Study into the Life Cycle Cost of Ductile Iron and Stainless Steel Pumps

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Abstract

The Water Corporation has a relatively small number of large (>75kW) stainless steel pumps compared to ductile iron, being approximately 10% of a total population of 200. They are interested in investigating the benefits and costs of increasing the population of stainless steel pumps through the use of life cycle cost analysis. Life cycle analysis has shown that the capital cost of a pump can account for as little as 4% of the whole of life cost. The more significant cost is the operating cost which can account for over 90% of the total costs. The aim of this research project was to design a life cycle cost (LCC) model for comparing whole of life costs of stainless steel and ductile iron pumps. This has been accomplished through the integration of parametric maintenance and purchase cost estimation equations, and previously developed pump degradation models. The initial analysis on a medium to large pump with a duty power of 318kW indicated ductile iron to be the most favourable material for clear water applications. Additional research is required on the internal casing degradation of ductile iron pumps to increase the reliability of the initial findings. The model developed will allow the situation to be reviewed as more information comes to hand.

1. Introduction

The Water Corporation currently operate between 200 and 250 horizontal split casing centrifugal clear water pumps with a motor rating above 75kW. Of these pumps approximately 10% have a stainless steel casing with the remainder being made of a coated ductile iron. The primary factors which have made coated ductile iron the preferred pump material are the lower capital cost and initially higher operating efficiency. To understand whether the decision drivers are reasonable they must be considered on a whole of life basis.

Current methods employed by the Water Corporation for pump selection involve the use of an annualised cost equation which includes purchase cost and operating costs based on original pump efficiency. Net present value analysis have been carried out on past projects to compare stainless steel and ductile iron pumps though a more complete investigation into cost estimates and the different degradation rates in operating performance between the two pump materials is necessary to improve the accuracy of the comparison. The developed model has been designed to be used as a decision support tool for both before and after tender.

Based on past tenders and interviews with pump suppliers a large stainless steel split casing centrifugal pump is approximately 2 to 3 times the cost of a similar ductile iron pump. This can result in an additional capital expenditure of $80,000 to $280,000 depending on the size and capacity of the pump. LCC analysis has shown that capital costs can account for as little as 4% (Europump, 2005) of the whole of life cost of a pump which may mean that the initial cost spent on a pump may be absorbed by other life cycle cost elements.

Interviews with pump suppliers have indicated that a new, as cast stainless steel pump can have an initial efficiency lower than a new coated ductile iron pump of 1-2%. A 1% drop in efficiency can equate to an approximate additional cost of $1680 in a year for a 350kW pump operating for 2000 hours a year at 24c/kWh. Pump testing and coating observations during overhauls have called into question the long term integrity of the internal coating. Anecdotal evidence from within the Water Corporation suggests that cast iron pumps start with a higher efficiency than stainless steel pumps, but become less efficient after several years of operation due to coating deterioration and internal casing corrosion.

The Water Corporation's strong focus on sustainability, carbon neutrality and cost saving have been the driving forces behind the study into the effectiveness and whole of life cost between ductile iron and stainless steel pumps. The object of the LCC analysis is to identify the drivers that influence the whole of life cost difference between stainless steel and ductile iron pumps, and hence determine which material is most suitable for clear water pump applications.

1.1 Life Cycle Cost Modelling

Christensen et al. (2005) presents a step by step development of LCC modelling over the last 40 years. Original modelling steps involved defining life cycle analysis purpose, technically feasible options, cost estimates, equivalence measures, ranking and customer selection. The first modelling improvements were sensitivity analyses, followed by reliability analysis using Weibull distributions (Mazhar et al., 2007) and risk analyses with Monte Carlo simulations (Barringer, 1998 and Emblemsvag, 2003). An iterative reassessment feedback loop and a value of information (VOI) step have been included for when decisions are indeterminate or appear inaccurate (Christensen et al., 2005).

As LCC models advance, traditional methods of costing are being replaced by activity based LCC (Emblemsvag, 2003), while probabilistic sampling and artificial neural network techniques (Mazhar et al., 2007) are becoming more popular in attempts to more accurately model real complex systems.

