Session Eleven:
Practical Pumping System Design

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Abstract

Engineers are under increasing pressure to meet tight project timeframes. This raises the question: “is it possible to deliver optimised, quality design, rather than being forced into adopting overly conservative approaches?” It is the authors’ shared belief that optimised design can still be achieved.

This paper presents a set of guidelines / tools that have been developed for one major area of the engineering design process, namely pumping system design, and has discussed the application of these tools to the specific case of a refinery project.

The paper presents the basis of these guidelines / tools; the practicality of their application, and include a number of interesting examples of their real life application.

Introduction

We live in a society where our modern lifestyle can be characterised as being dominated by fast food, instant coffee, more speed and less time. Devices such as mobile phones, internet and email mean that we can seek (and expect!) instant answers to all our questions and demands. This demand for instant gratification is reflected in the demands that are being made of the engineering design process for large scale resource projects such as new mines or industrial developments. Quick answers are demanded; everything is meant to have been done yesterday, even though the required information won’t be here until tomorrow; the time allocated is generally inadequate; there is no time for improvement and design optimisation is frequently seen as a luxury rather than a fundamental expectation of good design. In these large projects, with the investments at stake frequently measured in billions of dollars, even very short delays can represent the loss of millions of dollars to shareholders and investors.

The pressures to deliver engineering designs on schedule, when those schedules are driven by the desire to reduce the overall time required for project completion, creates a significant challenge for engineering design companies. Given these time pressures, is it possible to deliver high quality engineering design that is not only fit for purpose but also optimised in terms of minimising overall energy consumption, minimising life-cycle (i.e. capital and operating) rather than just capital costs, and minimising the need for engineering redesign or rework? This paper focuses on one aspect of this discussion, namely whether or not it is possible to optimise the design process through the use of tools that allow design priorities to be identified and resources focused on critical issues. The paper focuses on the specific question of pumping system design. Pumps are the single largest energy consumers in industrial plants and the optimisation of these goes a long ways towards optimising the facility. Pumping system design is a typical area where these conflicts between time and costs occur. The problem is exacerbated by the lack of tools and systems available for pumping system design. While there is a significant body of literature available on fluid theory and there are some published guidelines for factors to use during the design of pumping systems, no guide exists that assists the pumping system designer faced with hundreds of systems to design, to determine as how to optimally achieve this.

This paper describes a number of practical tools that have been developed to assist the pumping system designer to minimise the time required for design, focus attention on the most important systems and improve the sizing of pumping equipment, for the different design phases on large projects, from conceptual design through to detailed engineering. The paper then presents and critically evaluates the application of these tools to recent projects. The overall objective is to canvass the potential for these design optimisation tools, to reduce the time required for engineering design, to meet the agreed schedules and to deliver better design outcomes, which may include energy reductions, capital and operating cost savings.

This paper is divided into four main sections. Section 2 briefly describes the phases through which large-scale projects develop and the desirable outcomes for pumping system design during each of these phases. Section 3 describes the tools that have been developed and how these tools have been integrated into the engineering design process. Section 4 then describes the application of these systems and tools to recent projects. Finally, Section 5 presents the conclusions of the paper.

It is assumed that the reader has a prior knowledge of hydraulics and pumping system design. Many good texts exist on these topics and the reader is pointed to Section 6 for a recommended selection of these.

Project Phases

A large project typically progresses through a number of phases as per Figure 2.1. These phases are Identification, Prefeasibility, Feasibility and Implementation Phases and are described in Sections 2.1 to 2.4 respectively. The schematic shows the traditional process by which engineering projects are identified, evaluated, developed and implemented. It is evident that with the sequential nature of this approach that the duration required is typically long.

- **Identification**

The Identification Phase occurs prior to all Engineering phases. During this phase the problem or opportunity is clearly defined, it is agreed that the problem or opportunity exists and is worth solving. Any additional information that needs to be considered and key elements is also identified. The desired outcomes from this phase are an agreement to proceed with Engineering, identification of the concept options to be considered, agreement on the level of Engineering required and the project’s priority and timing.

- **Pre-feasibility Study**

The Pre-feasibility Study Phase typically commences with a Kick-off Meeting. The meeting determines the extent of deliverables to be produced and the associated engineering effort required to produce them. Responsibilities are assigned to the various project team members for the execution of the Conceptual Engineering work, production of the deliverables and review of concept options. The Conceptual Engineering process outcomes should be that all alternatives/options have been identified and evaluated; the preferred solution has been selected, recommended and agreed; the project justification has been finalised and approved; and a Cost Estimate accurate to ±30% has been prepared. The aim of conceptual engineering is to achieve a clearly defined scope of an effective solution, accepted and signed off.

During conceptual engineering the pumping system designer should establish the number of pumpsets required, complete preliminary pump and pipe line sizings, provide preliminary motor size information to the electrical designers so that they can in turn determine the required sizes of electrical transformers, sub stations and motor control centres. The approximate physical size of the pumpsets should be provided to the layout designers so they can determine the required plot plans. The priority is to produce this information whilst expending the minimum possible number of engineering hours.

