Basic Cost Engineering

Third Edition, Revised and Expanded

Kenneth K. Humphreys
Paul Wellman

Basic Cost Engineering

COST ENGINEERING

A Series of Reference Books and Textbooks

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To the late Dr. James H. Black,
a dedicated colleague, mentor, and friend

Preface to the Third Edition

All cost engineering dissertations should be updated periodically to reflect the current state of the art. *Basic Cost Engineering* was first written for use as a textbook on capital and operating cost estimation. It was, and still is, intended to introduce cost engineering principles to those individuals who are entering the field and as a reference work and refresher for the experienced cost engineering professional.

Virtually all the material that appeared in the first two editions of *Basic Cost Engineering* is as valid today as it was when it was first published. With the exception of changes necessitated by U.S. tax laws and depreciation regulations, very little material from the second edition required revision. However, since the second edition was published, there has been a decided shift in the needs of industry with respect to cost estimating requirements. Industrial emphasis has moved in many cases from construction of new chemical processing plants to the retrofitting and expansion of existing plants. For this reason, a chapter has been added to discuss estimating of retrofit and expansion projects in existing, operating plants. The portions of the book dealing with factored estimating have also been considerably expanded to make them more comprehensive.

With the steady trend toward economic globalization and international economic development, interest has surged in estimating projects in various locations around the world. While estimating principles as discussed in this book do not vary with location, cost information, labor productivity, construction conditions, taxation, etc., do vary drastically from nation to nation. A chapter has therefore been added to provide some reference sources for international cost data.

Sections of the book on profitability analysis, risk analysis, and sensitivity analysis have also been completely revised and expanded. The discussion now covers the vital subject of life cycle cost analysis, a topic of major concern, particularly in government funded projects.

A new bibliography has been included that cites reference works, journals, and conference proceedings expected to be readily available to the reader for many years to come rather than specific articles from past periodical literature that rapidly become difficult to locate.

Throughout the book numerous problems and questions have been added for the benefit of students and educators. A solutions manual is available for use by college and university professors.

Finally, lest critics begin to complain that the book ignores computers, it doesn't. Computers are vital tools in cost engineering work, but this book is not a guide to computer applications. Rather, it is a basic text to explain and teach the fundamental aspects of cost estimating, not to explain computer applications. One cannot properly utilize modern cost engineering tools such as computers without understanding the underlying principles that apply to cost estimating and control. Robot-like use of estimating programs without being able to discern the reasonableness of the results and the validity of assumptions made in developing those programs is foolhardy. The estimator must first understand estimating principles and procedures before using computerized techniques. That understanding is what this book is designed to teach.

The authors wish to acknowledge the assistance of William R. Barry, CCE, and Dr. Harold E. Marshall, who provided considerable input in the preparation of the third edition. The authors also wish to acknowledge the contributions of Julian A. Piekarski and the late Sidney Katell to the earlier editions of this book. Many of their contributions have been carried forward to this edition.

Kenneth K. Humphreys
Paul Wellman

Preface to the Second Edition

The first edition of *Basic Cost Engineering* was written to fill a void in the literature on cost engineering by providing a basic text covering the principles of capital and operating cost estimating and profitability analysis that assumed no prior knowledge of these topics by the reader.

The first edition succeeded in meeting its objectives but did have a number of deficiencies, which the present edition is designed to correct.

Major changes include considerable expansion of the discussions of capital cost estimating techniques and of profitability analysis and the inclusion of material on risk analysis. The section on operating costs has been revised to include current depreciation guidelines and tax considerations as of January 1986. The appendix on cost engineering literature has been considerably expanded and reformatted to simplify its use in locating literature via keywords.

The bibliography is completely new and with a very few exceptions covers literature published since 1982. This is an exhaustive bibliography of current literature in the cost engineering field and is believed to be the most complete bibliography of its type. Over 600 complete bibliographic citations are provided with an alphabetized keyword cross-list.

Finally, an appendix of cost engineering problems, including a complete cost estimate, has been included for the use of instructors and students. For ease of use, all problems in the book have been placed in this one appendix rather than at the end of the various chapters as was the case with the first edition of *Basic Cost Engineering*.

Other changes include deletion of the former chapter on accounting considerations, which was felt to be peripheral to the main theme of the book, and the deletion of the former appendix of equipment cost charts. The cost charts were deleted because they become obsolete very rapidly and can also be easily misinterpreted. For information of the type included in these former charts, the reader should refer to any of the many excellent annual cost data books that are on the market.