The most widely used pump LCC models have been developed by the Hydraulic Institute (2005) and Barringer (1998). The Hydraulic Institute (2005) gives a step by step guide for developing simple annualised cost models required for specific cost investigations, while Barringer (1998) develops more complicated models which include effectiveness and Monte Carlo reliability analyses.

The deterministic model developed here is designed to incorporate principles of parametric and analogue cost estimation relationships based on pump duty power (AS/NZS, 4536 1999). State of the art probabilistic methods have also been used to explore the sensitivity and variability of the deterministic model in the face of uncertainties such as high variations in capital and maintenance costs.

2. Model Development

An initial LCC element tree was created and broken into several levels of cost activities. The level of refinement was stopped when acceptable costing was attainable for each activity based on available data. After investigation into costs associated with each cost element it was found that the primary cost influences were purchase cost, overhaul maintenance cost and operation cost. Design costs, installation costs, regular and unplanned maintenance costs and disposal costs were excluded from the model due to the cost elements being either the same for both stainless steel and cast iron, negligible over the life cycle, or insubstantial due to the time value of money.

The net present value (NPV) LCC method was used in the comparison model. Real discounted costs were calculated at 2009 dollars. The LCC model is an integration of cost estimation sub-models written as a spreadsheet in MS Excel. MS Excel was used as the platform for the model for its versatility, accessibility and familiarity, and its potential to use add in tools such as the Monte Carlo Crystal Ball application. Crystal Ball has the capacity to quickly run and store thousands of model simulations influenced by probability distributions for cost uncertainties, and deliver the most likely outcome along with the sensitivity to the cost uncertainties, confidence intervals and upper and lower result ranges.

2.1 Modelling Capital Costs

Capital costs were modelled using past tenders received by the Water Corporation over the previous 12 years. Parametric cost equations (AS/NZS 4536 1999) were developed linking duty power to purchase costs in 2009 dollar (refer to figure 2.1). Analogue relationships were used to convert the cast iron pump with a bronze impeller estimates to stainless steel pumps with a stainless steel impeller. Based on the limited number of stainless steel tenders and supplier advice, stainless steel pumps were expected to be approximately 1.9 times more expensive than ductile iron pumps with bronze impellers. The cost of stainless steel spare rotating elements were determined using the same parametric and analogue modelling technique, but applied to tender data acquired for bronze spare rotating element.

