OPTIMIZING PUMPING SYSTEMS TO MINIMIZE FIRST OR LIFE-CYCLE COST

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The IntelliFlow® technology featured in this paper has since migrated from AFT Mercury and AFT Titan to become the Automated Network Sizing (ANS) Module for AFT Fathom™ and AFT Arrow™. This module utilizes similar methods to provide the cost minimization as presented in this paper.

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Mr. Walters holds a BSME (1985) and MSME (1986), both from the University of California, Santa Barbara. He is a registered Professional Engineer in the State of California.

ABSTRACT

Numerical optimization methods offer a powerful new technology for pump users when combined with pumping system analysis software. Whether the design goal is to reduce first costs or life-cycle costs, this technology promises to significantly reduce pumping system costs and energy usage.

Optimization methods work by automatically selecting pipe and pump sizes to minimize cost. Design engineers define the constraints for the system, such as flowrate, NPSH margin, or fluid velocity. The optimization software then finds the combination of pipe and pump sizes to minimize the cost while satisfying the constraints.

A new design concept is introduced called the optimal pumping system operating point (OPSOP). In simple terms, the OPSOP uses cost data to identify the optimum tradeoff in pipe, pump, and (optionally) energy costs for a system that may have one or more duty points. Using this information, a new and improved method of pump sizing is described.

To establish benchmark comparisons for typical petrochemical pumping systems, these optimization methods were applied to four previously designed systems. With a modest amount of effort, first cost reductions were as much as 17 percent, and life-cycle cost reductions were as much as 72 percent (based on 10 years), with savings of over $100,000 in several cases.

INTRODUCTION

The potential cost and energy savings from pumping systems is great. Recent studies have found that pumping systems account for about 20 percent of world energy usage (Frenning, et al., 2001). Efforts that minimize wasted energy in these systems would not only have substantial economic savings, but an equally important environmental impact, as well.

Although savings can be made by optimizing existing systems, the greatest opportunities are in systems yet to be built. The reason being that in new designs the piping can be included as one of the variables that the engineer can modify to optimize the system. In large existing systems, it would be cost prohibitive to make a piping change.

Unfortunately, pumping system design engineers work in an environment where budget and schedule constraints limit their ability to optimize their designs using traditional methods. The number of variables in complex pumping systems makes such optimization impractical, even with modern hydraulic analysis software. Most of the design engineer's effort is focused on ensuring the system will merely function properly.

With the abundant opportunity for cost and energy reduction in new pumping systems, the need exists for technologies that will allow engineers to optimize pumping system designs to minimize cost and energy usage. The commercial software, AFT Mercury, addresses this need.

ANALYSIS VERSUS DESIGN

Before discussing the potential of modern optimization technology for the pumping industry, it is worth pausing to underscore the difference between engineering analysis and engineering design. Engineering analysis involves the application of engineering formulas and calculation methods to predict the behavior of a given system. The calculation methods might be applied in hand calculations, spreadsheets, or modeling software. Such methods are satisfactory for evaluating the performance of an existing system or design. However, applying engineering analysis to a new design is problematic in that it cannot answer the real question asked by the designer, "What design will best achieve the project goals?" There are numerous possible design goals, among which are to minimize cost, energy, or risk, or to maximize performance, safety, or reliability. With engineering analysis, the engineer must propose a design, and then use analysis to evaluate the proposed design. Good designs are typically defined as designs that function properly.

In contrast, true engineering design answers the real question being asked. Rather than evaluating a proposed design, a design-based method's output will be the design itself. The input data will be the design requirement to be satisfied.

OPTIMIZATION TECHNOLOGY OVERVIEW

Optimization technology consists of algorithms of mathematical procedures. The searching methods in these algorithms modify a design in ways likely to offer improvements. Analysis software tools do not lose their value in this context, but take on even greater value by acting as a critical subroutine to the optimization algorithms.

The development of modern numerical optimization techniques (hereafter referred to as "optimization") was highly influenced by the introduction of the digital computer. Such techniques started to appear in the 1960s (Schmit, 1960). For various reasons, engineering optimization has found its primary application in structural design. Optimization is considered a mature technology and is included in many leading structural finite element packages. In contrast, optimization of fluid and thermal systems is more rare, but an area ripe for application. A comprehensive survey of modern optimization technology was recently given by Vanderplaats (1999a).

The definition of the objective function is critical in an optimization analysis. The objective function is the function which one attempts to minimize (such as cost) or maximize (such as performance). The objective function depends on the value of the design variables (such as pipe sizes), as well as other parameters derived from the system response.

Although many different objective functions can be defined, the authors will focus here on optimization of monetary cost, with the goal being to minimize cost. All examples will be described in this context.

Two popular methods that can be used to find the optimal design are gradient-based methods and genetic algorithm methods. Additional discussion on how these methods work is given in the Appendix.

OPTIMIZATION OF PUMPING SYSTEMS

In order to implement optimization methods in pumping system design, a highly reliable and computationally efficient pumping system analysis software tool is required. This will be called the *hydraulic solver*. The hydraulic solver needs to be highly reliable because it may be called tens of thousands of times by the optimization engine (which will be called the *optimizer*). If the hydraulic solver fails to solve any of the systems called for by the optimizer, the optimization process itself will fail. Similarly, with tens of thousands of systems to solve, the hydraulic solver must be computationally efficient or computer runtimes may be unacceptably long. In addition to the optimizer and hydraulic solver, a third element that simplifies the optimization process is a user interface. The three elements are related as shown in Figure 1.

