# Table of Contents

Foreword ................................................................. xv
Acknowledgements ...................................................... xvii
About the Hydraulic Institute and Pump Systems Matter .... xxi
Europump ................................................................. xxi
Executive Summary ..................................................... xxiii
What is Life Cycle Cost? ............................................... xxiv
Getting Started ........................................................ xxv
Introduction .............................................................. xxvii

## 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 ($C_{d}$) .......... 9
1.3 Calculating Life Cycle Costs .................................. 9
  1.3.1 General ....................................................... 9
  1.3.2 Calculating Present Value (PV) .......................... 11
  1.3.3 Calculation Chart Using the Simplified Method ........ 13
  1.3.4 Example Using the Manual Calculation Chart .......... 13
1.4 Financial Decision Methods - Payback and Internal Rate
   of Return .......................................................... 17
  1.4.1 Simple Payback ............................................. 17
  1.4.2 Discounted Payback ........................................ 17
  1.4.3 Internal Rate of Return .................................... 19
Chapter • Two
Pumping System Design, 22

2.1 General .............................................. 22
2.2 System Design .................................. 22
2.2.1 Pipe Size ...................................... 22
2.2.2 Pump and System Curves ..................... 23
2.3 Output Control .................................... 25
2.4 Pump Type Selection ............................. 25
2.4.1 Pump Types .................................... 25
2.4.2 Ways to Reduce LCC When Selecting Pumps . 34
2.5 Selecting a Driver ................................ 39
2.5.1 Background ..................................... 39
2.5.2 Types of Electric Motors ................. 42
2.5.3 Efficiency and Energy Costs ............... 44
2.5.4 Variable Frequency Drives ............ 45
2.5.5 Additional Driver and Variable Speed Drive Information . 46
2.6 Auxiliary Services .............................. 46
2.6.1 Cooling Services ............................. 47
2.6.2 Heating ......................................... 48
2.6.3 Seal Flush Systems ......................... 48
2.6.4 Seal Quench Systems ...................... 49
2.6.5 Barrier Fluid Systems ...................... 49
2.6.6 Lubrication Systems for Sleeve Bearings . 49
2.7 Power Transmission ............................. 49
2.7.1 Summary of Power Transmission Characteristics . 49
2.8 System Effectiveness in Design and Output Control:
  A New Concept .................................. 50
  2.8.1 Process Requirements ...................... 50
  2.8.2 Specific Energy ............................ 54
  2.8.3 Summary ..................................... 60
2.9 Monitoring and Sustaining the System .... 61
  2.9.1 Maintaining Pump Efficiency ............ 61
  2.9.2 Organizing Maintenance and Monitoring . 67