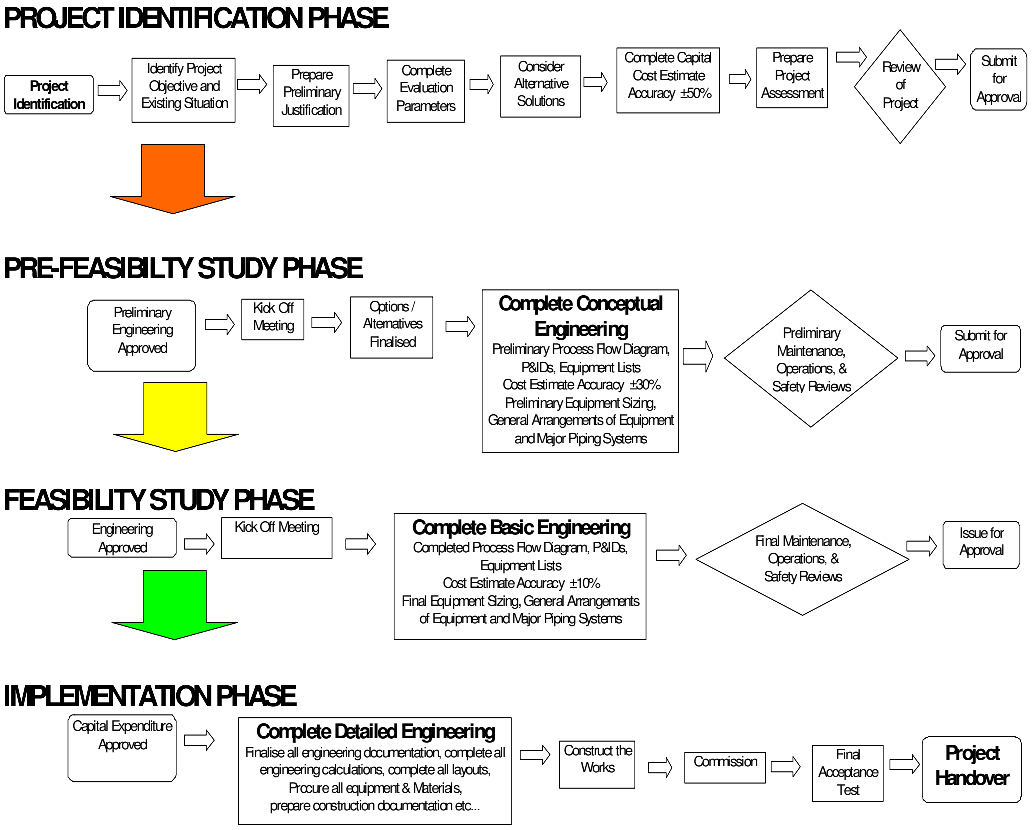


Figure 2.1

Typical Large Project Sequence

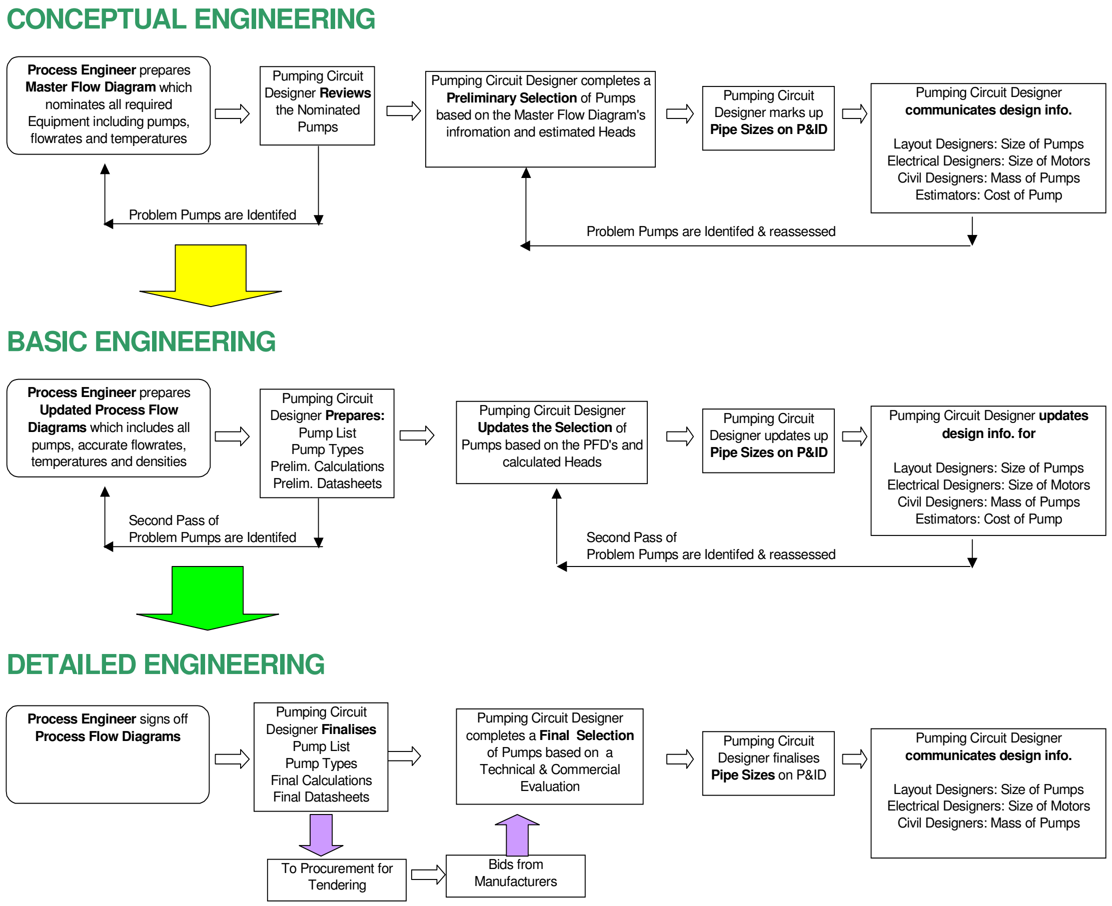


Figure 2.2

Typical Pumping System Design Sequence

- **Feasibility Study**

The aim of a feasibility study is to further develop the scope of project to allow the determination of a ± 10% estimate for the accepted solution. During the feasibility study there will be some changes due to scope growth, as the project becomes better understood. Client reviews will also generate change but this should be refinement in the direction of the project. The extent of Client review driven scope changes and additions is a direct measure of how well concept engineering defined an accepted scope. If the Client review driven scope changes were many and significant then the project is still in conceptual engineering not a feasibility study. If the changes result in a complete change in direction with different outcomes then the project has to be taken back to the assessment stage to get agreement that the project is still viable. At the end of the feasibility study phase the following has normally been completed: There is a firm scope description, process and engineering data and project justification; capital cost estimate with an accuracy of ±10% including quotations for all major equipment and components; an engineering resources cost estimate; a project schedule incorporating engineering, procurement and construction activities; a preliminary Hazard and Operability Study (HAZOP) with requirements incorporated into the scope definition; approved Process Flow Diagrams, Piping & Instrumentation Diagrams and approved General Arrangement Drawings.

During the feasibility study the purpose of pumping system design is to improve the accuracy of the work done during conceptual engineering. This is necessary to generate the +/- 10% estimate. Another important aspect is that engineering should be advanced so that on project approval the pumps can be purchased very early during the implementation phase.

- **Implementation**

Detailed engineering is based on a scope, budget and schedule that have been approved by the Client's management at the end of the feasibility study. As a project progresses through prefeasibility, feasibility and implementation phases it is likely that there are going to be ideas about better ways of delivering the project such as to cut construction costs, which may lead to change. There is a point where improvements will have a greater negative effect than any positives. This point is very early on in detailed engineering. Once databases have been populated, purchase orders placed and models progressed the flow on effect of a change is magnified greatly. A change which on the face of it will take two or three hours will have a flow on effect that will consume twenty or thirty design hours as well as introduce a higher probability of error during construction.

During detailed engineering the object of pumping system design is to complete the definition of the pumps to be used, to allow for their purchase, and the early release of associated design information to other disciplines such as civil, electrical and layout designers. There is also a requirement to finalise the piping sizes so that piping layouts can be completed. It is important that this information be of a high quality to minimise errors and the risk of expensive rework.

Discussion

This section includes sub sections on priorities, conceptual tools and decision making tools. Priorities identifies what aspects of the work are most important at each phase; conceptual tools includes a description of the design guides developed for use with pipe, pump, power and associated cost estimates; and the final section, decision making tools, identifies opportunities for improvement in the overall quality of pumping system design work.

- **Priorities**

During each engineering phase, there are different priorities and it is important to understand what these priorities are when designing tools for use at different phases. For example, during conceptual engineering it is important to delivery quick answers whilst expending minimum engineering time. During detailed engineering, the cost of the engineering time, can often be of secondary importance, whilst accuracy of information is very important. Engineers by their nature will typical have a tendency to be either too detailed or else not detailed enough. During Conceptual work, excessive detail can often cloud the larger picture whilst during Detailed Engineering, a lack of attention to detail could result in serious errors, resulting rework and adverse cost & schedule impacts. Table 3.1 below summarises which aspects have the highest priorities during each of the phases of engineering.

Table 3.1

Priorities versus Engineering Phase

ASPECT	**Conceptual**	**Basic**	**Detailed**
Time for Design	Shortest	Medium	Longest
Cost of Engineering Time	Lowest	Medium	Highest
Importance of Engineering Cost (relative)	Highest	Medium	Lowest
Evaluate Options	Important	Less Important	Not Applicable
Required Speed of Response	High	Medium	High
Dependant Disciplines	Low	Medium	High
Importance of Accuracy	Low	Medium	High
Consequence of Errors	Low	Medium	High

Overall, during Conceptual Engineering, the priority is to generate ballpark estimates with the expenditure of minimal engineering time. During Basic Engineering, the priority becomes to finalising major pump and piping sizings, and to provide reliable data that contributes to the generation of an accurate cost estimate. Finally, during Detailed Engineering, the priority is to generate very accurate answers, purchase pumps and piping, and provide reliable engineering information to other disciplines as early as possible. Engineering costs compared with the total project costs are comparatively low and thus of lesser importance during this phase. These priorities were taken into consideration when the engineering tools were developed.

- **Conceptual Tools**

Being able to produce quick estimates of lines sizes, pump sizes and pump powers is very useful during conceptual engineering. It was observed that a number of relationships held true and that a few “rules of thumb” facilitated the generation of conceptual estimates within an accuracy of ±30%. These assist with the making of good decisions

  - *Sizing Guide*

There are a number of “rules of thumb” that can be used to quickly estimate lines sizes, pump sizes and pump powers. These are of immense value during conceptual engineering work, where the exact accuracy of the sizing is not of primary importance. These “rules of thumb” are as presented in Table 3.2.1 below.

Table 3.2.1

Pump and Piping Sizing Guide

LINE SIZES:	150m^3/h requires a 6" pipe for 2.5m/s velocity. *e.g 600m^3/h => (600/150)$^{1/2}$ x 6" => 12" line for 2.5m/s velocity.*
PUMP SIZES:	Pump suction equals the discharge line size up to and including 8" lines Pump suction one size smaller than discharge line for discharge lines 10" and above *e.g 150m^3/h => 6" disch. line => 6x4 pump* *e.g 600m^3/h => 12" disch. line => 10x8 pump.*
PUMP POWERS:	For water: 100m^3/h of flow x 100m head => 37kW motor For slurries: multiply the water power by the slurry SG. *e.g 1500m^3/h x 40m Head x SG 1.5 => 1500/100 x 40/100 x 1.5 x 37kW = 330kW*

- *Power Estimates*

The recommended steps to quickly calculate required electrical power are:

1. Identify the maximum required flow for the pump (Q_{max})
2. Estimate the static head differential = (H_D - H_S)
3. Estimate the line length from a site plan (L)
4. Estimated the total Differential Head (H_{sys}) = (H_D - H_S) + 3% (L)
5. Hydraulic Power (P_H) = Q_{max} . H_{sys} . sg
6. Electrical Power (P_E)= Hydraulic Power / Pump Efficiency = P_H/75% typically.

