Session 2793

Optimal Life Cycle Cost Analysis and Design of Thermal Systems

Nand K. Jha and Bahman Litkouhi
Professor
Department of Mechanical Engineering
Manhattan College, Riverdale, New York, 10471

1. Introduction and background

Life cycle cost is the sum of all of the costs associated with a product from inception to disposal. LCC seeks to maximize thermal systems contribution to the society while minimizing combined cost of design, manufacturing, customer, and environment. Most researchers agree that decisions made during design of materials, manufacturing process, sizes, etc affect more than 75% of the LCC. Materials and manufacturing process used will affect the cost associated with reuse, recycle, disposal as well as environment. In industry, a life cycle cost design indicates that the first cost alone is not enough to evaluate fully an article for system, but that all costs occurred over the life of the system must be considered. A thermal system needs heavy financial investment and must include capital cost, operating cost, service and repair cost including total retirement cost. It has been found that due to governmental regulation, environmental concern and safety considerations, it is necessary to consider how to retire the system and costs related to retirement must be included in the optimal design. In order to achieve this goal, we should be able to formulate the design model and prepare the model for optimization based on the life cycle cost (LCC)[3]. In this paper, we discuss these steps in the context of a gas transmission system design. We develop a reasonably realistic model of a representative gas pipeline transmission system and use it as benchmark problem to evaluate the applicability of optimization technique. Although numerous optimization techniques are available and every one claims to obtain optimal solution for every kind of design problems but in reality it is not so. We have used Geometric Programming in this paper based on our experience of this technique in design and manufacturing problems. Other attribute of this technique is its ability to predict the proportions of various cost terms even before the design is attempted. However, we want to test the applicability of other similar nonlinear programming techniques to the optimal design problems based on life cycle costs and compare accuracy and other pertinent evaluation parameters later.

LCC is divided in to two main categories, 1) acquisition cost and 2) support cost. The acquisition costs are the costs associated with the design and build of the product. All of the cost required for research and development, design, tooling, other non-recurring cost and the product unit cost are included in the acquisition cost. The support cost is all of the cost incurred after the product is delivered to the customer. The support cost is typically very high in case of thermal system products.

Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition

The first consideration in determining the life cycle cost (LCC) of a product is to understand the complete support concept. This includes level of repair to accomplish the support tasks, the logistics of how and when are performed and general repair philosophy. The second consideration in a life cycle cost analysis is to know the technical details of the product to be supported. The design, modularity, complexity and technology of the product greatly influence the support concept and the LCC. The third consideration is to determine who is doing what tasks in the support process. Knowing who does what influences the initial setup, training needs, capacity planning and ongoing manpower required. The fourth consideration is what controls will be setup to monitor and coordinate the support activities. This determines the information that must be gathered and administrated. All of these items must be conceptualized before beginning a life cycle cost analysis. Since support concepts vary significantly across products, platforms, and contractors, it is sometimes difficult to evaluate approaches in an equitable fashion. Every request for a life cycle cost analysis should also be accompanied by an associated support plan describing the four items above. This provides the background for realistic evaluation of the concepts and LCC, as a whole.