Chapter • Three
Methods for Analyzing Existing Pumping Systems, 70

3.1 Introduction ................................... 70
3.2 Improving the System .......................... 70
3.3 System Components .............................. 71
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1 Pump</td>
<td>71</td>
</tr>
<tr>
<td>3.3.2 Control or Throttle Valves</td>
<td>72</td>
</tr>
<tr>
<td>3.3.3 Components</td>
<td>72</td>
</tr>
<tr>
<td>3.4 System Loads</td>
<td>73</td>
</tr>
<tr>
<td>3.5 Determining the Rates of Flow</td>
<td>73</td>
</tr>
<tr>
<td>3.6 Example of Minimizing Losses by Balancing a Branched System</td>
<td>74</td>
</tr>
<tr>
<td>3.6.1 Balancing the System</td>
<td>74</td>
</tr>
<tr>
<td>3.6.2 Changing the Pump</td>
<td>76</td>
</tr>
<tr>
<td>3.7 Examples for Achieving Energy Savings in Existing Systems</td>
<td>78</td>
</tr>
<tr>
<td>3.7.1 Example 1: Waste Collection System With Oversized Pumps</td>
<td>78</td>
</tr>
<tr>
<td>3.7.2 Example 2: System With a Problem Control Valve</td>
<td>82</td>
</tr>
<tr>
<td>Chapter Four</td>
<td></td>
</tr>
<tr>
<td>Examples of LCC Analysis, 86</td>
<td></td>
</tr>
<tr>
<td>4.1 Waste Collection System Example</td>
<td>86</td>
</tr>
<tr>
<td>4.1.1 Conclusion</td>
<td>87</td>
</tr>
<tr>
<td>4.2 Problem Control Valve Example</td>
<td>89</td>
</tr>
<tr>
<td>4.2.1 Conclusion</td>
<td>90</td>
</tr>
<tr>
<td>Chapter Five</td>
<td></td>
</tr>
<tr>
<td>Effective Procurement Using LCC, 94</td>
<td></td>
</tr>
<tr>
<td>5.1 Introduction</td>
<td>94</td>
</tr>
<tr>
<td>5.2 Enquiry Documentation</td>
<td>94</td>
</tr>
<tr>
<td>5.3 Life Cycle Cost (LCC)</td>
<td>95</td>
</tr>
<tr>
<td>5.4 Work Methodology</td>
<td>95</td>
</tr>
<tr>
<td>5.5 Contract Boundaries</td>
<td>96</td>
</tr>
<tr>
<td>5.6 Evaluating Tenders</td>
<td>96</td>
</tr>
<tr>
<td>5.7 Inspection - Performance Bonus or Penalty</td>
<td>96</td>
</tr>
<tr>
<td>5.8 Example</td>
<td>96</td>
</tr>
<tr>
<td>Chapter Six</td>
<td></td>
</tr>
<tr>
<td>Recommendations for Designing and Procuring Pumping Systems, 98</td>
<td></td>
</tr>
<tr>
<td>Chapter</td>
<td>Seven</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>References</td>
<td>102</td>
</tr>
</tbody>
</table>

Chapter • Eight

**Glossary of Terms and Symbols, 105**

Appendix A

**System Curves, 107**

A.1 System Curves ........................................ 107
   A.1.1 Operating Duty Point .................................. 107
   A.1.2 Characteristic Curves .................................. 109
   A.1.3 Branched Piping Systems ............................. 120
   A.1.4 Duty Modifications ................................. 124
   A.1.5 Viscous and Non-Newtonian Liquids ............... 127
A.2 Computer Software .................................... 128

Appendix B

**Pumping Output and System Control, 129**

B.1 Output Control ........................................ 129
   B.1.1 General ............................................... 129
   B.1.2 Determining Flow Requirements .................... 130
B.2 System Control ......................................... 133
   B.2.1 Control Parameters .................................. 134
   B.2.2 Start–Stop Control ................................... 136
   B.2.3 Throttling Control .................................... 139
   B.2.4 Variable Speed Regulation ........................... 140
   B.2.5 Eccentric Radius Adjustment in Vane Cell Pumps ... 143
   B.2.6 Stroke and Speed Regulation of Reciprocating Positive Displacement Pumps ............ 143
B.3 Summary ............................................... 144

Appendix C

**Pump Efficiencies, 146**

C.1 Pump Efficiencies ...................................... 146
   C.1.1 General .............................................. 146
   C.1.2 Nomenclature ......................................... 149
C.2 Regulation of the European Commission (EU) No 547/2012 for Water Pumps ................. 150
# Table of Contents

C.2.1 Overview .................................................. 150
C.3 U.S. DOE Conservation Standard for Certain Clean Water Pumps ........................................ 150
C.3.1 Overview .................................................. 150

## Appendix D

**Case Histories—Cost Savings Examples, 152**

D.1 Introduction .................................................. 152
Case History 1: Building services .................................. 155
Case History 2: Pulp and paper manufacture ......................... 157
Case History 3: Chemical processing .................................. 159
Case History 4: Water supply ........................................ 161
Case History 5: Waste water .......................................... 163
Case History 6: Steel making ........................................ 165
Case History 7: Petrochemical processing ............................ 167
Case History 8: Domestic electrical appliance ......................... 169
Case History 9: Mining ................................................ 171
Case History 10: Power plant .......................................... 173
Case History 11: Building services .................................... 175
Case History 12: Building services .................................... 176
Case History 13: Chemical industry ................................... 178
Case History 14: Food industry ........................................ 180