Example: How much power is required to deliver 1,000m^3/h of slurry, with an sg of 1.5, from a tank with a 4m level, to a tank at 25m, through a total line length of 500m?

H_{sys} = (25-4) + 3% (500) = 36m

P_H = 1,000m^3/h / 3600s/h x 36m x 1.5 = 150kW

Electrical Power (P_E)= 150kW / 75% = 200kW approx.

- *Cost Estimates*

It was next considered as to whether similar ‘rules of thumb’ could be developed to quickly estimate pump costs, and total installed costs. A comprehensive review of cost data from a wide variety of sources, gathered over several years, revealed that a number of relationships indeed held true. For confidentiality reasons, this raw data cannot be included with this paper, but the following representative graphs indicate how these relationships are evident.

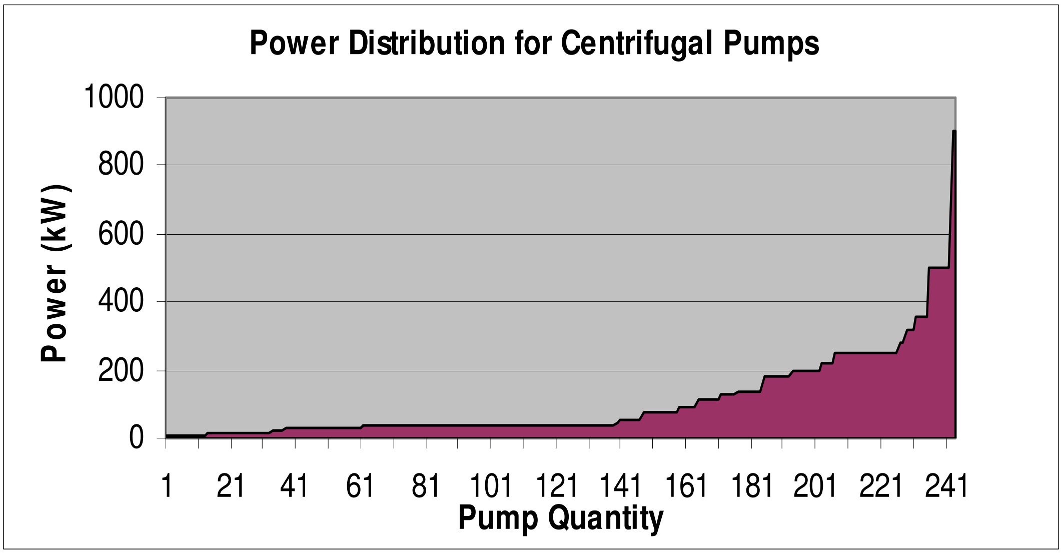


Figure 3.2.3.(1)

Power Distribution of Pumps in a Refinery (2004, typ.)

From Figures 3.2.3.(1) and 3.2.3.(2) is can be seen that the power of pumpsets range from a few kW's to over 1,000kW. The cost of these pumps (2004), ranged from about $5,000 to nearly $500,000.

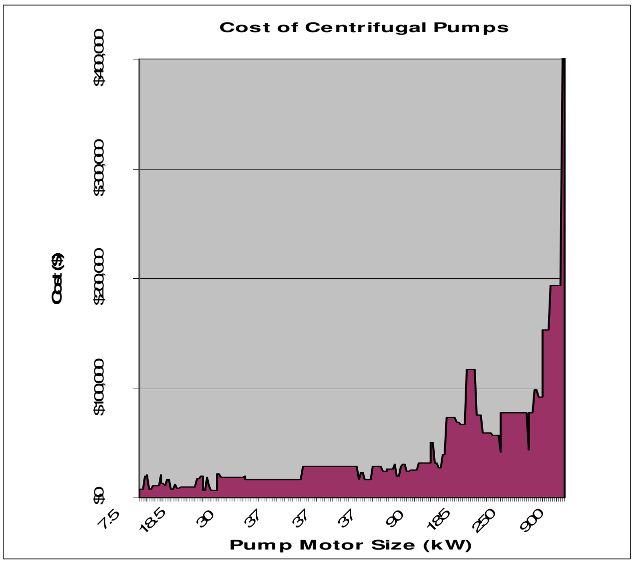


Figure 3.2.3.(2)

Cost of Pumps in a Refinery (2004, typ.)

If we consider the cost of pumps on a power basis, as shown in Figure 3.2.3.(3), it is evident that there is a good relationship between cost and kW's. It is also evident that the cost per kW of smaller pumps is greater than for larger pumps. Both of these findings could reasonably have been anticipated.

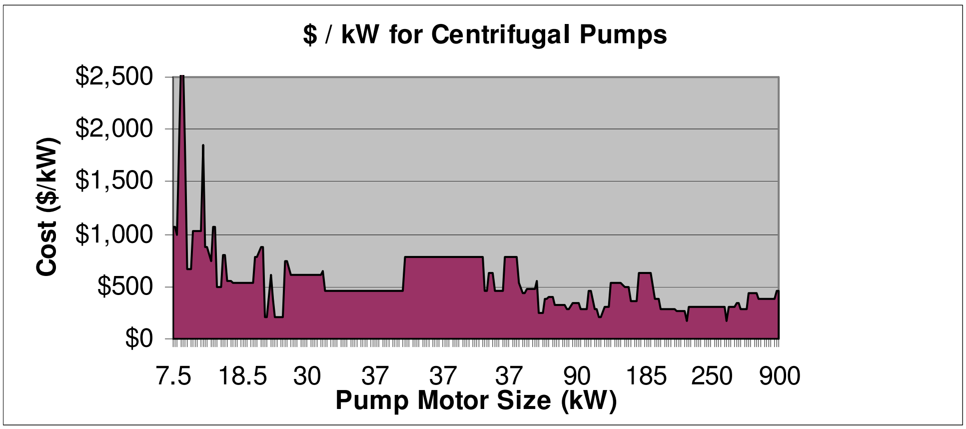


Figure 3.2.3.(3)

Cost of Pumps versus Power (typ.)

Following a similar review of historical information on the total installed costs for pumpsets, refer Figure 3.2.3.(4) below, it is again evident that that there is a good relationship between total installed cost and kW's. It is similarly evident that the total installed cost per kW of smaller pumps is greater than for larger pumps.

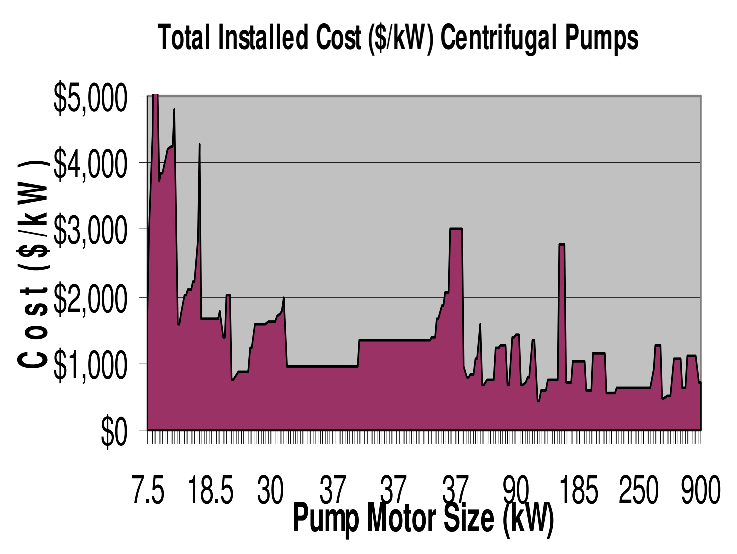


Figure 3.2.3.(4)

Total Installed Cost of Pumps versus Power (typ.)

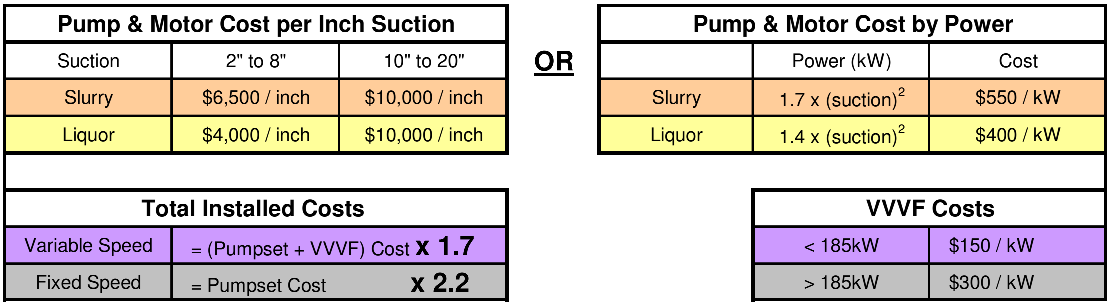
A number of key relationships, between pipe size, pump size, pump power and costs were established, and are as presented in Table 3.2.3.(1) below. These relationships are generally accurate to within ±30% as is typically required for conceptual cost estimates.

