# Table of Contents

Foreword ................................................................. xi  
Acknowledgements ...................................................... xiii  
About the Hydraulic Institute ......................................... xvii  
Europump ................................................................. xvii  
Executive Summary ..................................................... xix  
What is Life Cycle Cost? ................................................ xx  
Getting Started ........................................................... xxi  
Introduction ............................................................... xxiii

## Chapter • One

### Life Cycle Cost, 1

1.1 General ............................................................... 1  
1.2 Elements of Life Cycle Costs ........................................ 3  
   1.2.1 Initial Cost ($C_{ic}$) ........................................... 3  
   1.2.2 Installation and Commissioning (Start-up) Cost ($C_{in}$) 4  
   1.2.3 Energy Cost ($C_{e}$) .......................................... 5  
   1.2.4 Operating Cost ($C_{o}$) ....................................... 6  
   1.2.5 Maintenance and Repair Cost ($C_{m}$) ....................... 6  
   1.2.6 Downtime and Loss of Production Cost ($C_{s}$) .......... 8  
   1.2.7 Environmental Cost, Including Disposal of Parts and  
       Contamination from Pumped Liquid ($C_{env}$) .......... 8  
   1.2.8 Decommissioning and Disposal Cost,  
       Including Restoration of the Local Environment ($C_{d}$) 8

1.3 Calculating Life Cycle Costs ....................................... 9  
   1.3.1 General ......................................................... 9  
   1.3.2 Calculating Present Value (PV) ............................. 10  
   1.3.3 Calculation Chart Using the Simplified Method .......... 11  
   1.3.4 Example Using the Manual Calculation Chart ........... 14

## Chapter • Two

### Pumping System Design, 17

2.1 General ............................................................. 17  
2.2 System Design ..................................................... 17  
   2.2.1 Pipe Size .................................................... 17  
   2.2.2 Pump and System Curves ................................... 18  
2.3 Output Control ..................................................... 20
2.4 Pump Type Selection ................................................. 20
  2.4.1 Pump Types .................................................. 20
  2.4.2 Ways to Reduce LCC When Selecting Pumps .......... 28
2.5 Selecting a Driver .................................................. 36
  2.5.1 Background .................................................. 36
  2.5.2 Types of Electric Motors ................................. 36
  2.5.3 Efficiency and Energy Costs ............................ 38
  2.5.4 Variable Frequency Drives ............................... 39
2.6 Auxiliary Services .................................................. 40
  2.6.1 Cooling Services .......................................... 40
  2.6.2 Heating ...................................................... 41
  2.6.3 Seal Flush Systems ........................................ 41
  2.6.4 Seal Quench Systems ..................................... 42
  2.6.5 Barrier Fluid Systems .................................... 42
  2.6.6 Lubrication Systems for Sleeve Bearings .......... 42
2.7 Power Transmission ............................................... 42
  2.7.1 Summary of Power Transmission Characteristics ... 42
2.8 System Effectiveness in Design and Output Control: A
  New Concept ....................................................... 43
  2.8.1 Process Requirements ..................................... 43
  2.8.2 Specific Energy ............................................ 47
  2.8.3 Summary .................................................... 52
2.9 Monitoring and Sustaining the System ......................... 53
  2.9.1 Maintaining Pump Efficiency ......................... 53
  2.9.2 Organizing Maintenance and Monitoring ............ 60

Chapter • Three

Methods for Analyzing
Existing Pumping Systems, 63

3.1 Introduction ....................................................... 63
3.2 Improving the System ........................................... 63
3.3 System Components ............................................. 64
  3.3.1 Pump ......................................................... 64
  3.3.2 Control or Throttle Valves ............................... 65
  3.3.3 Components ............................................... 65
3.4 System Loads ...................................................... 66
3.5 Determining the Rates of Flow ................................ 66
3.6 Example of Minimizing Losses by Balancing a
  Branched System ................................................ 67
  3.6.1 Balancing the System ..................................... 67
  3.6.2 Changing the Pump ....................................... 69
## Table of Contents