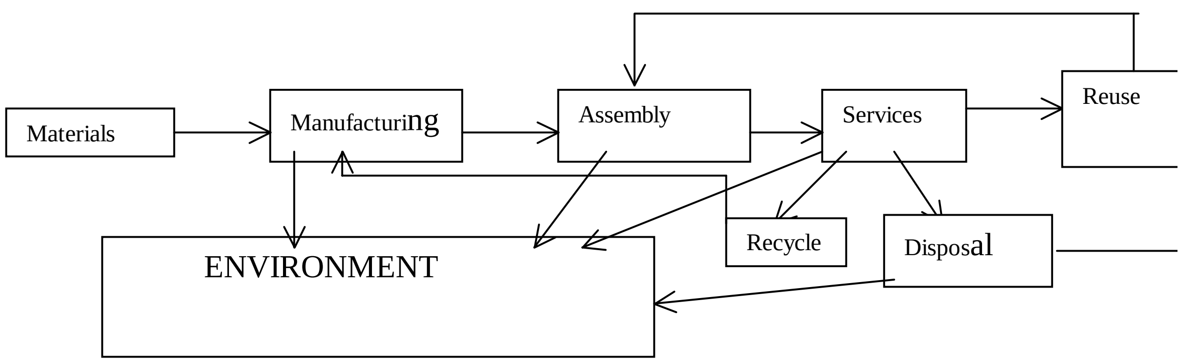

Fig1: Product Life-Cycle

Categorizing the inputs to the LCC model should be standardized so that LCC are repeatable and in the same format across products.

2. Product Life cycle

Life Cycle Cost has been a consideration on government programs for some time. With increased attention to the environment particularly in thermal system design, it is desired that we pay attention to the resources that is used in whole life of the system: solid materials, fluid and gas emissions, and energy. Life Cycle Cost has not been used extensively for smaller commercial-off-the-shelf hardware for procurement decisions in the thermal systems. As more of the shelf hardware is used in the thermal systems, the life cycle cost consequences must be understood to truly evaluate the "best value", Fig1.

There are inherent difficulties in using Life Cycle Cost (LCC) as an evaluation factor in procurement decisions. The life cycle cost varies greatly with the support approach, the personnel performing the support functions, and with the underlying assumptions used for the calculations. These variations make it difficult to evaluate competing acquisition proposals. This hardware has uncertain factors that drive the life cycle cost, such as, reliability, support approach, and support investment cost. The best approach to dealing with these issues is to standardize the life cycle cost calculations by utilizing industry standard tools.

3. Support cost components

The support cost portion of life cycle cost is divided into three major categories: Support Investment Costs, Annual Fixed Costs and Repair Activity Costs. Support Investment Cost is the cost of starting up a total system support structure. Test and support equipment, repair material lay-in, depot level spares, shop replaceable spares, and initial technical data costs are included in this cost. Annual Fixed Costs are the sustaining labor, equipment maintenance, program management, and obsolescence mitigation. This contains the primarily overhead-type costs required during the support period. Repair Activity Costs are associated with the return and repair of the product. This includes the disposition of returned material; repair labor and material costs and transportation costs.

4. Optimization Technique Used in Formulation and Solution:

We have attempted to formulate and solve the life cycle optimal design of a thermal system problem through geometric programming. For convenience of understanding, we present the basic formulation of signomial (generalized polynomial)[1,2]. The generalized geometric program is first formulated as primal geometric program (PGP) and then converted to dual geometric program (DGP) for solution.
We can formulate a signomial geometric program as
Minimize

$$g_0(X) = \sum_{t=1}^{T} \sigma_{0t} C_{0t} \prod_{n=1}^{N} X_n^{a_{0tn}}$$

s. t. constraints:

$$g_m(X) = \sum_{t=1}^{T_m} \sigma_{mt} C_{mt} \prod_{n=1}^{N} X_n^{a_{mnt}} \leq \sigma_m \quad \text{for m=1,2,....M.}$$

The signum function values σ_m and σ_{mt} are known are known from problem formulation. These values can be either +1 or –1.
In general GGP is non-convex nonlinear program and can contain multiple local minima.
Dual Program:
A PGP has associated with it dual geometric program. A new set of dual variables associated with each term in the objective function and constraints are defined as w_{mt}. And the dual geometric program (DGP) is presented as

Maximize

$$V(w_{mt}) = \left[\sum_{m=0}^{m=M} \prod_{t=1}^{T_m} \left(\frac{C_{mt} w_m}{w_{mt}} \right)^{\sigma_{mt} w_{mt}} \right]$$