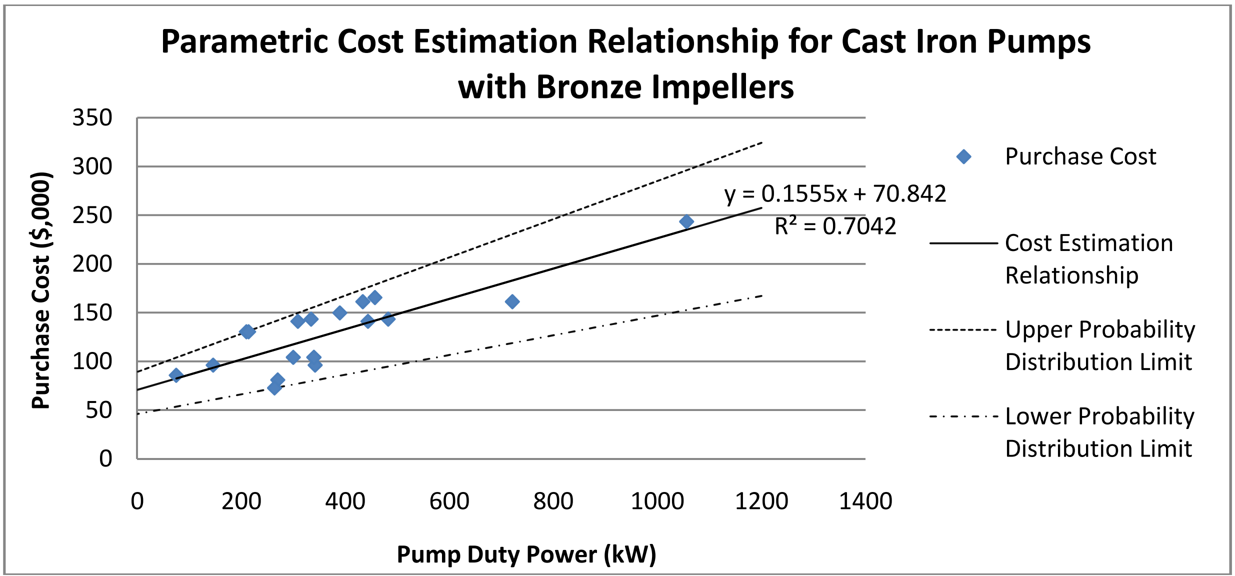

Figure 2.1 The cost estimation relationship between pump duty power and purchase cost for a cast iron pump with a bronze impeller and wear rings. Upper and lower limits for Monte Carlo probability distributions are shown

2.2 Modelling Overhaul Maintenance Costs

Large variations in overhaul costs made modelling the cost difficult following a deterministic approach. The general solution lay in dividing the costs into two activity branches, namely routine activities carried out during every overhaul and one off type activities incurred every 8-12 years. Depending on the pump operating conditions a pump could receive an overhaul every 3-5 years or just one to two times during its 25 year life. The more frequently a pump is overhauled the less the total cost of each will most likely be. At approximately 10 years additional costs will be incurred to account for replacing parts rather than a repair and reuse scenario. These additional costs appeared to be the underlying cause of the large overhaul cost range. All activities during the overhaul were allocated labour hours and a material cost. For small and invariable costs fixed values were used. Parametric equations were created for activities with large variations in labour hours or material costs, relating duty power to labour hours (hr/kW) and material cost ($/kW).

2.3 Modelling Operation Costs

Predicting the change in operating costs presented the greatest challenge. To predict the changes MacGeehan's (2006) pump deterioration models were used. MacGeehan (2006) identifies the primary losses in efficiency to be the opening of the wear ring clearance promoting recirculation (R) and the deterioration of the pumps internal casing increasing friction losses (K_z), refer to equations 1 and 2.

$$H_{f,z}(Q) = x_1\left((Q + R) + x_2\right)^2 + x_3 - K_z Q^2 \quad (1)$$

$$P_{f,z} = x_4((Q + R) + x_5)^2 + x_6 \quad (2)$$

Equation coefficients x_1, x_2... x_6 are calculated from the quadratic equation representing the pump curves. Q is the duty flow which is recalculated at the end of each year as the intercept between the system curve and the $H_{f,z}(Q)$ curve. The adjusted flow and power is used to determine the operating hours and power consumption of the pump for the following year. R is the recirculated flow given in equation 3 and K is the casing friction coefficient shown in equation 5.

$$R(c(t), H, c_0, d, l) = \frac{1}{1000} \propto dH^{1/2}\left(\sqrt{\frac{c(t)^3}{75c(t)+l}} - \sqrt{\frac{c_0^3}{75c_0+l}}\right) \quad (3)$$

$$c(t) = c_0 \ln(\beta t + e) \quad (4)$$

Variables α is 98.4 (√m/sec), H is the operating head (m), c_0 is initial wear ring clearance (mm), d is the wear ring diameter (mm), l is wear ring axial length (mm). c(t) is the wear ring clearance (mm) after t operating hours, β is the wear ring deterioration parameter which should be site specific but for comparative purposes in this report is set to 1.49E-3, representative of a 315kW pump operating in a clear water environment and *t* is time run since last overhaul (hr).

$$K_z = \eta_{loss} \frac{P_{(0)BEP}}{\rho g Q_{(0)BEP}^3} \quad (5)$$

η_{loss} is the loss of efficiency from internal surface condition at time t, $P_{(0)BEP}$ is original BEP power (kW), ρ is density (kg/L), g is gravity and $Q_{(0)BEP}$ is original BEP flow (L/s).

It is assumed other factors that affect efficiency are negligible in contrast and that motor efficiency and the system curve remain unchanged during the life of the pump. Pump failures are not accounted for in the analysis. Only single pump operating systems are being considered at this stage. For initial investigations a power cost of 24c/kWh has been used, this is in line with the Water Corporation's Energy Management Unit recommendations.