3.7 Examples for Achieving Energy Savings in Existing Systems ..... 71
   3.7.1 Example 1: Waste Collection System With Oversized Pumps ..... 71
   3.7.2 Example 2: System With a Problem Control Valve. ..... 75

Chapter • Four

Examples of LCC Analysis, 79

4.1 Waste Collection System Example ................................ 79
4.2 Problem Control Valve Example ................................. 80

Chapter • Five

Effective Procurement Using LCC, 91

5.1 Introduction ......................................................... 91
5.2 Enquiry Documentation ......................................... 91
5.3 Evaluation Sum .................................................... 92
5.4 Work Methodology ............................................. 92
5.5 Contract Boundaries ........................................... 93
5.6 Evaluating Tenders ............................................. 93
5.7 Inspection - Performance Bonus or Penalty ................. 93
5.8 Example .......................................................... 93

Chapter • Six

Recommendations for Designing and Procuring Pumping Systems, 95

Chapter • Seven

References, 99

Chapter • Eight

Glossary of Terms and Symbols, 103

Appendix A

System Curves, 105

A.1 System Curves .................................................. 105
   A.1.1 Operating Duty Point ................................. 105
A.1.2 Characteristic Curves ................................. 105
A.1.3 Branched Piping Systems ...................... 117
A.1.4 Duty Modifications ............................. 121
A.1.5 Viscous and Non-Newtonian Liquids ............ 124
A.2 Computer Software ................................. 125

Appendix B
Pumping Output and System Control, 127

B.1 Output Control ........................................... 127
B.1.1 General ............................................. 127
B.1.2 Determining Flow Requirements ............... 128
B.2 System Control .......................................... 131
B.2.1 Control Parameters ............................... 132
B.2.2 Start–Stop Control ................................. 134
B.2.3 Throttling Control ................................ 137
B.2.4 Variable Speed Regulation .................... 138
B.2.5 Eccentric Radius Adjustment in Vane Cell Pumps 141
B.2.6 Stroke and Speed Regulation of Reciprocating
     Positive Displacement Pumps .................. 141
B.3 Summary ................................................. 142

Appendix C
Pump Efficiencies, 145

C.1 Pump Efficiencies ................................. 145
C.1.1 General ............................................. 145
C.1.2 Nomenclature ..................................... 147