S.t. constraint:

$$\sum_{t=1}^{T_0} \sigma_{ot} w_{0t} = 1$$

$$\sum_{m=0}^{M} \sum_{t=1}^{T_m} \sigma_{mt} a_{mnt} w_{mt} = 0 \qquad \text{for n = 1,2,….N}$$

$$w_{m0} = \sum_{t=1}^{T_m} \sigma_{mt} w_{mt} \qquad \text{for m = 1,2,….M}$$

$$w_{mt} \geq 0 \qquad \text{for m = 0,1,…M and t =1,2, } T_m$$

Once the optimal dual variables w^*_{mt} are found out, the corresponding primal variables x^*_n can be determined from the following equations.

$$C_{0t} \prod_{n=1}^{N} (X^*{}_n)^{a_{mtn}} = w_{0t} \times V^*(w_{mt}) \quad \text{for t = 1,2,….} T_m$$

$$C_{mt} \prod_{n=1}^{N} (X^*{}_n)^{a_{mtn}} = \frac{w_{mt}}{w_{m0}} \qquad \text{for t = 1,2,…} T_m \text{ and m = 1,2,…..M.}$$

Term like degree of difficulty also helps in understanding the geometric programming formulation and solution. The degree of difficulty is defined as

D OD = T-(N+1) where T is defined as

$T = \sum_{m=0}^{M} T_m$ and N is number of primal variables.

5. Life Cycle Cost Modeling

There are many LCC modeling tools available in the industry. The best LCC tool is one that works and does what you require to influence the trade-offs and impact the decision-making process [3]. There are several good LCC software packages available. Two recommendations on LCC modeling software: 1) Select one that provides the capability to perform sensitivity analyses and 2) always validate new life cycle cost software using a duplicate technique for important decisions on:

- Level of Repair
- Reliability
- Unit cost and cost of spares
- Usage rate
- Turn around time
- Redesigns due to technology obsolescence

  Sensitivity analyses allow visibility to the optimal support solution for minimizing life cycle cost. It provides a necessary look into the reality of the unknowns that can significantly drive the life cycle cost.

5.1 Problem Formulation:

We present the Life cycle cost (LCC) formulation of transmission system for natural gas pipeline as illustrated in the Fig2 below, Process gases are required in a wide range of operations, pressures and temperatures; process gas compression is a complex unit operation providing either centrifugal or reciprocating compressors. Centrifugal Pumps have high capacity, low-line discharge pressures 1000 psia and flow rate with a range of 400 to 10^5 cu.ft/min, Whereas, the reciprocating pumps have lower capacity, high discharge pressures usually within a range of 100 to 25,000 cu.ft/min, and discharge pressure up to 4000 psi [4,5,6]. Centrifugal compressors are found in a variety of applications due to their operations characteristics, ease of repair and polytropic efficiency in the range of 70 % to 80%.

For cost estimating process, many variables such as volume or weight capacity (cu.ft/min or lb/hr), molecular weight s, k-values, and compression ratios as represented by the BHP parameters are considered. These calculations are required before optimization can be attempted. We have to find field-assembled costs for centrifugal machine with motor drive ranging from 200 to 3,000 BHP. Factors are included to adjust for other compression/drive combinations, Dollars amount should be added for foundation, field materials, field labor, and in directs from the installation modules required [7].

While modeling a thermal system involving a number of process components, a block diagram representation of physical system is required as shown in Fig2**.** It is required to pump 400 MMSCF/day of natural gas through a distance of 1000 miles. The compressor stations are to be placed at equal distances. The design variables are the diameter of pipe (D in.), compressor discharge and inlet pressures (P_1 and P_2 Pisa), length between stations (L miles). The LCC will include Capital cost, operating cost, labor cost, service cost, retirement cost, disassembly cost, and disposal cost.