When structured as in Figure 1, the hydraulic solver functions as a subroutine, called repeatedly by the optimizer to evaluate a series of designs. The hydraulic solver consists of traditional pumping system analysis software.

PUMP SIZING PROCESS—HISTORICAL PERSPECTIVE

Figure 2 relates different approaches to sizing pumps for systems. Each will be discussed in turn.

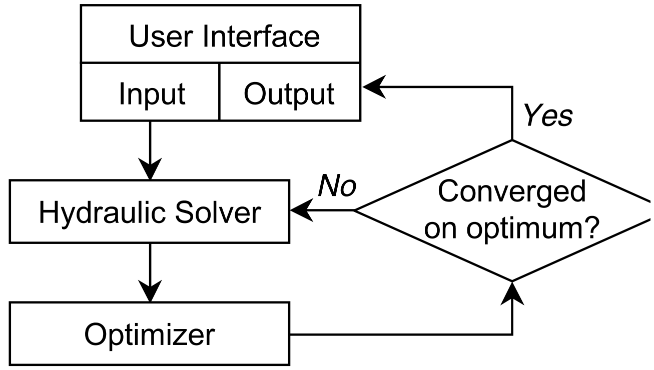


Figure 1. Logical Structure of a Pumping System Optimizer.

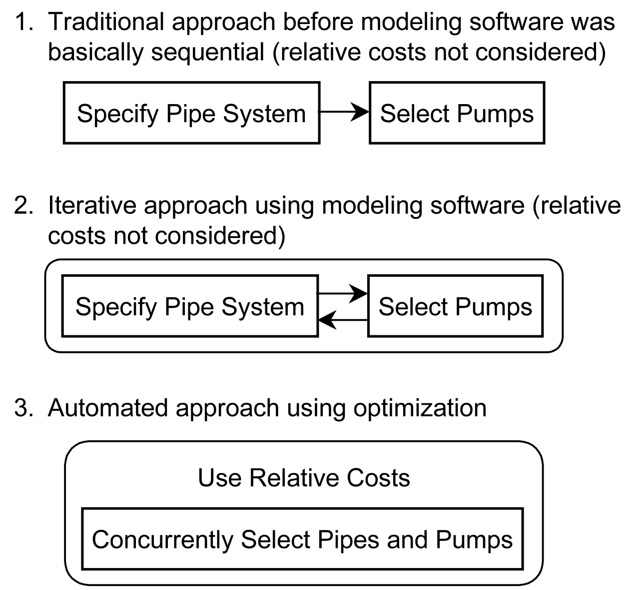


Figure 2. Historical Pump and Pipe Sizing Methods as Compared to Optimization Pumping System.

Traditional Approach

At the top is what can be called the *traditional approach*. The traditional approach involves specifying the pipe sizes, equipment, etc., and then selecting the pumps. Pumps and pipes are typically oversized, and operational problems with the system are dealt with by installing pressure drop devices (e.g., orifices) after the system is installed. The ability to consider relative cost between the pumping and piping is impractical and therefore not considered. It is worth noting that even with the availability of cost effective pumping system analysis software for over a decade, the traditional approach is still used by many large engineering organizations. It is also worth noting that it is not uncommon for pumping systems designed with the traditional approach to have operational problems.

Iterative Approach

The second approach in Figure 2 is what can be called the *iterative approach*. Because this method uses system analysis software, it allows different pipe and pump configurations to be assessed quickly on the computer. The iterative approach is a significant improvement over the traditional method, and allows greater ability to verify that different operating cases can be satisfied before the system is actually built. Even with modern modeling software, it remains impractical to perform any realistic pump versus pipe cost optimization. Hence this is rarely done, missing opportunity for cost and energy savings.

Automated Approach

The third approach in Figure 2 is what can be called the *automated approach*. This method couples system analysis software with modern optimization technology to actually search for a system that meets the design requirements while minimizing the system cost. The automated approach accounts for the relative costs between pumping and piping because cost data are the basis for the optimization. Note that the automated approach allows the user to specify the criteria for optimization, meaning that the system can be optimized to minimize either first cost or life-cycle cost (LCC). This will be discussed subsequently. Also note that the automated approach allows the optimization to be performed over multiple operating cases, thus ensuring all operating cases are adequately accounted for in the final optimum design.

DEFINING THE OBJECTIVE

Before performing an optimization, the objective must be defined. In the context of this study, the objective is to minimize monetary cost. But what costs should be included? At first blush one might respond that all costs should be included. If one includes all costs, then one is designing the system based on LCCs. However, very few companies actually do this today. Most pumping systems are designed to minimize the first cost of the system. When doing so, a number of important (even dominant) cost items are neglected (*Chemical Engineering Magazine*, 2000; Frenning, et al., 2001; Hovstadius, et al., 2000). When one designs for first cost, one neglects operating (i.e., energy) costs and maintenance costs and is in effect deciding that these costs will be excluded from the objective. The objective function to be minimized is thus a different function than when optimizing for the life cycle.

One powerful aspect of using optimization is that either first cost or LCC can be defined as the objective. Indeed, once the model is set up, one can perform separate optimizations for each of these objectives and assess the design differences. Should business reasons lead one to opt for a design optimized for first cost, optimization allows this to be an informed decision rather than one made in ignorance.

DESIGN CONSTRAINTS

Another important aspect of optimization is design constraints. Design constraints are derived from the design requirements. For example, typical pumping system design constraints are minimum flowrate, maximum pipe pressure, and adequate pump NPSH. These are defined in the input area of the “User Interface” shown in Figure 1.