The authors wish to acknowledge the assistance of Julian A. Piekarski in the preparation of the material on profitability and risk analysis and the many contributions of Sidney Katell, who coauthored the first edition.

Kenneth K. Humphreys
Paul Wellman

Preface to the First Edition

Cost engineering is defined as "the application of scientific and engineering principles and techniques to problems of cost estimation, cost control, business planning and management science." Implicit in this definition are problems of profitability analysis, project management, and planning and scheduling of major engineering projects. Cost control, project management, planning, and scheduling are major topics of the first book in this series, *Applied Cost Engineering* by Clark and Lorenzoni. The present book deals with the remaining aspects of cost engineering, cost estimation, and profitability analysis with emphasis on both capital and operating costs. Emphasis is placed upon the evaluation and planning phases of major projects only, and no effort is made in the present work to define techniques for developing detailed analyses of costs of major projects.

Most of the literature in the cost engineering field is rather advanced and assumes a substantial cost engineering background on the part of the reader. The basic principles of cost engineering, those that bridge the gap from classical "engineering economics" to detailed cost estimation and control on major projects, are often brushed over lightly. In truth they are the most critical cost engineering topics which must be understood and used by virtually every engineer and engineering student. These basic principles include preliminary capital cost estimating, operating cost estimating, and profitability analysis. These three topics are the major focus of this book.

Most cost engineering decisions which are made in industry are made on projects for which little detailed information is available; engineering designs have not even begun in most cases, and at best a detailed flowsheet of the proposed process is available. Obviously, with this lack of information, a detailed cost estimate cannot be performed. However, using the basic principles of cost engineering, a preliminary capital and operating cost estimate and a profitability analysis can be made with sufficient accuracy to enable management to decide whether or not to proceed with further development of the project.

The authors wish to acknowledge the valuable assistance of the staff of the Coal Research Bureau, College of Mineral and Energy Resources, West Virginia University in typing, editing, and the preparation of graphs and illustrations for this text.

Kenneth K. Humphreys
Sidney Katell

Contents

Basic Cost Engineering

Part I

Capital Cost Estimates

1

Capital Cost Estimating
An Overview

Capital cost estimating has been a much maligned vocation due to serious cost overruns on too many construction projects. There are many reasons for the problem, but the estimator must accept at least part of the responsibility. However, there are sufficient causes for this phenomenon to allow some of the blame to be lavishly distributed throughout our plant construction organizations. In fact, these organizations may well be a part of the problem.

Estimating equipment costs does not afford the magnitude of error that installation cost estimates seem to contribute to overall estimating inaccuracies.

Process equipment estimating tends to be dependent upon the "scope of work," process flowsheets, material and energy balances, and a complete descriptive equipment list. Obviously, to have all of these items, considerable preliminary engineering must be completed and properly incorporated into the support for the estimate. With the above information the equipment estimates are normally very accurate.

Difficulties begin to develop in the determination of the bulk accounts such as concrete, piping, instruments, electrical, and so on. In preliminary estimates, these are poorly defined and the engineer must use factors that do not normally include such items as interconnecting piping, electrical distribution, fire water loops, cooling towers, and cooling water distribution. Even the most experienced estimator will occasionally grossly underestimate these accounts.

The other accounts which are often underestimated are sometimes termed the "offsites." These are systems required for plant operations but are not actually processing units. They include steam generation and distribution, water supply, wastewater treatment, environmental systems, administrative buildings, parking lots, fences, raw material receiving, product shipment, etc. In the normal evolution of a project, these systems are engineered last; therein lies part of the problem.

A review of available literature dealing with capital cost estimation indicates a lack of a comprehensive reference on the subject. Therefore, an attempt to fill this need without getting too involved in the numerous related subject areas is the aim of this book.

Capital estimating is as old as civilization and the reasons for estimating have remained much the same from the beginning; that is, before embarking upon a significant construction project or other endeavors requiring expenditures of large sums of money, those concerned need to know and, therefore, ask how much it will cost. One of the rudest awakenings a young science or engineering major receives upon leaving school is that the boss, after hearing how great his or her new idea is, wants to know the costs. In fact, large corporations make capital expenditure estimates for ten years or more in advance to aid in planning corporate strategy.