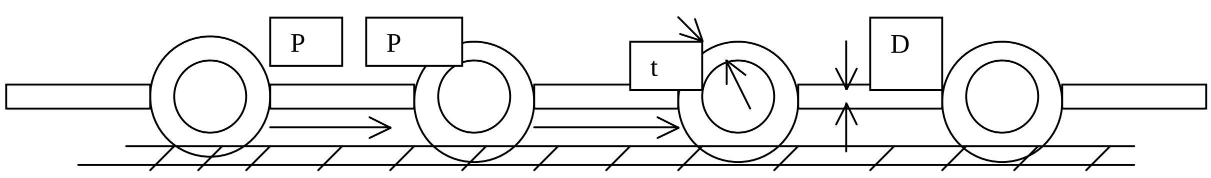

Fig2: Gas Transmission System

As shown above, usually higher pressure service is achieved in stage, with maximum pressure ratios of 3 to 4 found in each stage, a maximum pressure rise in each stage limited to 1000 psi. Precise specification of piping is almost never required in preliminary design analysis of thermal systems. However, we have attempted to define precisely the bore diameter as well as thickness of the piping material and included them in the design formulation. We think this to be essential, as it will relate to the mechanical strength of fittings and type of fitting connections to be used. In terms of connections, normally available options are; threaded, socket welded, and butt -welded. Flanges can be used or not used with any of these types and flanges are most expensive of any elements in the system. When cost or space is major consideration, slip-on flange is mostly selected. We have looked beyond the design of the system in this paper but we must note that these considerations are essential in laying out the system in the field.

Capital Cost**:**

We assume the following cost and other relevant data from Guthrie[6], Sharma et al[4], Ahern et al[5]. Most of the data and empirical relationships are adopted from these articles, as we could not find any latest cost data from other sources. The initial compressor cost based on horsepower of compressor is presented as:
Initial compressor cost = $ 50,000 + ($290)(hp).
The pipeline cost is obviously based on the piping material. All these cost are on steel.

Pipeline cost = $312/ton. Before installation of pipeline in a gas field, we need to do surveying, leasing and other engineering work such as leveling etc. Most job sites require extensive preparation before foundation work and equipment setting can start. The extent and cost of this preparation depends on the amount of surface cleaning, rock blasting, grading, and excavation pilling, etc. Quantity data are not always available in early conceptual works in this case and we have proposed an analytical way to include this cost[6,7].

Surveying, leasing and engineering cost = $10,000/mile. The pipeline installation cost will depend on the weight of pipeline and in turn on the thickness of pipe and so the pipeline installation cost is presented as below.
Installation of the pipeline = $820/mile per inch of pipe diameter. The labor and supervision cost at each compressor station and along the pipeline is extremely difficult to estimate analytically, however, Ragsdell et al[4,5,8] has presented it based on the horsepower of the compressor as:
Labor and supervision at each compressor station = $(1200+1.0(hp)) month. The maintenance and other service costs depend on the service operations and frequencies of maintenance and services, Maintenance and service cost is presented is prorated monthly based on the horsepower of compressor as
Maintenance and utilities = $(0.30)(hp)/month. The operating cost of compressor is based on the fuel consumption and internal charge of fuel.
Internal charge for fuel=$0.34/MSCF.
Fuel consumption = 12SCF/(hp-hr). All the cost data are converted to annual cost and then added together to get the annual total life cycle cost. To get the annualized capital costs we use a depreciation rate of 15%.

The fixed cost of the pipeline facility is the sum of the costs of the pipe and the compressors. These are prorated to annual costs using a 15% depreciation rate. The total annual cost (fixed +operating) can be computed in terms of the design variables D, P_1, P_2, and L.

A relation for horsepower of compressors in terms of work is developed first. We can see that number of compressors for 1000 mile length of gas transmission line will be as follows by assuming that compressors are installed at distance of L miles between them.