All pumping systems will have design constraints, and the optimization will thus be a constrained optimization. More information on constrained optimization numerical techniques is given by Vanderplaats (1999b).

FINDING THE PUMP “SWEET SPOT”

Once the pipe system is laid out and the objective is defined, optimization can identify the pump “sweet spot.” This is the pump operating point that, when combined with the optimized piping system, yields the absolute lowest cost. The technical term for this point is the *optimal pumping system operating point (OPSOP)*.

Modeling Considerations

Consider the cooling water system shown in Figure 3. This system has two parallel (centrifugal) pumps; each controlled by a flow control valve, which supply cooling water to three heat exchangers. As part of the layout, the pipe lengths are already defined, as are the heat exchangers and their associated hydraulic characteristics. The system will use steel pipe of standard sizes. The question here is what size pumps and pipe sizes should be used. The answer, of course, depends on whether we are optimizing for first cost or LCC and, if LCC, the design lifetime of the system. For this example the authors will optimize the system over a relatively long life cycle of 20 years. Details are given elsewhere (Applied Flow Technology, 2001, Chapter 12), and will be summarized here.

Standard cost data for the steel pipe (per length) and fittings of various sizes can be found in standard sources (e.g., MEANSDATA, 2001). However, it is not possible to specify the cost of the pumps because the pumps are not yet selected. To get around this dilemma, one must create a “generic pump,” with cost data that vary with power. In the Figure 3 example, a cost data curve was constructed using MEANSDATA (2001) for pumps at the design flowrate (300 gpm in this example) for power levels (varying with head) from one to 100 hp. This established the cost for purchasing and installing the pumps as a function of power. The basis for approaching pump sizing in this way is discussed in the literature (e.g., Darby, 2001). The step of creating a generic pump can be referred to as *Phase 1* of the pump sizing process. Figure 4 shows the generic pump cost data.

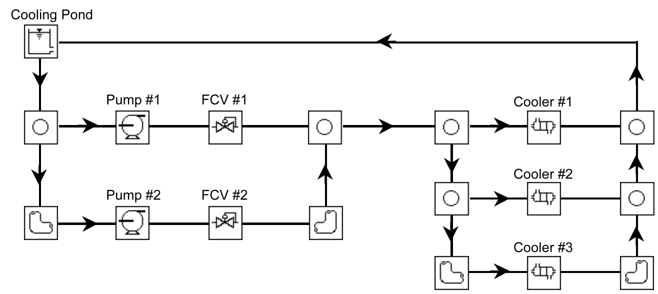


Figure 3. Cooling Water System Schematic Optimization Example.

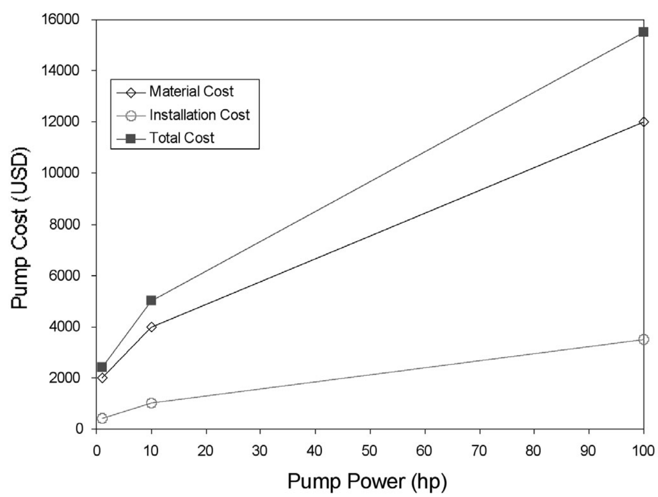


Figure 4. Assumed Cost for a 300 GPM Generic Pump Based on Power.

Maintenance and operation costs can be significant (Frenning, et al., 2001), and can be included as recurring cost items in the optimization. Maintenance costs were neglected for this example for brevity’s sake. Operation costs were included by specifying the cost for power (assumed to be \$0.06/kW-hr) and the overall efficiency of the generic pumps (assumed to be 70 percent). In addition, the time value of money can be an important aspect of designing for LCC. This too can be included in the optimization, but was neglected here for brevity’s sake.

Optimization Results

The system in Figure 3 was optimized for a 20-year life cycle and it was found that the optimal pumps will each generate about

40 ft of head, resulting in about 4.3 hp each. The optimization took about 15 seconds on a 933 MHz computer, and required 521 calls to the hydraulic solver. The optimizer selected this design from among 4.8 million possible designs. For reference, the LCC for the optimal system was $116,500.

The 40 ft/4.3 hp pumps represent the optimal size that minimizes the cost over 20 years given the previously discussed assumptions. This is the sweet spot (OPSOP) for the Figure 3 system. Once the optimum point is identified using a generic pump, one can select actual pumps with actual cost data. With actual data, the system can be reoptimized for each candidate pump.

The step of using actual pump performance and cost data can be referred to as *Phase 2* of the pump sizing process. Assuming the performance, efficiency, and cost do not significantly differ from the generic pump operating at the OPSOP, the reoptimized (i.e., Phase 2) systems should not differ significantly from the optimum system found in Phase 1.