A limitation to this approach is that it only considers the pumpset and does not include the cost of the associated piping system. Thus, potentially using this method, the pumping system could potentially be 'optimised' at the expense of piping costs. Quick methods for the estimation of piping system costs do exist and they could be readily incorporated into this method. That is however outside of the scope of this paper.

It should be noted that during conceptual engineering, where uncertainties exist on the basis of design, it is better to err slightly on the conservative side. It is considerably easier to reduce rather than increase a pump, motor or line size in the latter phases of engineering as the knock on effect of late changes in a design can be significant. It is generally much easier to accommodate a reduction, rather than an increase, in power, size or NPSHR at the latter stages of design.

Table 3.2.3.(1)

Cost Estimate Guide



Pump & Motor Cost per Inch Suction		
Suction	2" to 8"	10" to 20"
Slurry	\$6,500 / inch	\$10,000 / inch
Liquor	\$4,000 / inch	\$10,000 / inch

OR

Pump & Motor Cost by Power		
	Power (kW)	Cost
Slurry	1.7 x $(\text{suction})^2$	\$550 / kW
Liquor	1.4 x $(\text{suction})^2$	\$400 / kW

Total Installed Costs	
Variable Speed	= (Pumpset + VVVF) Cost **x 1.7**
Fixed Speed	= Pumpset Cost **x 2.2**

VVVF Costs	
< 185kW	\$150 / kW
> 185kW	\$300 / kW

Table 3.2.3.(2)

Examples of Use of Sizing and Cost Estimate Guides

Example 1: How much would a **VARIABLE SPEED**, 8x6 **SLURRY** Pump cost?

Pump Cost: 8 inch x \$6.5k per inch = \$52k

Motor Size: 1.7 x (8 inch suction)^2 = 110kW

VVF Cost: 110kW x \$150 = \$16k

Total Installed Cost: = (\$52k + \$16k) x 1.7 = **\$115k per pump**

Example 2: How much would a **FIXED SPEED,** 10x8 **LIQUOR** Pump cost?

Pump Cost: 10 inch x \$10k per inch = \$100k

Motor Size: 1.4 x (10 inch suction)^2 = 140kW

VVF Cost: N/A

Total Installed Cost: = \$100k x 2.2 = **\$220k per pump**

Example 3: How much would a **VARIABLE SPEED SLURRY** pump delivering 1000m^3/h, 40m TDH, SG = 1.5 cost?

Motor Size: =1000 / 100m^3/h x 40 / 100m x 1.5 x 37kW = 225kW

Pump Cost: 225kW x \$550/kW = \$125k

VVF Cost: 225kW x \$300/kW = \$67k

Total Installed Cost: = (\$125k + \$67k) x 1.7 = **\$325k per pump**

Example 4: How much would be saved by reducing a **VARIABLE SPEED SLURRY** pump flow from 1200 to 1000m^3/h?

1200m^3/h requires a (1200/150)$^{1/2}$ x 6" = An 18" discharge line

For an 18" discharge line, assume pump would be a 16 x 14

Pump Cost: 16 inch x \$6.5k per inch = \$104k

Motor Size: 1.7 x (16 inch suction)^2 = 440kW

VVF Cost: 440kW x \$300 = \$132k

Total Installed Cost: = (\$104k + \$132k) x 1.7 = \$400k per pump

Assume savings are in direct ratio of flow reduction => 200/1200 x \$400k = **\$70k per pump**

Decision Making Tools

The pumping system designer should be looking to not just produce designs that are "good enough" but rather be striving to produce designs that are "the best they can be." The information contained within this section provides guidance as to how to achieve excellent outcomes from pumping system design work.

- **Benchmarks**

A good pumping system designer should generally know what the expected answer is before starting any calculation. The calculation should be seen as an assistant to decision making, rather than a replacement of the need to apply judgement. As part of the decision-making process, there should be a number of "alarms" that sound, in the event that important ratios are not met, these include but are not limited to:

Min speed / Max speed < 70%

Pump Efficiency < 80% for liquor and < 70% for slurry pumps at normal flow

Line velocity exceeds 3.5m/s at normal flows

Normal Power / Max Power < 70%

- **Saving Energy**

Centrifugal pumps should be designed to operate at their best efficiency point and the pump type, impeller size and overall efficiency should be optimised to produce the lowest life cycle cost for the pump. A low capital cost pump operating far from the best operating point can generate excessive on-going maintenance and operating costs (eg. power consumption) which over the life of the equipment can make it considerably more expensive than a slightly higher capital cost unit.

There are several ways minimize energy consumption of pumping systems. Systems can be designed with lower capacity and total head requirements. It should not be assumed that these requirements are fixed, in fact a good designer will continuously challenge the flow basis presented by the process engineers. Flow capacity, for example, can be reduced through use of lower velocity in heat exchangers and elimination of open bypass lines. In slurry applications, increasing the percentage of solids, reduces the required flowrate. Total head requirements can be reduced by: lowering process static gauge pressure, minimizing elevation rise from suction tank to discharge tank, reducing static elevation change by use of siphons, lowering spray nozzle velocities, lowering friction losses through use of larger pipes and low-loss fittings, and eliminating throttle valves.

The designer should avoid allowing for excessive margin of error in capacity and/or total head. It typically will be less expensive to add pumping capacity later if requirements increase. Small differences in efficiency between pumps are not as important as knowing and adjusting to the service conditions. Energy savings may be as high as 20% if pumps are sized based on reasonable system heads and capacity requirements. Savings result from operating at a more efficient point on the pump curve, and in some cases, this also avoids the need to throttle pump capacity or operate at a higher capacity than necessary. Despite the tendency to emphasize initial cost, energy is saved by selecting the most efficient pump type and size at the onset. This is further discussed in the European Commission's "Study on Improving the Energy Efficiency of Pumps' (2001).

Variable-speed drives should be used to avoid losses from throttle valves and bypass lines, except when the system is designed with high static heads. In such instances, extra concern must be shown when calculating the savings, since the pump affinity laws cannot be used without regard to the change of pump and motor efficiency along the system curve. It is important to ensure that the operating point of the pumps remains within the allowable/recommended limits specified by the pump manufacturer.

Two or more smaller pumps can be used instead of one larger pump so that excess pump capacity can be turned off when not required. Two pumps can be operated in parallel during peak demand periods, with one pump operating by itself during lower demand periods. Energy savings result from running each pump at a more efficient operating point and avoiding the need to throttle a large pump during low demand. Another alternative is to use one variable-speed pump and one fixed-speed pump.

- **Overly Conservative?**

It is important that the pumping system designer understand that a set of rules that, taken one by one, seem quite reasonable, cumulatively can result in pumps and motors in many instances being oversized. Motors that are not utilised to capacity run at low efficiencies, therefore require more power than would otherwise be the case. By using conservative design criteria and design allowances, both pump and motor can be oversized, thus compounding the inefficiencies that result.

Ultimately, motor duty is a function of pump duty, which in turn is a function of the capacity and pressure required to convey the plant fluids through pipework and equipment. Pressure has two components; a static component and a dynamic component. The static component is usually well defined and is independent of the rate of flow. No allowances need to be made to compensate for uncertainties in the rate of flow or uncertainties in the fluid dynamic calculations. An exception to this is where the static head consists of a vapour pressure. In this case, allowances have to be made for possible variations in temperature.

It is thus clear that any over sizings that may occur, generally result from factors and allowances applied to the calculations that determine the dynamic component of a pump duty. In particular the allowances made for the build-up of scale within the pipework and the roughness factors that are assumed for the internal pipe surface are important factors in determining pipe friction, as will be evident from the following: Pipe resistance is a function of the 5th power of diameter (for turbulent flow). A build-up of scale of 3% of diameter, i.e. 10mm in a DN300 pipe, would result in 1.4 times the friction for clean pipe based on diameter reduction alone. An application of a surface roughness of 0.5mm, will increase the friction factor by a multiplier of 1.8. A combination of both, which on the face of it does not appear to be an unreasonable assumption, will result in a final frictional loss of 2.5 times that for clean pipe.