Appendix D
Case Histories–Cost Savings Examples, 149

D.1 Introduction ........................................... 149
Case History 1: Building services .................. 152
Case History 2: Pulp and paper manufacture .... 154
Case History 3: Chemical processing ............... 156
Case History 4: Water supply ......................... 158
Case History 5: Waste water ......................... 160
Case History 6: Steel making ......................... 162
Case History 7: Petrochemical processing ......... 164
Case History 8: Domestic electrical appliance ... 166
Case History 9: Mining ................................. 168
Case History 10: Power plant ......................... 170
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7b</td>
<td>Maximum attainable efficiencies for PD pumps with fluids below 1000 mPa s</td>
<td>27</td>
</tr>
<tr>
<td>2.8</td>
<td>Indication of the influence of viscosity on the efficiency for different types of PD pumps</td>
<td>28</td>
</tr>
<tr>
<td>2.9</td>
<td>Example of a performance curve for a rotodynamic pump showing the preferred operating region</td>
<td>29</td>
</tr>
<tr>
<td>2.10</td>
<td>Variations in efficiency for a 30-kW 4-pole motor</td>
<td>38</td>
</tr>
<tr>
<td>2.11</td>
<td>Efficiency curve of a typical variable frequency drive</td>
<td>39</td>
</tr>
<tr>
<td>2.12</td>
<td>Duration diagrams for two different pumping systems</td>
<td>44</td>
</tr>
<tr>
<td>2.13</td>
<td>System curve</td>
<td>45</td>
</tr>
<tr>
<td>2.14</td>
<td>Lines of constant efficiency (broken) superimposed over speed-regulated pump curves (solid)</td>
<td>46</td>
</tr>
<tr>
<td>2.15</td>
<td>The operating point on the reduced speed curve moves relatively higher on the pump curve as the speed is reduced</td>
<td>46</td>
</tr>
<tr>
<td>2.16</td>
<td>Example of specific energy as a function of static head and overall efficiency</td>
<td>49</td>
</tr>
<tr>
<td>2.17</td>
<td>Three different system curves A, B and C, all passing through the same duty point at full speed and the associated curves for specific energy</td>
<td>50</td>
</tr>
<tr>
<td>2.18</td>
<td>Throttling a valve changes the rate of flow by adding pressure drop in the valve, thus moving the duty point along the pump curve</td>
<td>51</td>
</tr>
<tr>
<td>2.19</td>
<td>Compared with regulation by throttling, variable speed drives always save on energy</td>
<td>51</td>
</tr>
<tr>
<td>2.20</td>
<td>Parallel pump operation</td>
<td>52</td>
</tr>
<tr>
<td>2.21</td>
<td>Reduced efficiency and head caused by leakage losses</td>
<td>54</td>
</tr>
<tr>
<td>2.22</td>
<td>Clearances from left to right: semi-open impeller clearance; closed impeller radial clearance; closed impeller axial clearance</td>
<td>54</td>
</tr>
<tr>
<td>2.23</td>
<td>Examples of clearances (s) in rotating positive displacement pumps: a) screw pump; b) gear pump</td>
<td>58</td>
</tr>
<tr>
<td>2.24</td>
<td>Pressure signals of a hydraulically acting diaphragm pump: a) healthy pressure signal; b) leakage in the hydraulic chamber (replenishing window [RW])</td>
<td>59</td>
</tr>
<tr>
<td>2.25</td>
<td>Structure-borne noise signal and pressure signal of a reciprocating PD pump: a) healthy pump; b) leaking suction valve</td>
<td>59</td>
</tr>
<tr>
<td>2.26</td>
<td>Preventive maintenance in terms of total maintenance costs</td>
<td>61</td>
</tr>
</tbody>
</table>
Table of Contents

3.1 Branched piping system showing the rate of flow in the various paths ........................................... 67
3.2 Branched system showing the differential pressure in bar across the throttle valves needed to throttle the rate of flow to the set value ................................................................. 68
3.3 The branched piping system with flows balanced and pump impeller trimmed to eliminate excessive differential pressure across the control valves ......................................................... 69
3.4 The pump curve for the larger and smaller impeller trim; rate of flow for unbalanced flow is 166 m$^3$/h (720 USgpm), balanced rate of flow 120 m$^3$/h (520 USgpm) ............................................. 70
3.5 Pressurized forced main system pumping down the sump using on/off control; evaluating changing pumping rate for lower operating costs ................................................................. 71
3.6 Total head as a function of rate of flow for the sump pump system ..................................................... 73
3.7 Pump curve for the pump selected for 30 m$^3$/h ................................................................................. 74
3.8 Sketch of pumping system in which the control valve fails ................................................................. 76
3.9 System resistance curve and pump curve showing the operation of the system ................................... 77
3.10 Pump curves and system curves showing the operation of the original system and the modified pump impeller ................................................................. 77
3.11 LCC comparison for the waste collection system ................................................................. 82
4.2 LCC comparison for the problem control valve system ................................................................. 85
6.1 New pumping system ................................................................. 96
6.2 Existing pump systems ................................................................. 97
A.1a Operating duty point at $H_{pump} = H_{syst}$ for a rotodynamic pump .................................................. 106
A.1b Operating duty point at $H_{pump} = H_{syst}$ for a positive displacement pump ................................. 106
A.2 Example of simple piping system ................................................................. 107
A.3 System curve ................................................................. 109
A.4 Piping systems with the same static head ................................................................. 109
A.5 Piping system with $H_{stat} = 0; H_{syst} = H_j$ ................................................................. 110
A.6 System with $H_j = 0$ ................................................................. 110
A.7 Resultant pump curve for series operation ................................................................. 111
A.8 Parallel pump operation ................................................................. 111
| A.9  | Parallel operation of two similar pumps with different system curves | 112  |
| A.10 | Pumping systems with different static heads                        | 112  |
| A.11 | System curve with varying static head                             | 113  |
| A.12 | Consequences of incorrectly calculated pipe losses                | 114  |
| A.13 | The effect of deposits (scale, rust, etc.) on pipelines           | 115  |
| A.14 | The effect of varying levels                                     | 116  |
| A.15 | The effect of adding margins to calculated system curve           | 116  |
| A.16 | Branched circulation system                                       | 118  |
| A.17 | Branched piping system, $H_{\text{stat}} = 0$                    | 118  |
| A.18 | Branched pipe system with different static head                   | 119  |
| A.19 | Branched piping system with positive suction static head          | 120  |
| A.20 | Pump performance by reduced impeller diameter                    | 121  |
| A.21 | Pump performance by variable speed                                | 122  |
| A.22 | Variable pitch propeller pumps                                    | 123  |
| A.23 | Mixed-flow pumps with adjustable inlet guide vanes                | 123  |
| A.24 | Pump and system curves for more viscous liquids as compared with water | 124  |
| A.25 | Pump and system curves for water and pulp suspension              | 125  |
| B.1  | The duty point is the intersection between the pump and system curves: rotodynamic pump (RD); positive displacement pump (PD). | 128  |
| B.2  | Flow as a function of time – operating curve                      | 129  |
| B.3  | Duration curve of the flow                                        | 129  |
| B.4  | Graphical integration method to determine mean rates of flow      | 130  |
| B.5  | Illustration of Equations B-1 and B-2                             | 131  |
| B.6  | Control at (a) constant pressure, (b) constant flow, and (c) proportional level control | 135  |
| B.7  | Pump and drive system                                             | 138  |
| B.8a | Examples of performance curves for a speed regulated rotodynamic pump | 139  |
| B.8b | Performance curves for PD-pumps with speed regulation             | 139  |
| B.9  | Pump power requirement for speed-regulated rotodynamic pump with hydraulic coupling transmission | 140  |
Table of Contents