While it is unnecessary, it is nevertheless informative to look at optimal pumping systems away from the OPSOP. This is shown in Figure 5. A number of different optimization models were created with the pump head fixed at levels from 35 to 70 ft. Each system was optimized, and thus represented the best possible system for pumps of that head level. Figure 5 confirms that the best possible system should generate about 40 ft of head and cost about $115,000. As mentioned previously, the optimal cost for Figure 3 was $116,500, consistent with the Figure 5 sweet spot.

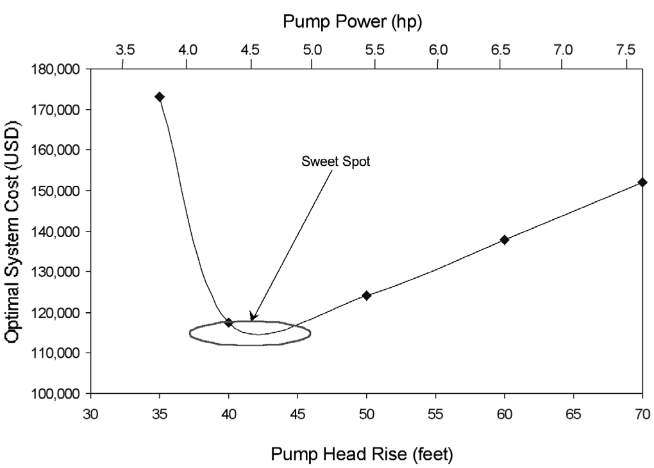


Figure 5. Optimized Systems for Pumps of Different Head Levels and Power Show Sweet Spot Locations.

There is something else vitally important that can be learned from Figure 5. The best possible systems that can be designed for pumps sized higher (or lower) than the sweet spot (OPSOP) will yield significantly higher costs. For example, a pump sized at 70 ft will result in LCCs almost 30 percent more for the optimal system! If the system using a 70-ft pump is not optimized, as is the case with a majority of today's systems, the cost will be even higher. This demonstrates the importance of concurrently sizing the pump and system upfront when the design engineer has the most latitude.

Comparison with First Cost Optimization

Interestingly, when the Figure 3 system was optimized for first cost, the optimal pumps generated about 70 ft of head and required about 7.6 hp. This is the sweet spot for a pump optimized for first cost. The cost was slightly over $150,000, consistent with Figure 5. A detailed comparison of the results of the Figure 3 system for initial cost and 20-year LCC is given by Applied Flow Technology (2001, Chapter 12). The major cost categories are summarized in Table 1.

Table 1. First Cost and Life-Cycle Cost Comparison for Optimized Cooling System.

Optimized for:	**Material** (pipes, fittings & pumps)	**Installation**	**Total System**	**Operation** ($.06/kW-hr)	**Total** (system + operation)
First cost 20 yr	22,000	11,800	33,700	117,000	150,700
Life Cycle cost 20 yr	33,800	16,400	50,100	66,300	116,500

Table 1 shows that in order to achieve the reduction from $150,700 to $116,500 over 20 years, one must spend about 50 percent more initially (increased from $33,700 to $50,100).

By performing optimizations over different life-cycle periods, one can see that the sweet spot is a function of the design lifetime (Figure 6). As the lifetime increases, lower power pumps (with correspondingly larger pipe diameters) become a better choice.

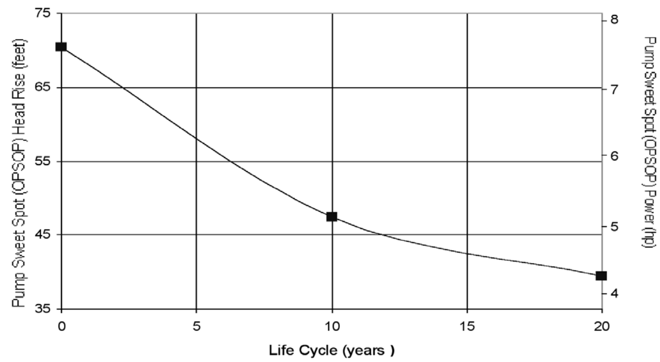


Figure 6. Pump Sweet Spot for Different Life-Cycle Periods for the Cooling System Example.

MULTIPLE OPERATING POINTS

It is not uncommon for pumping systems to have more than one operating point. This can be handled by a pump system optimizer as outlined in Figure 1. A pump optimal pumping system operating point still exists. However, because there are multiple operating points, the OPSOP becomes a *composite* operating point. The composite point curve would still look like Figure 5, where the pump power would be derived from the maximum required power among all operating points.

WEIGHT OPTIMIZATION

To simplify the data gathering required to perform an optimization analysis on pumping systems, rather than minimize cost, one can minimize weight. Because weight increases with pipe diameter as does cost, pipe weight tracks fairly closely with first cost. And pipe weight is much easier to estimate than cost. However, when optimizing for weight, monetary cost issues are ignored. Optimizing pumping systems for weight has important advantages and disadvantages. These are discussed in Table 2.

Table 2. Issues Encountered with Weight Optimization.

Advantages	No detailed cost data required Fast and easy to implement Useful to minimize initial cost
Disadvantages	Only pipes are optimized Cannot be used for optimal pump sizing Cannot perform Life Cycle optimization

REAL WORLD APPLICATIONS

To evaluate the cost-saving ability of the software, a benchmark must be established with which to compare costs. A worthy benchmark must be rooted in the real world. The benchmarks for this study were actual pumping systems from various plants of a large international chemical company. All these systems were originally designed and built using traditional design methods. They are typical systems, not especially poorly designed or well designed. Because these are real systems, they have real requirements and constraints. Therefore, each one has different opportunities for improvement. These systems were specifically chosen based on their type of opportunities in order to evaluate the software's ability to optimize them.