Number of compressors = 600/L

Volumetric flow rate = $100x10^6$ SCF/day

$=100x10^6/(159)=2.785x10^5$ moles/day

Horsepower of each compressor can be obtained using the adiabatic compression work for an ideal gas, which is given by

$$W = (\frac{\gamma}{\gamma - 1})\left(\frac{RT_0}{\eta}\right)\left[r^{\frac{\gamma-1}{\gamma}} - 1\right]$$

where W = work in BTU/lb.mol

r = P_1/P_2 (design variable)

R= gas constant = 1.987BTU/(lb.mol. ^{0}R)

T_0 = gas temperature = 492^0 R

γ = ratio of specific heats = 1.28

η = efficiency of compressor = 0.75

hp= $2.7168x10^4(r^{.219}-1)$

<u>Annual Cost:</u>

1) Annual cost for all installed compressors:
   $0.15(1000/L)[50{,}000+290(2.7168x10^4)(r^{0.219}-1)]$
   $= 7.5/Lx10^6+11.82/L(10^8)(r^{0.219}-1)$
2) Annual operating cost of all compressors
   $(0.34/1000)(12)(24)(365)(1000/L)(2.7168x10^4)(r^{0.219}-1)$
   $= 9.71/L(10^8)(r^{0.219}-1)$
3) Annual maintenance and service costs of all compressors
   The Life cycle maintenance and service may be estimated as :
   $$(0.30)(2.7168)(10^4)(r^{0.219} - 1)(12)(1000 / L)$$
   $$= \frac{9.78}{L}(10^7)(r^{0.219} - 1)$$

Above cost depend on set of maintenance and service operations including the frequencies of maintenance and services.

4) Annual labor and supervision cost:- Labor cost is prorated to horsepower rating of compressors. For gas transmission line installation, special training and service may be required.

$$(\frac{1000}{L})\left[(1200(12) + 1.0(12)(2.71868)10^4(r^{0.219} - 1)\right]$$

$$= \frac{1.44(10^7)}{L} + \frac{3.26(10^8)}{L}(r^{0.219} - 1)$$

<u>Fixed Costs of Pipeline</u>:

5) Installation cost = 820(1000)D(0.15) = 1.23(10^5) D
6) Cost of surveying, leasing and engineering (10,000)(1000)(0.15)= 500,000. It is a fixed value and will not affect the optimal design of the thermal system.
7) Pipeline costs: The cost of pipeline is a function of its weight, which is given by

   Weight(tons/mile)= π/144)(D+t)(t)(5780ft/mile)(480lb/ft^3)(ton/2000lb)

   = 27.646(D + t) t

   t is thickness of the pipe in inches. The thickness can be calculated by hoop stress formula

   t = D.P_1/(2(S-0.6P_1)) = D.P_1/(2S)

   where S is tensile stress, 2500 psi, then

   Weight(tons/mile)=27.646.D^2(1+P_1/50,000).(P_1/50000)= 7.646.D^2(P_1/50,000).

Now annual cost of pipe can be found as

$$\text{Annual cost of pipe} = 0.15(1000)(400)(27.646D^2 \frac{P_1}{50{,}000})$$

$$= 33.1752 D^2 P_1 .$$

The initial inlet pressure P_1 may be replaced in terms of L, r, and D from the volumetric equation as below. The volumetric flow[4,6] is given as

$$Q = 3.39\left[\frac{(P_1^{\,2} - P_2^{\,2})D^5}{fL}\right]^{1/2}$$

, where f is friction factor in pipeline $f = 0.01D^{-1/3}$. The compressor volumetric flow (Q) is assumed for a centrifugal compressor as 100 million ft^3/day and converted to 4.17(10^6) SCF/hr.

hence,

$$4.17(10^6) = 3.39\left\{\frac{(P_1^{\,2} - P_2^{\,2})D^5}{0.01D^{-1/3}L}\right\}^{1/2} = 3.39\left(\frac{P_1}{r}\right)\left\{\frac{(r^2-1)D^{5\frac{1}{3}}}{0.01L}\right\}^{1/2}$$