- **Design Factors**

The above should make clear that it is important that the pumping system designer should at all times keep a realistic eye on the safety margins and other factors that may be compounding. To attempt to cover all contingencies and fluctuations by a simple factor on flow is fraught with problems. The most basic problem is when such a factor is carried throughout the calculations; it affects the pump duty and consequently the motor size to the 3rd power. For instance, by applying a 10% factor to flow the frictional component will increase by 20%. When this is further calculated through to establish power requirements, which are a function of flow x head, the increase will be 33%. In piping systems where the frictional component is predominant such a design margin, coupled with some “reasonable” assumptions regarding scale and roughness, can lead to quite serious over estimation of pump and motor duty.

Clearly, in the calculations an assembly of considerations that taken individually made good sense, collectively, can cause equipment to be significantly over-sized. The highest margins will result where the pump duty is entirely determined by friction. Experience has shown that pump and motors may generally be over-sized, and that a more considered approach to determining pump and motor duties is required. Typically operating conditions include:

- Emptying of tanks that usually operate full;
- The level range over which specified pump duties must be maintained for tanks in which levels may vary;
- Temporary increases in flow that may occur during outages;
- Temporary increases in density and/or concentration;
- Significant variations in viscosity; and
- Temporary flows, such as may occur during cleaning, when pumps normally used in the process are used for other purposes.

In the case of item 1 above, the pump duty would increase significantly if the pump is designed to maintain full flow over a large part of the draw-down. Where pumps are normally required to pump from one high open tank into another high open tank, and both normally operate full, the static head component is usually low. The main losses are then dynamic losses and unless the tanks are far apart, the required pump duties are normally moderate. If the pump is then designed to maintain full flow while the level in the upstream tank is drawn-down by say 15 metres (to about 25% level in a 20 metre high tank), it could easily double the required pump head. The question then arises for what head the pump should be designed and whether a gradual decline in flow, as the level is drawn-down, is acceptable to operations. Much will then depend on pump selection. Pumps with flat, or nearly flat curves would be unsuitable. Their duty point would not rise with declining flow. To be effective the selected pumps must have a steeply rising curve. Even then it is unlikely that large changes in level could be accommodated without unacceptable low flows towards the bottom of the level range.

- **Design Procedure**

In order to ensure that pump installations are not oversized, but still suitable for the required duties, the step by step approach to pump system design, in Table 3.3.5, should be followed:

Table 3.3.5

Pump System Design Steps

Step	Notes
Consider each duty and % of total operating time in this duty.	**Do not simply size the installation for the maximum flow.**
Calculate each duty	
Determine other possible duties	Do not make any further allowances or provide tolerances to either the flow or the calculated pump head.
Do not compound different maxima	**Such as maximum flows and maximum densities or viscosities, unless one is the cause of, or is associated with the other.**
Produce a system/pump curve for each duty.	A less steep curve means it is easier to adjust process flow. In variable speed drive systems try to have the system curve follow Best Efficiency curve.
Consider drive type	Variable Speed Drive or Fixed speed belt or direct coupled.
Do two or more pumps operate in parallel?	Pay close attention to the pump characteristics, especially in erosive service when pump curves are relatively flat & the performance of the pumps may not always be exactly equal
Slurry Pump	Consider using a pump with a larger impeller that will run at a lower speed and therefore reduce wear rates
Pump Trips	Consider the consequential effects of a trip, in particular possible overloading of associated pumps.
Torque	Check the torque needed to operate the pump when it is bogged and compare it with the starting torque of the motor.
Do not select a motor size for duty of maximum size impeller.	Do not provide a maximum size motor for all pumps on the off chance that it may be required for some pumps.
Where motors are required to be non-overloading, add 10% to the required hydraulic power.	Together with the 10% safety margin already provided in the standard motor, this will provide a real margin of 20%.
When the calculated motor size falls close above a standard motor size, do not automatically select the next available motor size.	Consider the case on its merits, especially where existing pumps and motors are being upgraded. Take into account if max power is only required occasionally.
Motor Frame Size	Determine the maximum motor size for the selected pump with max. size impeller but with the pipe work remaining as is. Use this to determine maximum motor frame size.
Check Baseplate sizing	Should be capable of accommodating the maximum motor frame size without having to be altered.
Electrical cabling	Ensure that the electrical cabling is capable of accommodating the maximum size motor for the selected pump furnished with the maximum size impeller.

- **Required Outcomes**

The pumping system designer should strive to meet the outcomes listed in Table 3.3.6.(1).

Table 3.3.6.(1)
Desired Outcomes

Outcome	Notes
Sizes all pumps and lines correctly	Most importantly the largest units.
Minimises engineering time spent	Particularly time evaluating multiple options and avoid getting bogged down with excessive detail during conceptual engineering.
Provides timely input	To assist with decision making processes.
Provides timely outputs	Information to dependant designers.
Picks pumps that are fit for purpose, reliable and with maximum commonality	
Know the status of the hydraulic work at all times	Important when judgement calls are required.
Is conservative with estimates	So that as level of detail increases, net changes are minimal.

The designer is likely to meet the outcomes listed above by complying with Table 3.3.6.(2).

Table 3.3.6.(2)
Ways to meet Desired Outcomes

Method	Way to Achieve
Understanding of hydraulics	Has an excellent understanding and continually works at increasing understanding and knowledge of the topic.
Uses proven rules of thumb	During conceptual engineering to develop quick estimates of pumping requirements and line sizes.
Is well organised and systematic	
Uses proforma documentation	Well structured to allow easy reviewing and checking.
Starts design conservatively	But as the level of certainty increases, reduces the level of conservatism.
Challenges overly conservative approaches	To avoid energy inefficient selections. This requires the engineer to be proactive in negotiating with others.
Maintains a Master Pump List	This summarises the overall status and the status by a variety of categories
Uses a robust revision system	Thus knows the status of all calculations and pump datasheets
Completes work only to the required level of detail,	Avoids excessive detail during the conceptual phase.
Attention to detail	Most importantly during the final sign off.
Uses software as a tool	To optimise selections, but not to replace sound engineering judgement.
Uses a design criteria	To minimise effort spent reinventing the wheel and to achieve consistency & standardisation across a project.
Provides timely feedback	To other designers such as electrical, layout, civil, procurement etc…
Concentrates on larger pumpsets	Prioritises efforts on these and on pump with the least uncertainty.

- **Flow Control**

In pumping systems, variable speed drives are generally preferred for flow regulation. Variable speed drives regulate flow by shifting the head capacity curve downwards thus reducing the capacity for a given system curve as per Figure 3.3.7.(1) below.

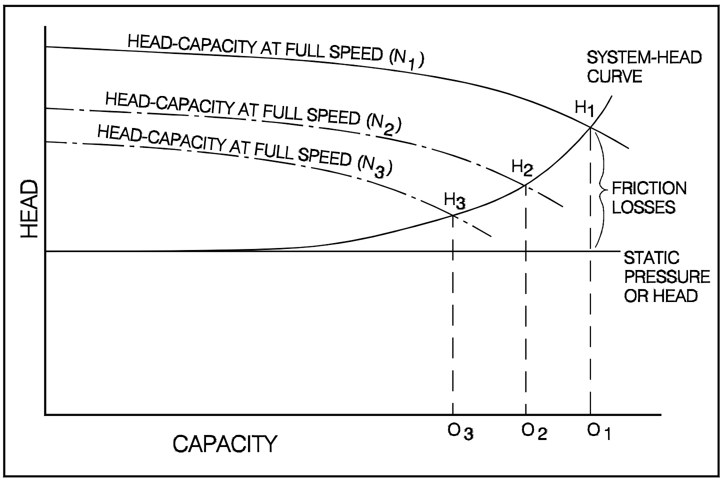


Figure 3.3.7.(1)

Variable Speed Flow Regulation

Installing a control valve (flow restriction) after pumps regulates the flow by artificially generating head and thus shifts the system curve upwards to the left and thereby reduces flow. This is a wasteful process as the friction loss across the valve increases and more motor power is consumed for less flow per Figure 3.3.7.(2) below.

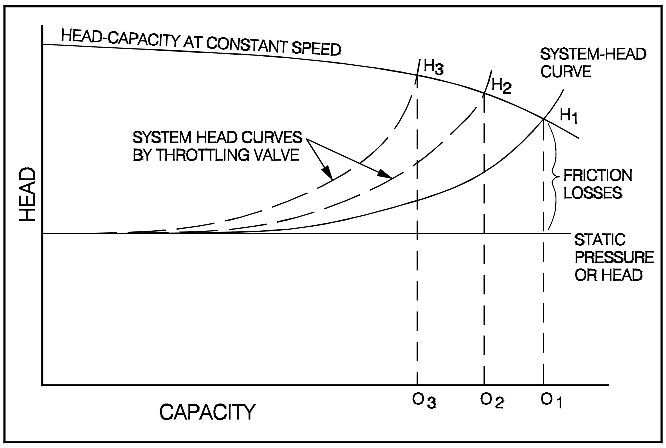


Figure 3.3.7.(2)

Control Valve Flow Regulation

Control valves after the pump are acceptable however the valves are subject to arduous operating conditions which can generate downstream problems such as flashing in hot fluids leading to unacceptable piping vibration and abrasive wear both of which generate high maintenance costs. For these reasons the use and location of control valves should be carefully considered and if possible alternative flow control methods employed.