Four systems were evaluated. One system had a control valve doing the turndown of the flow. This system was optimized with a variable frequency drive. Another system had a gravity-fed flow. The third system had material of construction tradeoffs to consider. The fourth one had high maintenance costs due to an improperly sized pump.

All four of these cases represent typical design issues found in pumping systems in the petrochemical industry. The first case, the one with the control valve, is extremely prevalent with the majority of the industry's systems controlled by control valves. The second case with the gravity-fed flow is relatively unusual. Because of the lack of experience with sizing such lines, this line was sized as a pump-fed pipe—which was conservative. Being too conservative is indeed a typical design issue the industry faces. The third case has a choice of material for the pipe. The one choice is inexpensive metal, but must use large diameter pipe to limit the corrosion aggravated by velocity; the other choice is more expensive material, but can use standard size pipe. Material tradeoff decisions are common in the industry. The last case study is all too common—an improperly sized pump. In this case, the pump is actually undersized rather than the more typical oversized pump that results from all the fudge factors added in by everyone associated with the design. Undersized or oversized, the optimization process is the same.

To assess the software, each system as it was originally designed (without the optimization software), was first evaluated by the software with the optimization feature turned off so as to establish the benchmark cost of the system. Then the constraints were set and the system was optimized. The two costs, "benchmark" and "optimized," were then compared. In every case, the software was able to reduce the cost of the system, whether it was first cost, LCC, or both.

The following are the details of the evaluations.

Control Valve Versus VFD

The first system is a tempered water supply for a heat exchanger in a chemical intermediates plant in the Northeastern United States. The flowrate required to cool the heat exchanger not only depends on the production rate, but which of two products is being formulated, and the temperature of the river water. As a result of these variables, the flow demand had more than a 4:1 turndown, ranging from 80 to 400 gpm. The original system had a control valve making the turndown; the optimized system has a variable frequency drive (VFD). Refer to Table 3 for the flow demand of the system, and corresponding control valve or VFD settings, in addition to the distance the pump must operate from the best efficiency point (BEP).

Table 3. Flow Demand and Corresponding Control Valve or Variable Frequency Drive Settings Required to Attain Those Flows, Plus the Distance the Pump must Operate from BEP.

Flow Rate (gpm)	**Duty Cycle** (% of time)	**Control Valve dP Setting (psid)**	**& Pump % of BEP**	**VFD RPM Setting**	**& Pump % of BEP**
400	10	1	86%	1750	87%
280	30	17	31%	1225	86%
120	50	30	26%	508	90%
80	10	31	17%	315	95%

For this system, depicted in Figure 7, the tempered water pump ("Recirc Pump") receives its river water supply from the river water booster pump ("P-54"), which in turn takes its water from the raw water supply header. Only the tempered water system, which is circled in Figure 7, was evaluated for this study. The rest of the system (i.e., the header, booster pump, and other users) was already in service; the project only included the tempered water system.

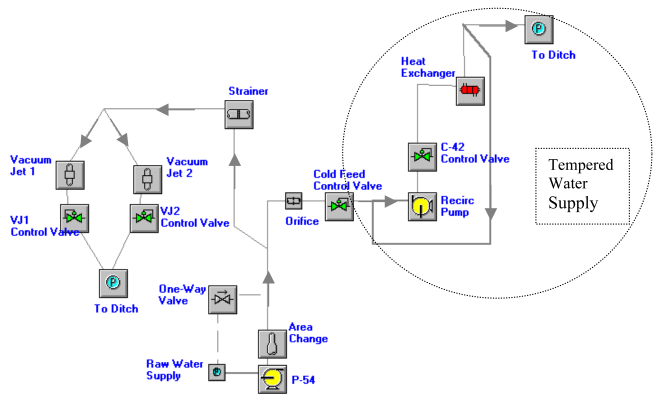


Figure 7. Tempered Water System Schematic.

The original design had the temperature control valve controlling the flow to the heat exchanger. Not only was the 4:1 turndown expensive in terms of energy costs, but the 3 inch Monel® control valve was expensive in terms of first cost. Also, the turndown forced the pump back on its pump curve, which adversely affected the reliability of the pump and increased maintenance costs. (Details regarding how the pump reliability is affected by where the pump is operated on the pump curve will be discussed in the IMPROPERLY SIZED PUMP section.)

The optimization software did not find more cost-efficient piping; it did, however, find that by replacing the control valve with a variable frequency drive, the energy savings would be 71 percent (or $3875) over five years and again 71 percent (or $14,582) over 10 years. This energy was saved because, instead of having the excess pressure that the pump is generating dissipate across the control valve, the VFD controlled the speed so the pump never generated the pressure in the first place. The savings in maintenance cost from running the pump slower resulted in savings of 84 percent (or $24,890) over five years and the same 84 percent (or $41,830) over 10 years. Even the first cost would have been reduced, by $4700. This savings stems from the difference in price between the VFD and the control valve. The percent savings in the first cost of the material for the entire project, which includes the Monel® pipe but not the heat exchanger (which was already in service before this project), would have been 17 percent ($4700). The percent savings in LCC for the project would have been 54 percent ($38,267) for a five-year life cycle, and 62 percent ($61,113) for a 10-year life cycle. Refer to Table 4 for the summary of the possible savings in first cost and a five-year LCC. Refer to Table 5 for the summary of savings using a 10-year life cycle.