B.10 Typical stroke adjustable drive element of a reciprocating positive displacement pump. 142

B.11 Power requirement for single stage rotodynamic pumps with flow control using various methods, in a system with a low ratio: \( \frac{H_{\text{stat}}}{H_0} \). 143

C.1 Typical single-stage, single-suction volute casing pump. 145

C.2 Maximum attainable efficiencies, \( \eta_{\text{max}} \), of single-stage, single-suction volute casing pumps dependent on specific speeds and rates of flow. 147

C.3 Average attainable industrial pump efficiencies, \( \eta_{\text{avg}} \), of single-stage, single-suction volute casing pumps dependent on specific speeds and rates of flow. 148

E.1 Losses in a typical 75 kW induction motor. 181

E.2 Typical efficiencies of 2-pole, 3-phase asynchronous submersible motors. 182

E.3 Loading profile for a circulator. 183

E.4 (1) Uncontrolled circulators; (2) Circulators with voltage controlled motors; (3) Circulators with frequency controlled motors. 184

List of Tables

1.1 Factor \( \frac{C_p}{C_n} \) for a single cost element after \( n \) years. 12

1.2 Discount factor (df) for constant yearly expenditures. 13

2.1 Control methods – applications and limitations. 21

2.2 Application ranges of positive displacement pumps. 33

2.3 Properties of commercially available PD pumps; \( \frac{PH}{PS} = \text{hydraulic power/ shaft power} \). 34

2.4 Positive and negative aspects of specific transmissions. 43

3.1 Operation and annual operating cost of the three-branched piping system in the various operating modes. 70

3.2 Work sheets (a) and (b) showing how the rate of flow is calculated by pumping down and filling a sump. 72

3.3 Cost comparison for energy cost for the 60 \( \text{m}^3/\text{h} \) (260 USgpm) and 30 \( \text{m}^3/\text{h} \) (130 USgpm) pumps. 75

3.4 Cost comparison for Options A through D in the system with a failing control valve. 78

B.1 Control methods – applications and limitations. 132
Table of Contents

B.2 Some control parameters used for pumps ......................... 134
D.1 Summary of Case Histories ........................................... 150
E.1 Positive and negative aspects of specific transmissions ........ 194