An important aspect of pumping system design is to design / test the system for the most frequent (prevailing) conditions and use this as the basis for design. Then test for the extremes. All too frequently the extremes are used as the sizing basis resulting in oversized systems. The system should be optimised around the most likely conditions. It is important to make allowance for the system as it will become, i.e. either partly scaled up, or reduced pumping efficiency due to impellers that wear rapidly.

Caution should be exercised where two or more pumps are operating in parallel into a common outlet system. Having two pumps operating does not necessarily give twice the flow because as the flow through the pump discharge and suction piping increases the friction losses will increase due to higher velocities and thus output is affected. Multiple pumps discharging into a common outlet can result in one or more of the pumps taking a disproportionate portion of the load and the remaining pumps "loafing" which is an inefficient pumping method.

Table 3.3.7.(1)
Flow Control Checks

CHECKS	NOTES
Sustaining normal flow conditions	Establish flow reliability requirements Use redundant equipment to meet reliability criteria.
Extreme conditions	Consider the extreme conditions the system will need to satisfy
Viscosity	Check for the viscosity being affected by temperature or liquor concentration
Adequate suction conditions	Provide adequate suction conditions remembering most NPSHR curves are based on 3% cavitation

Table 3.3.7.(2)
Additional Slurry Flow Checks

SLURRY CHECKS	NOTES
How will solids content affect:	
Pump Selection	
Operating range for the pump	
System velocities	Keep low to avoid wear
How will particle size distribution affect system velocities	Minimise to avoid wear
How will extraneous material affect system	Design for scale lumps, process debris or mill scats
For abrasive fluids	Limit maximum velocities to avoid wear
For settling solids	Ensure minimum velocity exceeds settling velocity
For corrosive fluids	Careful selection of the system materials. Careful selection of pump sealing method.

- **Variable Speed Systems**

There are a number of advantages by using variable speed drives (VSD) which include: for low motor power (eg. <10 kW), the total installed cost of a VS flow control is usually less than that of a butterfly control valve system; maintenance savings due to reduced pump wear as a result of lower operating speeds and the elimination of control valve wear can be significant on abrasive slurry systems; the use of VS drives often allows the maximum size impeller to be installed and operated at a lower speed which improves hydraulic efficiency and lowers NPSHR compared to a fixed speed drive. Spare parts and maintenance costs are also eased by using standard impeller sizes. VS drives avoid the high inrush currents and mechanical loads of fixed speed starting and also save electrical energy by only generating the minimum head required for immediate operating requirements. Accurate calculation of system head is also far less critical which is of a major practical advantage. This is particularly relevant when the relative inaccuracy of predicting slurry behaviour as considered by Durand (1953) and Wilson et al (1992) for settling slurries and by Metzner & Reed (1955) and Darby (1992) for non- settling slurries. Table 3.3.8 indicates general considerations for the selection of Variable or Fixed Speed drives for flow control.

Table 3.3.8

Variable Speed Pump Selection Factors

Variable Speed suited to:	Fixed Speed suited to:
Abrasive slurry service	Clean fluids
High friction head	High static head
Large flow range	Near-constant flowrate
High power cost	Low power cost
Low power/Low Voltage motor	High power/High Voltage motor

During implementation of VS pump drives the motor and VVVF unit should both be rated to operate up to 120% of nominal supply frequency. Hydraulic calculations and selections should be based on achieving the Maximum flow pump duty (including all margins and allowances) between limits of 110% and 80% of nominal supply frequency and Minimum flow pump duty at no less than 50% of nominal supply frequency. All VS process pumps should be direct-driven, with impeller diameter reduced only when unavoidable.

- **Fixed Speed Systems**

Fixed speed pump drive motors, where practicable, should be non-overloading. Where non-overloading motors are impracticable, the following margins on fixed speed motor power should be used as a guide: up to 7.5 kW use 20%; between 7.5 kW to 37 kW use 15%; over 37 kW use 10%. For belt drive pump sets, a further 5% should be added.

These margins are based on maximum flow at normal density and maximum differential pressure.

- **Pump Selection**

Pumps should be selected so that they can operate continuously at the “Design” conditions nominated by the Pump Data Sheet. The choice of a pump depends on the service needed from the pump. Considerations are flow and head requirements, inlet pressure or net positive suction head available, and the type of liquid to be pumped. Maximum attainable efficiency of a centrifugal pump is influenced by the engineer's selection of pump rotating speed as it relates to "specific speed."

  - *Head Ratio*

The methodology given in ANSI HI Standards (2006), should be applied to determine the Head Ratio (HR) and Efficiency Ratio (ER). On slurry service, due to viscosity and/or SG differential, centrifugal pumps produce significantly less head than shown on (water) test curves. Data sheets should specify the required head on slurry, and an estimate of the HR and ER to be applied for the particular service. If significant pump wear is expected, a further de-rating factor may be applied.

  - *Net Positive Suction Head margin*

Pumps should be selected with a Net Positive Suction Head Required (NPSHR) at least 1m less than the Net Positive Suction Head Available (NPSHA). NPSHA should be based on the conditions of maximum flow, minimum pressure at the pump suction and maximum fluid temperature.

  - *Pump Duty Point*

For fixed speed pumps, the pump duty point should normally correspond to the pump maximum total dynamic head (including margins) at the maximum flow. For variable speed pumps, the pump duty point should normally correspond to the pump total dynamic head (including margins) at the normal flow. On a flow basis, the pump duty point should normally be within the region of 80 to 110% of the pump’s Best Efficiency Point.

Some Practical Examples

- **Project Overview**

The bauxite mine and alumina refinery was located in Australia’s Northern Territory. The alumina refinery undertook a major expansion costing several $billion, to increase annual production from 2 to 4 million tonnes.

As part of the project scope there is a need to install new pumping systems. These systems included over 300 pumps, ranging from a few kilowatts (kW) to 1500kW, with a combined installed power of over 50MW. The installed cost of the pumpsets was estimated at over fifty million dollars and the associated piping systems at several hundred million.

A feasibility study was completed in mid-2004, which brought engineering to about 20% complete. In this time the pumping system design work went from zero to 60% complete. Overall more than half of the calculations were at 80% (ready for final review), and all calculations at least at 40% (ready for first review). The pumping system design could not have efficiently progressed beyond the 60% complete at that time, as there were several areas with process and layout design inadequately advanced to warrant detailed work.

During the feasibility study, the basis of design underwent continuous change. This change was necessary to keep the project financially attractive to the refinery owners by maximising the return on investment from the project. The capacity was incrementally increased from 1.2 to 1.5 to 2.0 million tonnes per annum. The process design went through a total 28 different options, with the finally selected option, undergoing three significant revisions. Clearly, any pumping system design work completed early in the feasibility study, was very likely to become out of date. Tracking these changes across the 300 pumps would have been virtually impossible and it was decided early in the project to utilise a "gate" type system for tracking the pumping system design.

Furthermore, during the feasibility study, there were a number of substantial process concept changes that directly affected the pumping system design work. These changes included, elimination of some process areas, substantial changes to other process areas and changes to the overall plot plans. Moreover, these change occurred at different times of the project, thus compounding the effect. It is estimated that about 30 to 40% of the pumping systems were affected by these concept changes. In many cases, calculations that were being reported as 60% complete, reverted back to being 20% complete. Overall, it is estimated that there was about 15-20% rework resulting from these concept changes. However, as a direct result of the organised, systematic approach to the pumping system design work these changes were accommodated with minimal fuss. It can generally be expected that a number of substantial changes will occur throughout the duration of a feasibility study.

Traditionally pumping system designers like to get a fully complete basis to work from and then progress, without interruption to reaching their own, fully complete status. In "time is of the essence", fast-tracked projects, it is essential that the designers see their work as a continual process, with several iterations and updates being required. This additional work, in revisiting the same thing several times over is often required during modern projects. It is not necessarily a bad thing, but certainly requires significantly increased levels of organisation by the designer to be able to work effectively.

- **Pumping System Design**

If a pump is sized incorrectly, it is more likely to fail. The consequences of failure of a pumping system depend on a number of factors, including availability and reliability of spares, time to repair, criticality of service etc . . .