## Appendix E

**Drivers, Transmissions, and Variable Speed Drives, 182**

E.1 Induction Motors ............................................. 182
E.1.1 Introduction .................................................. 182
E.1.2 Definitions of Motor Efficiency ............................... 183
E.1.3 Minimum Efficiency .......................................... 185
E.1.4 Selecting a Motor ............................................ 191
E.2 Considerations for Electric Motors to Improve System Efficiency ............................................. 192
E.3 Variable Frequency Drives (VFD) ................................. 196
E.3.1 Overview of VFDs .............................................. 196
E.4 Power Transmission ............................................. 206
E.4.1 Efficiency and Characteristics of Various Types of Transmissions ...................................... 206
E.5 Key takeaways ................................................ 212
List of Figures

Typical LCC for a medium-sized industrial pumping system ........ xxvi
1.1 Manual calculation chart of LCC. ........................................ 15
1.2 Example 4.1.b using the manual calculation chart ................. 16
2.1 Key cost components for a pumping installation as related
to pipe size .............................................................. 23
2.2 Typical pump performance and system curves – rotodynamic
pumps ................................................................. 24
2.3 Typical pump performance and system curves – positive
displacement pumps .................................................. 24
2.4 Pump selection diagram for rotodynamic pumps with
standard drivers handling clean liquids. ............................ 28
2.5 Average attainable industrial pump efficiency, $\eta_{\text{avg}}$,
for rotodynamic volute pumps with closed impellers and for
clean cold water ....................................................... 29
2.6 Typical pump selection diagram for positive displacement
pumps (PD pumps) ...................................................... 30
2.7a Maximum attainable efficiencies for PD pumps with
fluids below 100 mPa s ................................................. 31
2.7b Maximum attainable efficiencies for PD pumps with
fluids below 1000 mPa s .............................................. 32
2.8 Indication of the influence of viscosity on the efficiency
for different types of PD pumps ...................................... 33
2.9 Example of a performance curve for a rotodynamic centrifugal (radial
flow) pump showing the preferred operating region ................ 35
2.10 Variations in efficiency for a 30-kW 4-pole motor ................. 44
2.11 Efficiency curve of a typical variable frequency drive ......... 46
2.12 Duration diagrams for two different pumping systems ........ 51
2.13 System curve ........................................................ 52
2.14 Lines of constant efficiency (broken) superimposed
over speed-regulated pump curves (solid) ......................... 53
2.15 The operating point on the reduced speed curve moves
relatively higher on the pump curve as the speed is reduced. ... 53
2.16 Example of specific energy as a function of static head
and overall efficiency ............................................... 56
2.17 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 .............................. 58
2.18 Throttling a valve changes the rate of flow by adding pressure drop in the valve, thus moving the duty point along the pump curve ................................................ 59
2.19 Compared with regulation by throttling, variable speed drives always save on energy .................................................. 59
2.20 Parallel pump operation ................................................. 60
2.21 Reduced efficiency and head caused by leakage losses .... 61
2.22 Clearances* from left to right: semi-open impeller clearance; closed impeller radial clearance ........................................... 62
2.23 Examples of clearances (s) in rotating positive displacement pumps: a) screw pump; b) gear pump ...................... 65
2.24 Pressure signals of a hydraulically acting diaphragm pump: a) healthy pressure signal; b) leakage in the hydraulic chamber (replenishing window [RW]) ....................... 66
2.25 Structure-borne noise signal and pressure signal of a reciprocating PD pump: a) healthy pump; b) leaking suction valve .......................................................... 67
2.26 Preventive maintenance in terms of total maintenance costs .... 68
3.1 Branched piping system showing the rate of flow in the various paths ................................................................. 74
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 .................................................. 75
3.3 The branched piping system with flows balanced and pump impeller trimmed to eliminate excessive differential pressure across the control valves ...................... 76
3.4 The pump curve for the larger and smaller impeller trim; rate of flow for unbalanced flow is 166 m³/h (720 USgpm), balanced rate of flow 120 m³/h (520 USgpm) ...................... 77
3.5 Pressurized forced main system pumping down the sump using on/off control; evaluating changing pumping rate for lower operating costs ............................................. 78
3.6 Total head as a function of rate of flow for the sump pump system ................................................................. 80
3.7 Pump curve for the pump selected for 30 m³/h ...................... 81
3.8 Sketch of pumping system in which the control valve fails ...... 83
# Table of Contents