Cost overruns are not new although such occurrences seem to be more prevalent in recent years. Saint Luke's gospel refers to a man who started to build a house and ran short of funds as a fool. When the United States was very young, the actual cost to build "Old Ironsides" was three times the estimate. Poor estimating probably has a history as long as estimating.

After reading the preceding paragraph, one might simply ask, "If estimating is this bad, why continue to estimate?" Like any other professional product, the poor estimates get the publicity; the estimates that were correct do not. For every extremely poor estimate, probably ten were done well or at least adequately for the purpose intended.

Estimates are prepared and used for different purposes, including the following:

1. Feasibility studies
2. Selection from among alternate designs

3. Selection from among alternate sites
4. Selection from among alternate investments
5. Presentation of bids
6. Appropriation of funds

Estimates may be and are made at all stages of the development of a project from research to production. There are available today good systems and procedures for each stage which, when properly implemented, produce a capital estimate which is acceptable and most useful to management for decision making. However, the estimator retains, throughout all levels of estimating, a relative importance because it is impossible to rid any estimate of some judgments on the part of the person doing the work.

This book reflects the chemical engineering background of the authors, but it is not intended to exclude estimates for other disciplines which may be accomplished using similar procedures.

QUESTIONS

1.1 What part of a capital cost estimate is generally accurate?

1.2 What two areas of capital estimating contribute most to the inaccuracies of an estimate?

1.3 What is the stated purpose of this book?

1.4 What are capital estimates used for?

2

Classification of Capital Cost Estimates

AACE International (formerly the American Association of Cost Engineers) has proposed three classifications of cost estimates. In increasing order of accuracy, the various major types of estimates proposed by AACE are:

Type	Accuracy
Order of magnitude	–30% to +50%
Budget	–15% to +30%
Definitive	–5% to +15%

Other authors have used different labels for the various types of estimates. As a frame of reference and again in increasing order of accuracy, one finds "quickie," "original," "study," "preliminary," "official" or "budget," and "final" or "definitive." Appendix A, a glossary of cost engineering terminology, defines some of these estimate types in more detail.*

* Appendix A covers a great many cost engineering terms in some detail, many of which are not otherwise discussed in this book. All of the terms, however, are commonly encountered in cost engineering work, and thus are included for ready reference.

AACE previously had proposed five classifications of estimates as follows:

1. Order-of-magnitude (ratio) estimate
2. Study (factored) estimate
3. Preliminary (budget authorization) estimate
4. Definitive (project control) estimate
5. Detailed (final) estimate

The two AACE lists illustrate the confusion in terminology relating to classification of estimates, and while they appear to be inconsistent, they really are not if one considers that budget estimates as currently defined by AACE include the previous categories of factored and budget authorization estimates. Similarly, the current category of definitive estimates includes the prior categories of project control and final estimates. Thus the earlier grouping is really an expansion of the current terms. The expanded list of categories is used in the following discussion.

It should be kept in mind that rarely does an estimate fully meet all of the requirements of a particular classification until one gets to the final detailed estimate. That is, estimates normally require combinations of methods for attaining any desired level of accuracy.

One of the risks taken in establishing any capital number is that the estimate produced is usually stripped of qualifying statements and taken as the absolute number. Therefore, capital estimators must be able to communicate effectively the limitations placed on any capital estimate made early in the development of a project.

ORDER-OF-MAGNITUDE (RATIO) ESTIMATES

The order-of-magnitude or ratio estimate costs the least to prepare and has the least accuracy when finished. At best the accuracy of such an estimate is –30 to +50% for an uncomplicated plant and probably worse for a large complex installation. The accuracy is absolutely dependent upon historical data for support of the exponent used in the following equation:

$$C_x = C_k \left(\frac{E_x}{E_k} \right)^n$$

where

C_x = Cost of plant and/or equipment item of size E_x

C_k = Known cost of plant and/or equipment item of size E_k

n = Cost capacity exponent

This cost-capacity equation is often called the six-tenths rule or the seven-tenths rule because the exponent, n, has an approximate value of 0.6–0.7 for many types of plants and equipment. The 0.6–0.7 factor derives from the fact that costs tend to be proportional to surface area of a container while capacity is proportional to volume. In actual practice, the exponential factor varies widely, particularly when applied to total processing systems (plants) as opposed to equipment items. The range of variance is from about 0.3 to greater than 1 under certain unusual circumstances as illustrated by Tables 2.1 and 2.2. Therefore, without extensive historical data, considerable error may be and often is introduced by the choice of exponent.