Table 4. First Cost and Five-year Life-Cycle Cost Comparison of Tempered Water System's Control Valve Option (Actual) Versus VFD (Optimized). ("Weighted" Cost Refers to Using the Duty Cycle Listed in Table 3 to Calculate the Costs.)

	First Cost	**Weighted Energy Cost**	**Weighted Maintenance Cost**	**Cost of Control Valve/VFD**	**Piping Cost**	**Life Cycle Cost**
Control valve	$28,550	$12,260	$29,482	$11,000	$17,550	$70,292
VFD	$23,850	$3,584	$4,592	$6,300	$17,550	$32,025
VFD system savings	$4,700	$8,676	$24,890	$4,700	0	$38,267
VFD % savings	17%	71%	84%	43%	0	54%

Table 5. First Cost and 10-Year Life-Cycle Cost Comparison of Tempered Water System's Control Valve Option (Actual) Versus VFD (Optimized). ("Weighted" Cost Refers to Using the Duty Cycle Listed in Table 3 to Calculate the Costs.)

	First Cost	Weighted Energy Cost	Weighted Maintenance Cost	Cost of Control Valve/VFD	Piping Cost	Life Cycle Cost
Control valve	$28,550	$20,604	$49,547	$11,000	$17,550	$98,701
VFD	$23,850	$6,022	$7,717	$6,300	$17,550	$37,588
VFD system savings	$4,700	$14,582	$41,830	$4,700	0	$61,113
VFD % savings	17%	71%	84%	43%	0	62%

Gravity-Fed Flow

The second system was a simple municipal wastewater transfer system at a chemical manufacturing plant in Spain. Refer to Figure 8 for the schematic. The water was pumped from a tank up a hill to a collection box that then gravity-fed to the municipal sewer on the bottom of the other side of the hill. Upon optimization, the gravity-feed line was found to be oversized. The design engineer used the same size pipe to go up the hill as he did for flowing down it. But the economics are different. For a pumped fluid, the size of the pipe must be balanced between minimizing the cost of the pipe, where smaller is better, versus the cost of the energy it takes to pump through the line, where bigger is better. In a gravity-feed line, there is no energy tradeoff. As long as the gravity head can push the required flow through the pipe, the pipe can be quite small. In this case, the 4000 ft of 18 inch PVC pipe could have been 12 inch, with no increase in energy expenditure, while still transporting the required flow. The optimum sized pipe would have saved the project seven percent in first cost, or $124,955. Refer to Table 6 for a breakdown of the pipe cost savings.

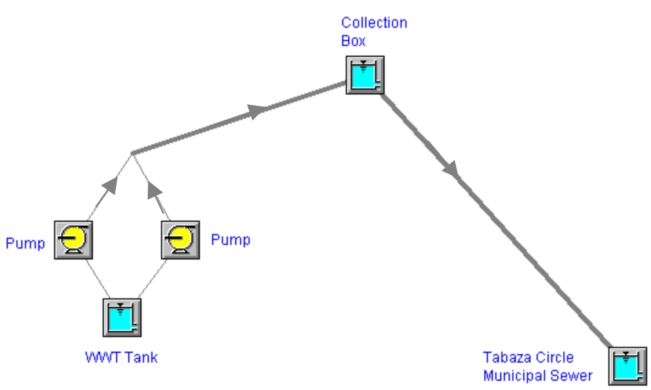


Figure 8. Municipal Wastewater System Schematic.

Table 6. Piping Cost Comparison of Municipal Wastewater System (Includes Materials and Labor).

Original System	Optimized System	Savings ($)	Savings (%)
$1,711,604	$1,586,649	$124,955	7%

Material of Construction

The third system was a 93 percent sulfuric acid unloading station at a pigment plant in the Gulf Coast. Refer to Figure 9 for the schematic. The original design exceeded the recommended maximum velocity limit of 3 ft/s for carbon steel pipe. The corrosion of carbon steel increases dramatically with the velocity of sulfuric acid flowing in the pipe. Figure 10 depicts the relationship between the velocity and rate of corrosion for various velocities for ambient temperature sulfuric acid in carbon steel pipe. With a velocity of 6 ft/s in the original design, the system incurs a high cost of maintenance for replacing the corroded pipe. Besides replacing the existing carbon steel pipe with larger diameter carbon steel pipe, another viable option is to replace it with stainless steel pipe. Stainless steel is not sensitive to the velocity of sulfuric acid in the line. Refer to Figure 11 for the sensitivity of various metals to the velocity of sulfuric acid.

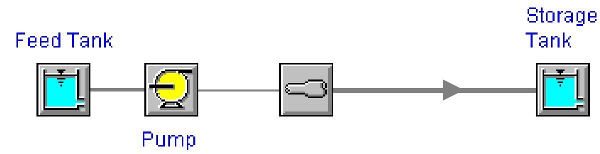


Figure 9. Sulfuric Acid Unloading System Schematic.