. We get P_1 as:

$$P_1 = 0.123(10^6)\, r\left\{\frac{LD^{-5\frac{1}{3}}}{r^2-1}\right\}^{1/2}$$

. If we replace P_1 equation in the annual pipeline cost, we get the final annualized pipeline cost as below.

$$= 4.1(10^6)L^{1/2}rD^{-1/3}(r^2-1)^{-1/2}$$

8) Total Retirement Cost of the Gas Transmission System**:**

It is supposed that at the end of useful life the gas transmission system including the pipe and compressors will be retired. It has been noticed that the compressors loose their usefulness even before the pipes. However, it can be stipulated that once the compressors are retired so the pipes. The design of compressors and pipes are based on the pressure ratios, volumetric flow and horsepower required of the compressors. This will also affect the volume as well as the weight of the components for the transmission system. Ultimately these parameters will affect the disassembly and retirement costs. The total retirement cost can be stipulated as combination of disassembly and reprocessing cost of cluster of reusable components [3].

Total retirement cost = Disassembly cost + $\sum_{i=1}^{n}(reprocessing\ cost)$

Where n refers to the total number of clusters disassembly. However, we assume here that all components are salvaged and never reused again for safety and environmental reasons. Sometimes or most of the times they may have to be dumped in the landfill and so this cost must be added to the retirement cost. We can think of disassembly cost on the time to remove component, time to remove fasteners, time to remove or undo process and total number of components in the system. The disassembly itself is depended on the pressure ratios and volumetric flow. Therefore, the disassembly cost based on the volumetric flow and pressure ratios and it is assumed as K_2=10% of pipeline cost.

$$D_s' = 4.1(10^5)L^{1/2}rD^{-1/3}(r^2-1)^{-1/2}$$

The disassembly cost (D_s) needs to be annualized. We have assumed 20 year life of all the components and an interest rate of 10% and so the annualized disassembly cost is

$$D_s = \frac{i}{(1+i)^n - i}\times D_s' = 0.017(4.1)(10^5)L^{1/2}rD^{-.33}(r^2-1)^{-1/2} = 7(10^3)L^{1/2}rD^{-.33}(r^2-1)^{-1/2}$$

The land cost for disposal should be added to the total retirement cost. Most jobsites require extensive preparation before foundation work and equipment setting can start. The extent and cost of this preparation depends on the amount of surface cleaning, rock blasting, grading, and excavation pilling, etc. Quantity data are not always available in early conceptual works in this case and we have proposed an analytical way to include this cost. We assume that it will depend on the volume of material to be disposed. The total volume consists of the pipe material, compressors, and other related components. We assume at this stage that even if the compressors are unfit to be reused but it could be traded with junk dealers and it may not be required to be buried in the ground at present. Therefore, the land cost is taken as proportional to the volume of the pipeline system as:

$$Land\ cost = K_1\frac{\pi}{144}(D+t)t\left(\frac{5780}{mile}\right)1000.$$

where K_1 represents the land price per square feet assumed as \$5.00.

The land cost should be annualized as before. Annual Land cost:

$$\text{Land cost} = 0.017(5)\frac{\pi}{144}(D+t)t(5780)(1000) = 1.07(10^4)(D+t)t$$

Hence, the total retirement including the land cost for dumping is (TRC):

$$TRC = 7(10^3)rL^{1/2}(r^2-1)^{-1/2}D^{-0.33} + 1.07(10^4)rL^{1/2}D^{-0.33}(r^2-1)^{-1/2}(r^{0.219}-1)$$

6. Optimal Design

The Total Cost of the pipeline including operation of compressors is given by adding costs (1) through (8):

$$TLCC = \frac{7.5}{L}(10^6) + \frac{11.82(10^8)}{L}(r^{0.219}-1) + \frac{9.78}{L}(10^7)(r^{0.219}-1) + \frac{1.44(10^7)}{L} + \frac{3.26(10^8)}{L}(r^{0.219}-1) + 1.23(10^5)D + 15(10^5) + 4.1(10^6)L^{1/2}rD^{-0.33}(r^2-1)^{-1/2} + 7(10^3)rL^{1/2}D^{-0.33}(r^2-1)^{-1/2} + 1.07(10^4)rL^{1/2}D^{-0.33}(r^2-1)^{-1/2}(r^{0.219}-1)$$