The use of the cost-capacity formula is also limited in accuracy because the exponent generally is not constant and does change as equipment size increases. For this reason and because of structural differences as equipment is increased in size, the formula should generally be limited for maximum accuracy to capacity ratios of 2:1 or less and, in any event, should never be used at ratios above 5:1.

In using the cost-capacity equation, the data must first be adjusted to take into account the time that the data were originally obtained because the base data are generally historical. Cost indexes are available to bring such data up to date. The equation for bringing cost data up to date is:

$$C_A = C_B\left(\frac{I_A}{I_B}\right)$$

where

C_A = Cost of plant and/or equipment at index value I_A

C_B = Cost of plant and/or equipment at index value I_B

Table 2.1 Cost Capacity Exponents for Scaling Costs of Plants

Plant or process unit	Exponent
Refrigeration, centrifugal	0.68
Refrigeration (incl. auxiliaries)	0.85-0.96
Refrigeration (no auxiliaries)	0.81
Desalting crude oil	0.60
LP-gas recovery in refineries	0.70
Solvent extraction units	0.73
Polymerization, small plants	0.73
Polymerization, large plants	0.91
Solvent dewaxing units	0.82
Lubricating oil manufacture	0.89
Clay treating, percolation (incl. regeneration)	0.55
Clay treating, contact	0.53
Cracking, catalytic	0.83
Cracking, thermal (also reforming)	0.51-0.70
Cracking, thermal, 2-coil	0.79
Natural gasoline plants	0.73
Gas-cycling plants	0.69
Desulfurization, cata. (old)	0.80
Hydrodesulfurization (recent)	0.57
Hydrodesulfurization of gases	0.75
Desulfurization of gases	0.41
Coking (old data)	0.72
Coking (recent)	0.81
Topping (old data)	0.58-0.67
Topping (recent)	0.62
Topping	0.64
Vacuum distillation (old data)	0.80
Vacuum distillation (recent)	0.57
Vacuum flash (old data)	0.64
Vacuum flash, small units	0.41
Vacuum flash, large units	0.32
Hypersorption	0.43
Coke oven gas separation	0.82
Steam generation, package units	0.61
Steam generation, refinery (no auxiliaries)	0.72
Steam generation, large, 200-psi	0.61
Steam generation, large, 1000-psi	0.81
Steam generation, indoor	0.66

Table 2.1 (*Continued*)

Plant or process unit	Exponent
Steam generation, outdoor	0.61
Power generation, 2,000-20,000 kW-hr	0.88
Power generation, oil field, 20-200 kW-hr	0.50
Cooling towers	0.64
Pipelines (cost vs. dia. squared)	0.72
Gas dehydration (field practice)	0.61
Water-gas manufacture	0.81
Fischer-Tropsch (complete)	0.77
CO and CO_2 removal from hydrogen	0.74
Peterson sulfuric acid towers	0.73
Soybean extraction plant	0.70
Water-gas shift conversion	0.69
Sulfuric acid (contact process)	0.66
Sulfuric acid, general	0.78
Sulfuric acid, akylation acid	0.89
Sulfur from H_2S	0.64
Sulfur from H_2S, package plants	0.40
Nitric acid or urea	0.93
Oxygen plants	0.65
Styrene plant	0.65
GR-S synthetic rubber	0.63
Ammonia, alone	0.90
Ammonia, and nitric acid or urea	0.98
Ammonia, and other products	0.95
Ammonia, most complete	1.02
Ethylene	0.86
Hydrogenation stalls, vapor or liq.	0.32
Chlorine plants, electrolytic	0.75
Reforming, cata.	0.62
Aklylation, small plants	0.67
Alkylation, large plants	0.60
Refineries, small	0.57
Refineries, large	0.67
Hydrogen mfr., steam hydro	0.72
Hydrogen sulfide removal	0.55
Average:	0.69