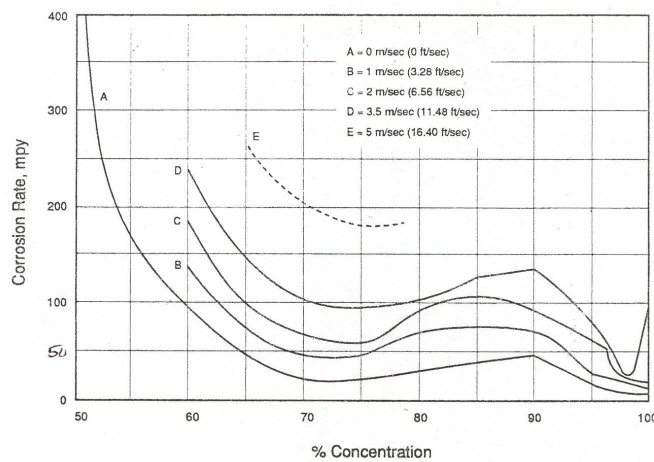


Figure 10. Graph of Corrosion Rate of Carbon Steel with Respect to Velocity of Ambient Temperature 93 Percent Sulfuric Acid. (Courtesy of Indiana Ordinance Study PE-13)

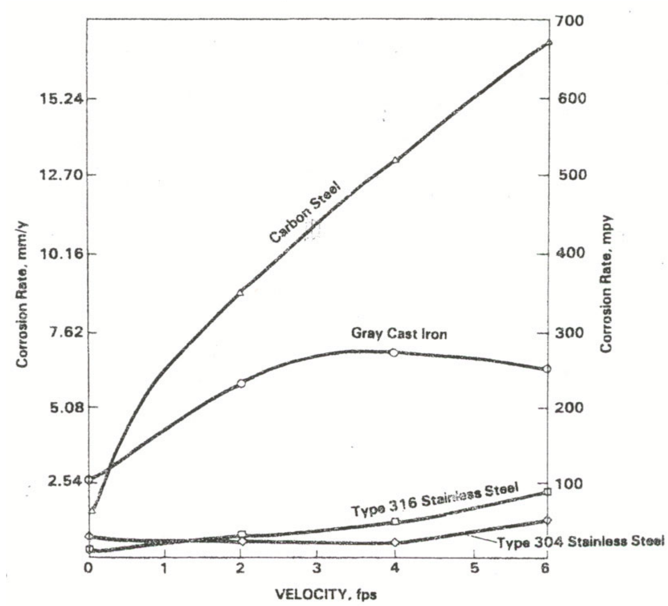


Figure 11. Graph of Corrosion Rate of Various Metals with Respect to Velocity of 95 Percent Sulfuric Acid at 120°F. (Courtesy of The International Nickel Company, Inc.)

The optimization software evaluated the existing system and determined whether it would have been more cost-effective to use stainless steel or use large diameter carbon steel. For first cost, the least expensive option is, of course, the "disposable" pipe of the existing system. This option is 15 and 75 percent cheaper than the other options. As for LCC, for a five-year life cycle, the most cost-effective design was the stainless steel system. This design would have saved 35 percent, or $60,000, over the existing design, which does not include the cost of lost production due to the downtime. Refer to Tables 7 and 8 for the cost summary of the options for five- and 10-year life cycles.

Table 7. First Cost and Five-Year Life-Cycle Cost Comparison of 93 Percent Sulfuric Acid Unloading System.

Pipe Option	First Cost	Maintenance Cost	Operational Cost	LCC Savings Over Existing	LCC % Savings Over Existing
Existing 6 ft/s c.s.	$47,470	$96,788	$25,808	0	0
Larger diameter c.s.	$54,438	$74,840	$5,546	$35,242	21%
Stainless steel	$84,185	0	$25,834	$60,047	35%

Table 8. First Cost and 10-Year Life-Cycle Cost Comparison of 93 Percent Sulfuric Acid Unloading System.

Pipe Option	First Cost	Maintenance Cost	Operational Cost	LCC Savings Over Existing	LCC % Savings Over Existing
Existing 6 ft/s c.s.	$47,470	$162,661	$43,373	0	0
Larger diameter c.s.	$54,438	$125,775	$9,320	$63,971	25%
Stainless steel	$84,185	0	$43,416	$125,902	50%

It would be up to the business team to weigh first cost against LCC, not to mention the importance of safety and uptime. How ever the importance is placed, the software generates the data to make the right decision.

Improperly Sized Pump

The final system was a molten sulfur transfer system at an acid plant on the Gulf Coast. Figure 12 is the schematic of the system. The actual pump installed was significantly undersized and running to the far right of the BEP of the pump curve. Using Barringer and Associate's chart (Barringer, 1997) relating the effect of distance from the BEP to the reliability (Figure 13) and coupling that with the cost of labor and material for repair, Figure 14 was used to relate the distance from BEP to the cost of maintenance.

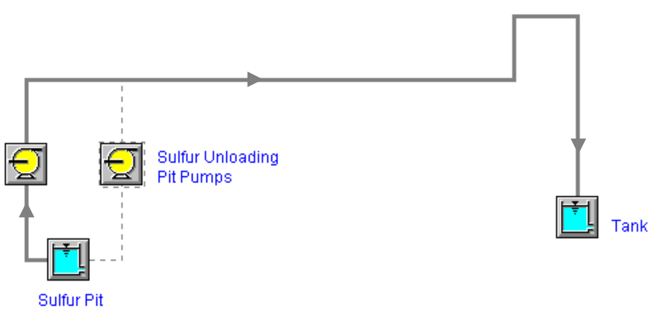


Figure 12. Molten Sulfur Transfer System Schematic.

Installing a properly sized pump for this application would have saved the project $73,692, or 70 percent in LCC with a five-year life cycle. For a 10-year life cycle, the savings would have been $123,401, or 72 percent. Although the original pump was undersized, the optimum pump actually had a smaller casing than the original and therefore was less expensive than the original. This resulted in a small savings in first cost. The savings was $653 or seven percent. Refer to Table 9 for the cost summaries.