After replacing, $L = x_1, r = x_2, D = x_3 and (r^2-1) = x_4$. This replacement will change the TLCC equation into signomial form and a constraint to the mathematical model. After adding similar terms, we get final total life cycle cost equation as below.

$$TLCC = -3.435(10^9)x_1^{-1} + 25.768(10^8)x_1^{-1}x_2^{0.219} + 1.23(10^5)x_3 - 4.09(10^6)x_1^{1/2}x_2x_3^{-0.33}x_4^{1/2} + 1.07(10^4)x_1^{1/2}x_2^{1.219}x_3^{-0.33}x_4^{1/2}$$

subject to constraint:

$$x_4x_2^{-2} + x_2^{-2} \leq 1$$

it is converted to geometric programming format as

For a feasible design, $x_1>0$, x_2 (compression ratio) > 1, and $x_3>0$.
The TLCC equation is now in signomial (Generalized Geometric Programming) form.

The above formulation is called as primal geometric program (PGP). PGP needs to be converted to dual geometric program (DGP) before solution. In geometric programming, we can test the degree of difficulty (DOD) =T-(N+1). T is total number of terms in PGP and N is number of decision variables. In this model, we have T=7 and N=4, so DOD=2. The DOD indicates that we will be short of two equations in the DGP for unique solution of optimum variables. Several algorithms for solution of positive degrees of difficulties problems are available. There is one another approach known in geometric programming which can provide a range of optimal values for TLCC. This approach seeks to convert the positive degree of difficulty problem to one degree of difficulty by dropping the requisite number of terms from the TLCC model. We can change this model to one degree of difficulty by dropping the first term [8,9].

$$TLCC = 25.768(10^8)x_1^{-1}x_2^{0.219} + 1.23(10^5)x_3 - 4.09(10^6)x_1^{1/2}x_2x_3^{-0.33}x_4^{-1/2} +$$
$$1.07(10^4)x_1^{1/2}x_2^{1.219}x_3^{-0.33}x_4^{-1/2}$$

subject to constraint:

$$x_4x_2^{-2} + x_2^{-2} \le 1$$

$$x_1 > 0, x_2 \;\; > 1, x_3 > 0\,.$$

It has been proved in geometric programming that maximum of DGP is equal to minimum of PGP. We can now write the DGP formulation as

Maximize

$$D(w_{mt}) = \left(\frac{25.768(10^8)}{w_{01}}\right)^{w01}\left(\frac{1.23(10^5)}{w_{02}}\right)^{w02}\left(\frac{4.09(10^6)}{w_{03}}\right)^{-w03}\left(\frac{1.07(10^4)}{w_{04}}\right)^{w04}$$
$$\left(\frac{w_{10}}{w_{11}}\right)^{w11}\left(\frac{w_{10}}{w_{12}}\right)^{w12}$$

Subject to constraints:

$w_{01} + w_{02} - w_{03} + w_{04} = 1$ (Normality constraint)

$-w_{01} + 1/2w_{01} - 1/2w_{03} + 1/2w_{04} = 0$ (Orthogonal constraints)

$0.219w_{01} - w_{03} + 1.219w_{04} - 2w_{11} - 2w_{12} = 0$

$w_{02} + 0.33w_{03} - 0.33w_{04} = 0$

$1/2w_{03} - w_{04} + w_{11} = 0$

$w_{mt} \ge 0, m = 0,1,2.....M, t = 0,1,2....T$ (DGP)

