else:
                print("    Valve did not close within the specified time
span.")
                print(f"    Final state at t={solution.t[-1]:.4f}s: θ =
{np.rad2deg(solution.y[0, -1]):.4f} °, dθ/dt = {solution.y[1, -1]:.4f}
rad/s")
                closure_times[H][theta_initial_deg] = np.nan
        except Exception as e:
            print(f"    Error during ODE integration: {e}")
            # traceback.print_exc()
            closure_times[H][theta_initial_deg] = np.nan
# Print the calculated closure times
print("\n--- Calculated Valve Closure Times (seconds) ---")
for H in H_values:
    print(f"H = {H} m:")
    for theta_initial_deg in theta_initial_values_deg:
```

```
        closure_time_val = closure_times[H].get(theta_initial_deg,
np.nan)

        print(f"  θ_initial = {theta_initial_deg}°:
{closure_time_val:.6f}" if not np.isnan(closure_time_val) else f"
 θ_initial = {theta_initial_deg}°: N/A")

# Optional: Plotting the results

print("\n--- Plotting Results ---")

# Plotting Required Thicknesses (using the original calculated th)

fig1, ax1 = plt.subplots(figsize=(10, 6))

ax1.set_xlabel('Initial Angle (degrees)')

ax1.set_ylabel('Required Thickness th (m)')

ax1.set_title('Required Valve Thickness vs. Initial Angle and Water
Depth')

for H in H_values:

    angles_deg = []

    thicknesses = []

    # Iterate through theta_initial_values_deg to ensure consistent order
for plotting

    for angle_deg in theta_initial_values_deg:

        th_val = th_results[H].get(angle_deg, np.nan)

        if not np.isnan(th_val):

            angles_deg.append(angle_deg)

            thicknesses.append(th_val)

    if angles_deg:

        ax1.plot(angles_deg, thicknesses, marker='o', linestyle='-',
label=f'H = {H} m')

ax1.legend()

ax1.grid(True)

# Plotting Closure Times (using times calculated with fractionally
reduced th)

fig2, ax2 = plt.subplots(figsize=(10, 6))
```

```
ax2.set_xlabel('Initial Angle (degrees)')

ax2.set_ylabel('Closure Time (s)')

ax2.set_title('Valve Closure Time vs. Initial Angle and Water Depth
(using fractionally reduced thickness)')


# FIX: Iterate through all H_values for the closure times plot

for H in H_values:
    angles_deg = []
    times = []
    # Iterate through theta_initial_values_deg to ensure consistent order
for plotting
    for angle_deg in theta_initial_values_deg:

        time_val = closure_times[H].get(angle_deg, np.nan)

        if not np.isnan(time_val):

            angles_deg.append(angle_deg)

            times.append(time_val)

    if angles_deg:

        ax2.plot(angles_deg, times, marker='o', linestyle='-', label=f'H
= {H} m')

ax2.legend()

ax2.grid(True)


plt.show()
```

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