CONCLUSIONS

- Numerical optimization technology is a proven technology that has been successfully applied in other design arenas that, until now, have not been utilized in pumping system design.

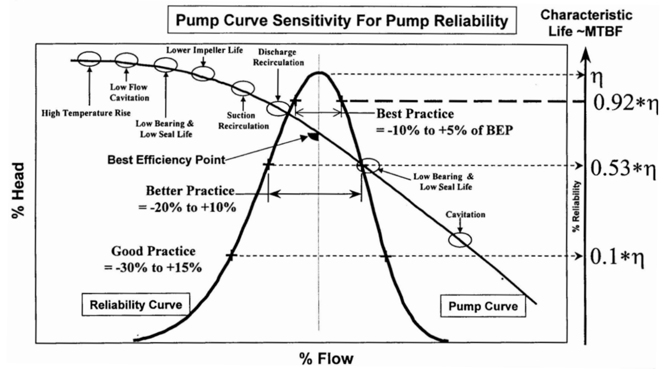
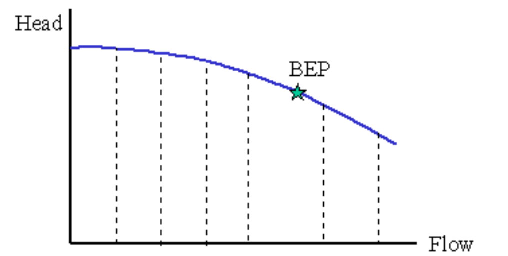


Figure 13. The Effect of Distance from the BEP on Reliability. (Courtesy of Barringer & Associates)



	%of BEP	20%	40%	60%	75-115%	140%	$/Failure	
Seals:	Life	2 Months	4 Months	1 Year	2 year	2 months	$1,000	Parts
	Failure/Year	6	3	1	0.5	6	$500	Labor
	Cost/Year	$9,000	$4,500	$1,500	$750	$9,000		
Bearings:	Life	1 Year	3 Year	4 Year	5 Year	1 Year	$500	Parts
	Failure/Year	1	0.33	0.25	0.2	1	$500	Labor
	Cost/Year	$1,000	$333	$250	$200	$1,000		
Casing/Impeller:	Life	2 Year	5 Year	7 Year	10 Year	2 Year	$2,000	Parts
	Failure/Year	0.5	0.2	0.014	0.1	0.5	$0	Labor
	Cost/Year	$1,000	$400	$285	$200	$1,000		
Total Cost/Year		$11,000	$5,230	$2,040	$1,150	$11,000		

Figure 14. The Effect of Distance from the BEP on Pump Maintenance Costs. (Reference Pump: ANSI 3×4-10 Stainless Steel Single-Stage, Horizontal Pump, with Dual Pressurized Seal, Running at 1750 RPM in a Mildly Corrosive Service.)

Table 9. First Cost, Five-Year, and 10-Year Life-Cycle Cost Comparison of Molten Sulfur Transfer System.

	First Cost	5-Yr LCC	5-Yr Savings $ & %	10-Yr LCC	10-Yr Savings $ & %
Original pump	$8,757	$105,116	---	$170,696	---
Optimized pump	$8,104	$31,424	$73,692 | 70%	$47,295	$123,401 | 72%

- Based on real world systems as the benchmark, using optimization software in place of traditional design techniques results in significant cost savings for both first cost and LCC.
- Besides being easy to use, the software proved to be versatile enough to manage different design issues commonly found in the petrochemical industry.
- This software has the potential to be a powerful tool in the effort to move from first-cost-focused design to LCC-focused because no additional work is required to compare the two different designs and their respective monetary tradeoffs.

APPENDIX

Following is a discussion of optimization methods that can be used to optimize pumping systems.

Gradient-Based Methods

For typical engineering systems, gradient-based optimization methods are the most efficient by a significant margin. Gradient-based methods search for the optimum using the partial derivative of the objective function (i.e., cost) with respect to each design variable (i.e., pipe diameter). From the starting point (the initial pipe sizes specified by the user), the gradient-based methods use the partial derivatives to determine new pipe sizes that will cause the overall objective to decrease.

Gradient-based methods search the design space in such a way as to meet all user design requirements (i.e., constraints). Designs that satisfy all constraints are called feasible designs. Designs that fail to satisfy one or more constraints are infeasible.

In complex systems, the partial derivatives of the objective function with respect to the design variables are frequently not available from analytical relationships. Therefore, the derivatives must be approximated by forward or central difference methods. For those interested, the mathematics behind these methods is discussed by Vanderplaats (1999b).

Genetic Algorithm Methods

Genetic algorithm methods work by simulating so-called biological evolution. An initial population of designs is randomly generated, and each design is evaluated by running the hydraulic solver for that design. The resulting objective function value (i.e., cost) and constraints are used to determine which designs are "fittest" (i.e., more optimal—least costly), and the better designs are crossbred while the worse designs are eliminated. The population breeds for some specified number of generations or until no further improvements are obtained.

Genetic algorithm methods are inherently discrete, and thus have the advantage (for pipe system optimization) of only considering discrete system designs. They also have the advantage of being better suited to finding the global optimum, rather than a local minimum. A major disadvantage is that they are slower than gradient-based methods. As the number of pipes increases, the performance significantly degrades as compared to gradient-based methods because they require many more calls to the hydraulic solver.

The performance of genetic algorithm methods can be significantly improved when used in conjunction with gradient-based methods (Applied Flow Technology, 2001, Chapter 14).

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