3. Results and Discussion

The primary factors which influenced the whole of life cost difference between ductile iron (DI) and stainless steel (SS) pumps are acquisition costs, duty power, power costs, overhaul regularity, pump internal surface condition, and real discount rate. An initial investigation on a 318kW pump operating for 4000hrs/year at 24c/kWh, calculated at a real discount rate of 6% and overhauled every 5 years, indicates that a ductile iron pump has a lower whole of life cost than stainless steel when used in clear water applications. The initial efficiency of the stainless steel pump was 1.5% less than cast iron due to the rougher cast surface finish. The ductile pump efficiency was assumed to degrade linearly by 0.2% per year as a result of internal coating degradation. Results for the 318kW pump analysis are given in table 3.1.

	NPV Total Life Cycle Cost ($,000)	
Casing Material	**Deterministic Model**	**Crystal Ball Results**
Cast Iron (CI)	5039	5026
Stainless Steel (SS)	5089	5136
SS and CI NPV Difference	50	110
Percent of Total LCC	0.99%	2.19%

Table 3.1 NPV life cycle costs for a 318kW stainless steel and cast iron pump

The deterministic model demonstrated a smaller LCC NPV difference between the two casing materials than the probabilistic model. The probabilistic results included a large degree of uncertainty in the purchase cost for the stainless steel pump due to the small sample size. The particular pump which set the probability distributions upper limit for uncertainty had an unusual duty point which resulted in a single supplier and a higher cost. By removing this pump from the sample data and bringing the distribution upper limit to the second highest data point, the probabilistic NPV difference reduces to $72,000. Reducing the uncertainty has the effect of increasing the risk of an incorrect result (Emblemsvag, 2003). The model is also designed for use after tender when exact purchase costs are known for both ductile iron and stainless steel pumps. Knowing the exact purchase cost eliminates the largest uncertainty.

Sensitivity analysis (Table 3.2) shows that of the various factors which can impact the output of the model, the possibility of a significant reduction in the purchase price of the stainless steel pumps (eg. 20%) and/or a combination of other factors could swing the balance in favour of stainless steel. Pump effectiveness parameters such as ease of overhaul and the theoretical infinite life of a stainless steel casing have not been quantified in this model.

	Original Input	Sensitivity Test New Input	Effect on NPV Diff.	
Sensitivity of LCC Inputs			**($,000)**	**(%)**
Decrease in SS Purchase Cost	$240,769	$216,692 (-10%)	26	-48%
Increase in Electricity Cost	24c/kWh	29c/kWh (+20%)	51	2%
Increased Overhaul Frequency	every 5yrs	every 3 yrs	37	-26%
Increase in Overhaul Labour Cost	$90/hr	$135/hr (+50%)	46	-8%
SS Efficiency Increase from Internal Polishing	-1.50%	0%	37	-26%
DI Efficiency Loss from Coating Deterioration	-0.2%/yr	-0.5%/yr	43	-14%
Higher Discount Rate	6%	10%	55	10%

Table 3.2 Sensitivity analysis of the primary cost drivers

4. Conclusions and Future Work

In the example studied the coated ductile iron pump demonstrated a lower whole of life cost compared to a similar stainless steel pump when used in a clear water application. An LCC framework was developed to compare the whole of life cost of a range of stainless steel and ductile iron pumps to assist in future decision making processes. The model developed is adaptable and capable of accommodating future data for improving LCC accuracy.

Future work is required on data collection. MacGeehan (2006) suggests additional wear ring clearance monitoring and more detailed condition reporting during overhauls to improve the accuracy of the wear rate model. Further pump testing and internal condition monitoring is also recommended to determine the exact rate of cast iron coating deterioration and corrosion for various operating scenarios. Additional information on the actual cost of stainless steel pumps is also required to further refine the model and improve its value as a decision support tool.

5. Acknowledgements

I would like to express my thanks to Simon Gilbert, Greg Treasure, Jarrod Hoffman, Chris Trianou and Barry Parker for their patience and guidance. I also wish to thank Bill Goode, Dr Jeremy Leggoe and Dr Melinda Hodkiewicz for their clear direction, enthusiasm and support.

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