3.9 System resistance curve and pump curve showing the operation of the system ........................................... 84

3.10 Pump curves and system curves showing the operation of the original system and the modified pump impeller. .... 84

4.1 LCC comparison for the waste collection system .................. 88

4.2 LCC comparison for the problem control valve system .......... 91

4.3 LCC comparison for the problem control valve system .......... 93

6.1 New pumping system .............................................. 99

6.2 Existing pump systems ............................................ 100

A.1a Operating duty point at $H_{\text{pump}} = H_{\text{syst}}$ for a rotodynamic pump ................................................. 108

A.1b Operating duty point at $H_{\text{pump}} = H_{\text{syst}}$ for a positive displacement pump ......................................... 108

A.2 Example of simple piping system ................................ 109

A.3 System curve .......................................................... 111

A.4 Piping systems with the same static head ....................... 111

A.5 Piping system with $H_{\text{stat}} \approx 0; H_{\text{syst}} = H_{j}$ ............. 112

A.6 System with $H_{j} \approx 0$ ............................................. 112

A.7 Resultant pump curve for series operation ...................... 113

A.8 Parallel pump operation ............................................ 113

A.9 Parallel operation of two similar pumps with different system curves ......................................................... 114

A.10 Pumping systems with different static heads .................. 115

A.11 System curve with varying static head .......................... 116

A.12 Consequences of incorrectly calculated pipe losses ........... 117

A.13 The effect of deposits (scale, rust, etc.) on pipelines ........ 118

A.14 The effect of varying levels ....................................... 119

A.15 The effect of adding margins to calculated system curve ...... 119

A.16 Branched circulation system ..................................... 121

A.17 Branched piping system, $H_{\text{stat}} = 0$ .......................... 121