The dual geometric programming (DGP) formulation has one degree of difficulty as we can see that there are 5 linear constraints and 6 dual variables. However, here it is solved by replacing variables in terms of one variable and then dual objective function is maximized. After finding dual variables, primal variables (design variables) are calculated by the relations presented in section 4.
The optimum dual variables obtained are as follows:

$$w_{01}^* = 4.086, w_{02}^* = 3.296, w_{03}^* = 7.277, w_{04}^* = .895.w_{11}^* = 4.086, w_{12}^* = 0.78, w_{10}^* = 4.866$$

The optimal primal variables are obtained as below.

$$D^* = 24'', L^* = 21.586 miles, \Pr essureratio(r^*) = 1.763, P_1^* = 144.787\,psia, P_2^* = 255.26\,psia$$

The thickness of the pipe, t is calculated as below.

$$t^* = \frac{D^2 P_1}{50{,}000} = 1.668 in \approx 1\frac{7}{8} inches$$ and optimum number of compressors=47

The range of total cycle cost is shown below.

$$4.05(10^{16}) < TLCC < 4.1(10^{6})$$

The optimum total life cycle cost (TLCC) range is very low and which confirms that exact optimum will lie somewhere in the range.

7. Conclusion

We have presented a methodology for total life cycle cost (TLCC) formulation for a 1000-mile gas transmission system. We have included not only the cost of hardware like compressors, pipes etc but also the cost of retirement, recycling, reuse, and dumping of the junk part of the thermal system. In our ME curriculum we put lot of stress on design aspects but never on recycling, reuse and retirement aspects of the thermal systems which are hazardous and unsafe for the society at large. We will also stress the fact that most of the times in design courses we talk a lot of engineering aspects of design but very little of economics. We believe that with the kind of formulation and solution presented here we will modify design courses particularly thermal design course based on total life cycle cost concept including retirement cost.

Bibliography

1) Geometric Programming-Theory and Application, Duffin, Peterson, and Zener, Wiley, 1967
2) Applied Geometric Programming, C.S. Beightler and Don T. Phillips, Wiley, 1976
3) K. Ishi, "Life-Cycle Engineering Design", Mechanical Design, ASME Trans., 42/Vol.117, June 1995.
4) F.W.Ahrens, Sharma,A.,Ragsdell,K.M., "Computer Aided Optimal Design of Compressed Air Energy Storage Systems", July 1980, Vol.102/437, Journal of Mechanical Design, ASME
5) A.Sharma, Chu H.H., Aherns F.W., Ahluwalia R.K., Ragsdell, K.M., "Design of Optimum Compressed Air Energy-Storage systems," Energy, Vol.4, 1979, pp.201-216
6) Capital Cost Estimating, K.W. Guthrie, W.R. Grace & Co.
7) Kartsounes, G.T., and Kim, C.S., "Study of turbo machinery options for compressed air energy storage plants", Proceedings of 14 Th Intersociety Energy Conversion Engineering Conference, Boston, Aug. 5-10, 1979.
8) Engineering Optimization, G.V.Reklaitis, A. Ravindran, and K.M.Ragsdell, 1983, John Wiley & sons.
9) Dembo, R.S.," The Current State of Art of Algorithms and Computer Software for Geometric Programming", J. optimization Theory Appl., 26, 149-183 (1978)
10) Design Analysis of Thermal Systems, R.F.Boehm, John Wiley & Sons, 1987.

NAND K. JHA

Nand K. Jha is a Professor of Mechanical Engineering at Manhattan College, Riverdale, New York. He has authored numerous publications on CAD, CAM, Automation in Manufacturing, and robotics. He has applied engineering optimization techniques to manufacturing problems and design automation. His research interest include multi -objective optimization, knowledge-based process planning and design, and control of engineering systems. He has edited ***Handbook of Flexible Manufacturing Systems*** published by Academic Press. He has chaired the ***Computer Integrated Manufacturing*** (CIM) division of ASME.