Table 2.2 Cost Capacity Exponents for Scaling Costs of Process Equipment

A. According to Peters and Timmerhaus[a]

Equipment	Size	Exponent
Blender, double cone, rotary c.s.	50–250 cu. ft.	0.49
Blower, centrifugal	1,000–10,000 cfm	0.59
Centrifuge, solid bowl, c.s.	10–100 hp drive	0.67
Crystallizer, vacuum batch, c.s.	500–7,000 cu. ft.	0.37
Compressor, reciprocating, air-cooled, two-stage, 150 psi discharge	10–400 cfm	0.69
Compressor, rotary, single-stage, sliding vane, 150 psi discharge	100–1,000 cfm	0.79
Dryer drum, single vacuum	10–100 sq. ft.	0.76
Dryer drum, single atmospheric	10–100 sq. ft.	0.40
Evaporator (installed) horizontal tank	100–10,000 sq. ft.	0.54
Fan, centrifugal	1,000–10,000 cfm	0.44
Fan, centrifugal	20,000–70,000 cfm	1.17
Heat exchanger, shell-and-tube, floating head, c.s	100–400 sq. ft.	0.60
Heat exchanger, shell-and-tube, fixed sheet, c.s	100–400 sq. ft.	0.44
Kettle, cast iron, jacketed	250–800 gal	0.27
Kettle, glass-lined, jacketed	200–800 gal	0.31
Motor, squirrel cage, induction, 440v, explosion proof	5–20 hp	0.69
Motor, squirrel cage, induction, 440v, explosion proof	20–200 hp	0.99
Pump, reciprocating, horizontal, c.i. includes motor	2–100 gpm	0.34
Pump, centrifugal, horizontal, cast steel, includes motor	10,000–100,000 gpm × psi	0.33
Reactor, glass-lined, jacketed (without drive)	50–600 gal	0.54

Table 2.2 (*Continued*)

Equipment	Size	Exponent
Reactor, s.s. 300 psi	100–1,000 gal	0.56
Separator, centrifugal, c.s.	50–250 cu. ft.	0.49
Tank, flathead, c.s.	100–10,000 gal	0.57
Tank, c.s., glass-lined	100–1,000 gal	0.49
Tower, c.s.	1,000–2,000,000 lbs	0.62
Tray, bubble-cap, c.s.	3–10 ft. diameter	1.20
Tray, sieve, c.s	3–10 ft. diameter	0.86
Average		0.60

B. According to the U.S. Bureau of Mines[b]

Equipment	Exponent
Heat exchangers	
0–3,000 sq. ft.	0.62
3,000–4,000 sq. ft.	0.95
500–5,000 sq. ft.	0.70
U-tube, 0–1,000 sq. ft.	0.53
U-tube, 1,000–4,000 sq. ft.	0.98
Air aftercoolers	0.62
Refrigeration coolers	0.68
General	0.51–0.59
Condensers	
Copper	0.54
Stainless	0.51
Tanks	
Oil-field	0.57
Rundown	0.60
Terminal cone-roof	0.70

Table 2.2 (*Continued*)

Equipment	Exponent
Floating-roof	0.73
Spherical, 15 psi	0.63
Spherical, 100 psi	0.56
Cylindrical pressure	0.53
API flat-bottom not erected	0.63
Redwood, 2–in.	0.59
Redwood, 3–in.	0.63
Horiz. cyl., 250–2,000 gal.	0.50
Horiz. cyl., 2,000–12,000 gal.	0.87
Carbon steel	0.44
Stainless	0.68
Spherical carbon steel	0.70
General	0.48
Average	0.61
Filters	
Sweetland	0.58–0.67
Sweetland, 2–in. spacing	0.63
Sweetland, 4–in. spacing	0.60
Oliver	0.69
Oliver, steel or wood	0.67
Vacuum	0.48
Plate and frame, c.i.	0.57–0.68
Plate and frame, wood	0.35
Plate and frame, recessed	0.58
Average (except wood)	0.62

Table 2.2 (*Continued*)

Equipment	Exponent
Towers	
Carbon, const. diameter	0.70
Carbon, const. height	1.00
Stainless, plate	0.63
Stainless, packed	0.55
Compressors, reciprocating	
Single-stage, 20–30 psi	0.67
Two-stage, 100 psi	0.75
One- and two-stage	0.90
Three- and four-stage	0.64
Gas-engine drive	0.89
General	0.87
Compressors	
Turbo 3,500 rpm	0.50
Centrifugal	0.78
Average	0.75
Electric motors	
440v	0.84
2,200v	0.38
Squirrel, dripproof	0.84
Wound rotor	0.66
1–10 hp	0.32
10–100 hp	0.55–0.60
Average	0.61
Pumps:	
Centrifugal	
Over 250°F	0.42
Under 250°F	0.46