For example, in the refinery, under consideration in the case study, there are about 600 pumps in total after completion of the expansion project. Of these pumps, about 30 (5%) are on "critical" duties, that is that an unexpected loss of the pump would result in significant production loss. The cost of this production loss can be considerable.

> For example, assume the loss of a critical pump reduces production by 50% and the time required to repair = 8 hours.
>
> Production loss = 8 hours x 500 tonnes/hour x $250/tonne = $1,000,000

If poor engineering means these pumps are more likely to fail, with a frequency increase from once in ten to once in five years, then the decreased reliability of the pumps would cost about:

30 pumps x (1/5 – 1/10) x $1,000,000 = **$3,000,000 / year**

For the other 570 pumps, if even only 10% of these, become twice as unreliable, and the mean time between failures decreases from 8000 to 4000 hours, with each failure costing $20,000, then the cost impact would be:

570 x 10% x $20,000 = **$1,140,000 / year**

If overall, the pumps are 2% less efficient than if they had been selected correctly, the additional power cost would be in the order of:

100MW x 8760hours / year x 2% x $0.12 / kWh = **$2,100,000 / year**

Clearly, costs of upwards of $5million per year could be attributable to poor engineering and consequential poor pump selections. There are other, non quantifiable benefits associated with selecting properly sized, reliable pumps. These include lower noise levels, reduced vibration, decreased safety issues associated with reduced failures etc…..

- **Cyclone Overflow Pumps**

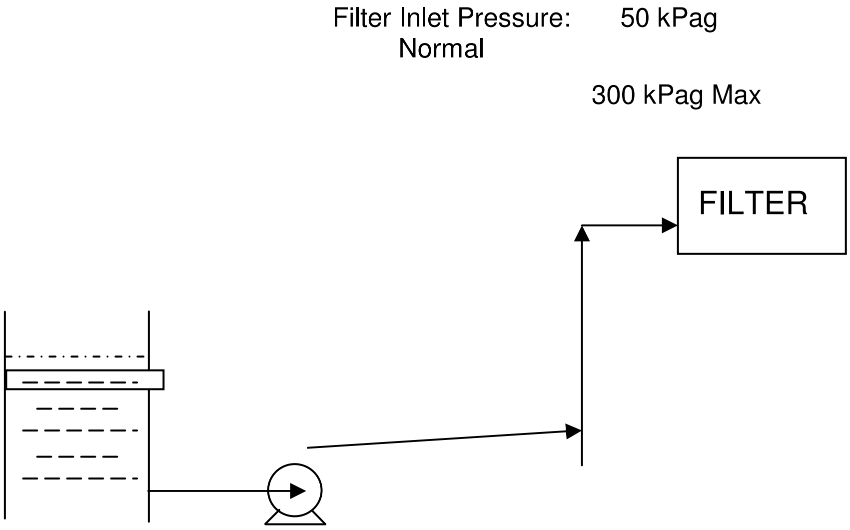


Figure 4.3

Pumping System Schematic

The **Cyclone Overflow Pump,** pump from the Cyclone Overflow Tank to the Filters with the flow basis as summarised in Table 4.3.(1) below. The traditional way to size such pumping systems is to simply design for the pump to deliver maximum flow against maximum filter inlet pressure. However, on investigation of the operation of this system it was discovered that the operation of the filter with a maximum inlet pressure is a very rare event and it would be acceptable for this design, to only be able to deliver normal flows on these occasions.

Table 4.3.(1)

Flow Basis

1	Line Number					2	7	3
2	Designation					DFS	DFS	DFS
3	**Flow Rate**	Mass	Maximum	m	t/h	1334	1250	1309
			Normal	m	t/h	1207	859	1186
4		**Volume**	**Maximum**	V	**m^3/h**	969	907	951
			Normal	V	**m^3/h**	877	623	861
			Minimum	V	**m^3/h**	646		634
5	Density at Operating Temperature			ρ	kg/m^3	1376	1379	1376
6	Operating Temperature			T	°C	58	58	58
7	Solids Concentration			W/V	g/l	216	221	216
				W/ W	% weight	15.5	15.9	16
12	Vapour Pressure			Pv	kPa a			
13	**Nominal Pipe Diameter**			**NB**	mm	**350**	**300**	**350**

The Key Design Variables and Assumptions were:

- Fluid viscosity is normally 25cP.
- Fluid temperature is a maximum of 58°C and Vapour Pressure is 14 kPa (a).
- Suction level is normally 50%, minimum 25%.
- Head and Efficiency Derating = 0.95.
- Scale is 2.5% normal, 1% minimum and 5% maximum.
- Roughness is 0.5mm normal, 0.25mm minimum and 1.0mm maximum.

Table 4.3.(2)

'Traditional' Case Combinations

Case	**From**	**To**	**Flow**	**Suction Level**	**Suction Pressure**	**Density**	**Viscosity**	**Roughness**	**Scale**	**Disch. Level**	**Disch. Pressure**
1	T123-305A	F456-101	Norm	Norm	N/A	Norm	Norm	Norm	Norm	Norm	Norm
2	T123-305A	F456-101	Min	Max	N/A	Norm	Norm	Min	Min	Norm	Norm
3	T123-305A	F456-101	Max	Norm	N/A	Norm	Norm	Norm	Norm	Norm	Max

Table 4.3.(3)

'Optimised' Case Combination

Case	**From**	**To**	**Flow**	**Suction Level**	**Suction Pressure**	**Density**	**Viscosity**	**Roughness**	**Scale**	**Disch. Level**	**Disch. Pressure**
4	T123-305A	F456-101	Max	Norm	N/A	Norm	Norm	Norm	Norm	Norm	Norm

It is important to understand that the cases documented represent both the 'most likely' and other 'extreme' scenarios. Numerous other combinations are possible, but are generally expected to fall within the extremes presented.

Table 4.3.(4)
Result Summary with Traditional Case Combinations

	Flow	Velocity		TDH	Speed	Efficiency	Hydraulic	NPSHA	NPSHR	Control
		Suction	Discharge				Power			Valve □P
	(m^3/h)	DN350	DN350	(m)	(rpm)	(%)	(kW)	(m)	(m)	(m)
Case 1	877	2.9	2.9	43	767	77	185	7.0	4.2	N/A
Case 2	646	2.1	2.1	27	601	77	86	11.2	2.2	N/A
Case 3	969	3.2	3.2	69	952	72	348	6.5	6.1	N/A
Selected Pump: Warman 12/10 G-AH										
Motor 370KW 1000rpm Drive Type: VVVF										

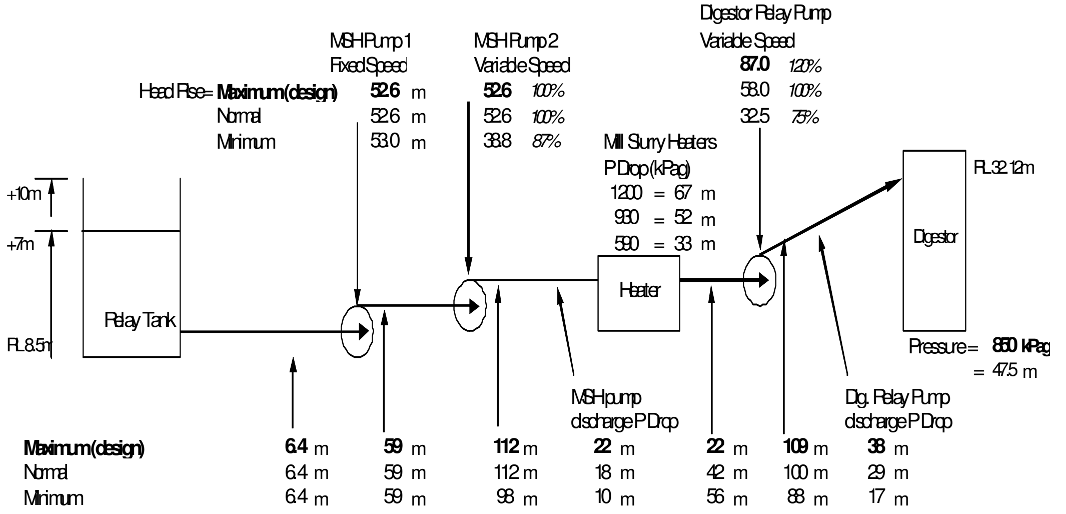
Table 4.3.(5)
Result Summary with Optimised Case Combinations

	Flow	Velocity		TDH	Speed	Efficiency	Hydraulic	NPSHA	NPSHR	Control
		Suction	Discharge				Power			Valve □P
	(m^3/h)	DN350	DN350	(m)	(rpm)	(%)	(kW)	(m)	(m)	(m)
Case 4	969	3.2	3.2	49	821	77	231	6.5	5.3	N/A
Selected Pump:		Warman 10/8 G-AH								
	Motor	250	KW	750	rpm		Drive Type:		VVVF	

It can be seen from the above example that the traditional method of sizing the pump would have resulted in a larger pump, with a significantly larger motor about 50% larger than for the optimised case. This was earlier discussed in section 3.3, decision making tools, whereby compounding maxima upon maxima can result in inefficient and oversized selections. Furthermore a larger pump would be drawing only about 50% of the rated motor power, which is also undesirable and inefficient.