A.18 Branched pipe system with different static head .............. 122

A.19 Branched piping system with positive suction static head .... 123

A.20 Pump performance by reduced impeller diameter ............ 124

A.21 Pump performance by variable speed ........................... 125

A.22 Variable pitch propeller pumps .................................. 126
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.23</td>
<td>Mixed-flow pumps with adjustable inlet guide vanes</td>
<td>126</td>
</tr>
<tr>
<td>A.24</td>
<td>Pump and system curves for more viscous liquids as compared with water</td>
<td>127</td>
</tr>
<tr>
<td>A.25</td>
<td>Pump and system curves for water and pulp suspension</td>
<td>128</td>
</tr>
<tr>
<td>B.1</td>
<td>The duty point is the intersection between the pump and system curves: rotodynamic pump (RD); positive displacement pump (PD)</td>
<td>130</td>
</tr>
<tr>
<td>B.2</td>
<td>Flow as a function of time – operating curve</td>
<td>131</td>
</tr>
<tr>
<td>B.3</td>
<td>Duration curve of the flow</td>
<td>131</td>
</tr>
<tr>
<td>B.4</td>
<td>Graphical integration method to determine mean rates of flow</td>
<td>132</td>
</tr>
<tr>
<td>B.5</td>
<td>Illustration of Equations B-1 and B-2</td>
<td>133</td>
</tr>
<tr>
<td>B.6</td>
<td>Control at (a) constant pressure, (b) constant flow, and (c) proportional level control</td>
<td>137</td>
</tr>
<tr>
<td>B.7</td>
<td>Pump and drive system</td>
<td>140</td>
</tr>
<tr>
<td>B.8a</td>
<td>Examples of performance curves for a speed regulated rotodynamic pump</td>
<td>142</td>
</tr>
<tr>
<td>B.8b</td>
<td>Performance curves for PD-pumps with speed regulation</td>
<td>142</td>
</tr>
<tr>
<td>B.9</td>
<td>Pump power requirement for speed-regulated rotodynamic pump with hydraulic coupling transmission</td>
<td>143</td>
</tr>
<tr>
<td>B.10</td>
<td>Typical stroke adjustable drive element of a reciprocating positive displacement pump</td>
<td>144</td>
</tr>
<tr>
<td>B.11</td>
<td>Power requirement for single stage rotodynamic pumps with flow control using various methods, in a system with a low ratio: $H_{stat}/H_0$</td>
<td>145</td>
</tr>
<tr>
<td>C.1</td>
<td>Typical single-stage, single-suction volute casing pump</td>
<td>147</td>
</tr>
<tr>
<td>C.2</td>
<td>Maximum attainable efficiencies, $\eta_{max}$, of single-stage, single-suction volute casing pumps dependent on specific speeds and rates of flow</td>
<td>148</td>
</tr>
<tr>
<td>C.3</td>
<td>Average attainable industrial pump efficiencies, $\eta_{avg}$, of single-stage, single-suction volute casing pumps dependent on specific speeds and rates of flow</td>
<td>149</td>
</tr>
<tr>
<td>E.1</td>
<td>Major features of an electric motor that affects efficiency</td>
<td>184</td>
</tr>
<tr>
<td>E.2</td>
<td>Motor efficiency versus load EPAct and NEMA premium comparison</td>
<td>191</td>
</tr>
<tr>
<td>E.3</td>
<td>Life cycle cost of an industrial AC induction motor</td>
<td>193</td>
</tr>
<tr>
<td>E.4</td>
<td>75 kW (100 hp) motor efficiency and power factor as a function of load</td>
<td>195</td>
</tr>
</tbody>
</table>
Table of Contents

E.5 VFD block diagram ........................................... 197
E.6 VFD operator interface (OI)/user interface (UI) ............... 197
E.7 VFD with optional bypass ..................................... 199
E.8 Pump system components ...................................... 200
E.9 Constant torque and variable torque pump load
   as a function of frequency or speed ............................ 201
E.10 A constant torque V/Hz ratio supplied to the motor .......... 202
E.11 A variable torque V/Hz ratio supplied to the motor .......... 202

List of Tables

1.1 Factor Cp/Cn for a single cost element after n years .......... 12
1.2 Discount factor (df) for constant yearly expenditures .......... 14
1.3 Simple Payback ............................................... 17
1.4 Discounted payback (Net Present Value) ....................... 18
1.5 Internal Rate of Return by trial and error ...................... 20
1.6 Internal Rate of Return by Excel Function ..................... 20
2.1 Control methods – applications and limitations ................ 26
2.2 Application ranges of positive displacement pumps .......... 38
2.3 Properties of commercially available PD pumps;
   PH/PS = hydraulic power /shaft power ....................... 40
2.4 Positive and negative aspects of specific transmissions ....... 50
3.1 Operation and annual operating cost of the three-branched
   piping system in the various operating modes .................. 77
3.2 Work sheets (a) and (b) showing how the rate of flow
   is calculated by pumping down and filling a sump .......... 79
3.3 Cost comparison for energy cost for the 60 m³/h (260 USgpm)
   and 30 m³/h (130 USgpm) pumps ............................. 82
3.4 Cost comparison for Options A through D in the system
   with a failing control valve .................................... 85
B.1 Control methods – applications and limitations ............... 134
B.2 Some control parameters used for pumps ..................... 136
D.1 Summary of Case Histories ................................... 153
E.1 IEC 60034-30 compared to NEMA MG-1 ....................... 191
E.2 Motor energy cost comparison ................................ 193