This case resulted in a reduction in installed power of 360kW (for two pumps) and a reduction in pumpset costs of nearly $150,000. The saving to total installed costs was closer to $250,000.

Mill Slurry Heating System



Notes

There are two pairs of MSH pumps (in series) and four Heaters/Digestor Relay pumps on-line at any given time.

Pressures are quoted in meters of slurry (UNO).

A "sensitivity analysis was completed for this system. The system was considered with both extremely low and high system resistances.

For 0% scaling, e=0.05mm, ¯=10cP, Digester 300kPag, D.I. Pump at min. speed (75%): the VS MSH pump would have to run at about 30%, 60% and 80% for Min/Norm/Max Flows resp.

For 5% scaling, e=3mm, ¯=500cP, Digester 850kPag, MSH at maximum speed: D.I. pump would have to run at about 75%, 105% and 135% for Min/Norm/Max Flows resp.

These extreme cases suggest that the VS pumps will adequately deliver the required flows under all but very extreme (and very unlikely) conditions.

Figure 4.4

Pumping System Schematic

The **Mill Slurry Heater Pumps** pump from the Relay Tanks to the Digesters. There are two trains of MSH pumps (in series) and four Heaters/Digester Relay pumps on-line at any given time. The digester vessel normal operating pressure is 500 kPag and it has a pressure rating of 850kPag.

Previous calculations (*by others*) had concluded that the two existing pumps would require replacement to achieve the required flows. As previously discussed, the traditional way to size such a pumping system is to design it based on delivering maximum flow, with maximum pressure drops, and against the maximum discharge pressure. In this case with the unknown viscosity of the mill slurry, there was an additional degree of complexity.

After a comprehensive analysis and investigation of this system it was discovered that the pumping system could deliver normal flows for all but few case combinations. A "sensitivity analysis was completed for this system. The system was considered with both extremely low and high system resistances.

It was found that for:

1. Low scaling, smooth walls, a low fluid viscosity of 10cP, digester at a low pressure of 300kPag, pumpset 1 running at minimum speed that pumpset 3 would have to run at 30%, 60% and 80% for minimum, normal and maximum flows respectively.

2. High scaling, rough walls, an extremely high fluid viscosity of 500cP, digester at a high pressure of 850kPag, pumpset 1 running at maximum speed that pumpset 3 would have to run at 40%, 70% and 80% for minimum, normal and maximum flows respectively.

It was thus concluded, that the existing pumps could adequately deliver the required flows under all but very extreme (and very unlikely) conditions. This case resulted in the retention of four of existing pumps, saving over $220,000 on new pumpset costs. The saving to total installed costs was estimated at about $380,000.

Use of Decision Making Tools

The decision making tools as previously described were applied to the project. Table 4.5 summarises some of the findings of this exercise.

Table 4.5

Pump System Optimisation

No.	Description	Advantages	Disadvantages	Savings
1	Use Spare Pumps to Achieve Catch Up Flows	Comfortably achieve normal flows with each pump. Does not reduce plant capacity and should not affect overall reliability. Capital reduction for smaller pumps, drives, VVVFs and piping. Less congested plant layout. Reduction in total installed power and MCC requirements. Motors would run closer to full load, increasing power factor and motor efficiency.	Would need to run spare pump to achieve maximum (catch up) flows. For a three pump installation, assuming each pump is unavailable two weeks per year, which would mean that for six weeks per year the catch up flows could not be achieved. However, catch up flows should generally be expected to occur perhaps less than 10% of the time. With reasonable planning and maintenance the amount of overlap between these cases could be minimised..	$3,500,000
2	Eliminate Spare Pumps	Still achieve maximum flows with each pump Does not reduce plant capacity directly. Capital reduction for less pumps, drives, VVVFs and piping. Simplified plant layout, with associated health and safety benefits. Reduction in MCC space requirements and total installed power.	May adversely affect overall reliability and thus plant capacity. The effect of this could be minimised by judicious selection of which spare pumps to eliminate. For this suggestion, it has been assumed that only a 50% reduction would occur. Would require “smart” planning and maintenance to minimise production loss. Motors would run on average at about 75% of full load, and thus at lower efficiency.	$4,000,000
3	Spare Pumps Fixed Speed	Still achieve current maximum flows. Does not reduce plant capacity. Capital reduction for eliminating some VVVFs. Minor reduction in MCC space requirements.	May adversely affect overall reliability and thus plant capacity. Parallel pumping would be problematic. Motors would still run on average at about 75% of full load.	$800,000
4	Size Spare Pumps for Normal Flows ONLY	Still achieve maximum flows with the duty pumps. Does not reduce plant capacity. Capital reduction for some smaller pumps, drives, VVVFs and piping. Marginally less congested plant layout, with associated health and safety benefits. Minor reduction in MCC space requirements and total installed power.	Spare pump would not achieve maximum (catch up) flows. Parallel pumping would be problematic. Different pump may require increase variety and thus cost of spares inventory. Potential for confusion between pump sets. Motors would still run on average at about 75% of full load.	$300,000

The savings were calculated on the following basis:

Option 1: Based on 50,000kW (process pump installed power) x 15% (assumed power reduction) x $475/kW (average total installed cost). Cost reduction estimate excludes MCC, piping, instrument and civil costs.

Option 2: Assuming 33% of slurry pumps and 35% of liquor / condensate pumps are spares. 50,000kW x 33% x $475/kW x 50% (assumed number of spare pumps that could be eliminated). Cost exclusions as per Option 1.

Option 3: Based on 20,000kW (approx slurry pump installed power) x $300/kW (VVVF $/kW) x 33% (% of spare pumps) x 25% (assumed number of spare pumps that could be made fixed speed) x 1.7 (installation cost multiplier). Cost exclusions are as per Option 1.

Option 4: Based on 50,000kW x 15% (assumed power reduction) x $475/kW (average total installed cost) x 33% (% of spare pumps) x 25% (assumed number of pumps that could be safely reduced). Cost exclusions are as per Option 1.

It was found during the project, that a number of overly conservative approaches had been applied to the design in some areas. Capital savings conservatively estimated at over $4million were identified and recommended for implementation.

Conclusions

Engineering design companies are under increasing pressure to meet ever-tighter timeframes on large-scale resource projects. These time pressures create a significant challenge for engineering design companies. This paper has described a set of tools that have been developed for one major area of the engineering design process for large industrial projects, namely pumping system design, and has discussed the application of these tools.

The aim of the systems and tools developed was to, first of all, reduce the time required for calculating the size and cost of pumping systems, thereby facilitating early decision making and allowing more time for the optimisation of important design aspects and thus increase the value of the conceptual design process.

The important aspects of pumping system design we wish to emphasise in this paper are:

1. Understand the different Phases of Engineering
2. Understand How and When to use Rules of Thumb
3. Focus the Design Effort with the 80/20 Rule
4. Understand Design Margins – *both the "use of" and the "misuse of".*
5. Sometimes it is necessary to Think Outside the Box – *e.g. question the design assumptions*
6. Use the ANSI/HI Standards

Suggested Further Reading

1. ANSI HI Standards 1.1 to 12.6 (2006)
2. Stepanoff, A.J., (1957), *'Centrifugal and Axial Flow Pumps'*, 2nd Ed., Krieger, Florida.
3. Gould Pumps Manual – "Pump Fundamentals"

   www.gouldspumps.com
4. Sulzer Pumps, (1998), *'Centrifugal Pump Handbook'*, 2nd Ed., Elsevier, Oxford, UK.
5. Weir Warman Slurry Pumping Manual & Technical Bulletins

   www.weirwarman.com
6. Metso (formerly Svedala) Slurry Pump Basic
7. Crane, (1992), '*Flow of Fluid Through Valves*', Crane Technical Paper 410, Crane Australia Pty Ltd, Sydney., pp. 1 – 35.
8. Sullivan, J. M., (2004), *'Optimised Pumping Circuit Design',* Master's Thesis, University of Queensland, Australia.