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Design of electrochemical reactors via a sequential factorial costing technique

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A simplified procedure for the design of electrochemical reactors based on Lang factors as a general strategy for assigning priorities in the assessment of costs and relative importance of process parameters is described. The importance of reactor geometry and its sensitivity to variation in cost components is illustrated by a specific industrial-scale design of a rotating bipolar cell equipped with wiper blades. The technique is applicable to any type of electrochemical cell.

List of symbols

a_c	electrode cost per unit area of electrode
A_T	total plant cost
A_S	total plant cost, assuming standard materials and construction
C_c	base delivery cost of a single cell
C_e	cost of special machining and electrode materials per single cell
C_i	installed capital cost
C_m	base delivery cost of motors
C_o	cost of major equipment made of standard material (carbon steel)
C_p	base delivery cost of pumps
C_{p1}, C_{p2}	cost of a.c. power required for electrolyte circulation in the two RBE compartments
C_r	base delivery cost of the total number of required rectifiers
C_{RM}	cost of raw materials per annum
C_u	cost of utilities per annum
d	thickness of wiper blades in RBE cell
D_S	total product cost per annum when plant is constructed with standard materials
D_T	total product cost per annum
G	dimension of gap between inner (RBE) and outer electrode
g	acceleration due to gravity
I	electric current flow
IC	indirect costs
L_i	ratio of installed capital cost to major equipment cost (Lang factor)
L	length of the working electrode
L_o	ratio of cost of system material to cost of standard material (Lang factor)
n	number of electrolytic cells per reactor
P_{mc}	power dissipated due to electrode rotation
P_{mw}	power required to overcome fluid frictional forces at the wiper blades
P_{pr}	energy imparted to electrolyte by each pump
P_{rr}	total d.c. power requirement
$(Re)_R$	radial Reynolds number (RBE radius as characteristic length) $= 2\Omega R_1^2/\nu$
$(Re)_Z$	axial Reynolds number (gap between RBE and outer electrode as characteristic length) $= 2Gv_Z/\nu$
R_1	radius of the RBE
(TGE)	total general expenses
(TMC)	total manufacturing cost
V_T	compartment terminal voltage in RBE
v_Z	axial flow velocity
w	number of wiper blades (2 in RBE cell); and cell compartments
x_c	actual cost of cell constructed from special alloy per base cost of cell
x_p	actual cost of pumps constructed from

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	special alloy per base cost of pumps
ν	kinematic viscosity of electrolyte
ρ	density of electrolyte
Ω	angular velocity of rotating electrode

1. Introduction

In the recent past, a number of papers have discussed various concepts and aspects of the economic operation of electrochemical processes. Wagner's [1] classical work was followed by efforts on finding optimal (or at least sub-optimal) operating cost-contour relations, e.g. [2] and relatively simple basic design relationships e.g. [3]. Specific optimization procedures based on the process dynamics of an electrochemical cell were also proposed [4, 5]; recently, a detailed analysis based on the concept of a 'figure of merit' for optimization of electrolysers was presented [6]. General electrochemical design concepts can be found in a recent textbook on electrochemical reactor design [7], which also contains basic design procedures for various electrode–cell configurations.

The purpose of the current paper is to present an alternative approach to the economic analysis of an electrochemical process; the approach is based on the further development [8] of a sequential factorial costing technique [9] used widely for rapid cost estimation in the chemical process industries. The principle of the technique is a cost-priority scheme, where costs are sequentially considered according to the relative importance of associated equipment or service. In a typical estimation sequence the costs directly associated with investment costs and reactor geometry are first determined and appropriate relationships (i.e., cost contours) are established. In the second step reactor-accessory costs (i.e., costs of peripheral items) are estimated and economic operating conditions are found. Finally, electric power costs are employed to arrive at a refined estimate of the economic feasibility of various possible applications of the electrochemical reactor. The approach, which, in principle, is not limited to a specific electrochemical process, is illustrated by the design of an industrial scale process based on the rotating wiper blade principle, as an illustrative example.

2. General analysis

The total cost of a manufactured product is considered to be the sum of (a) factory manufacturing costs, and (b) general expenses. To the former category belong: fixed charges (i.e., depreciation, rent, insurance, property taxes, etc.), direct production costs (raw materials, operating labour and supervision, maintenance, supplies, power, utilities, royalties, etc.), and plant overhead costs (safety, medical, payroll overhead, packaging, storage, control laboratories, recreation, salvage, etc.). The second category comprises: administrative expenses (executive and clerical salaries, office supplies, communications), distribution and selling expenses, research and development costs, financing expenses, and expenses pertinent to gross earnings; this item depends on various interests held by the company and it need not be accounted for, in a preliminary cost estimation routine.

Since detailed and accurate cost estimation is seldom possible (or profitable), a logical procedure is to consider from *experience* relative proportions of major cost areas: the chemical engineering literature carries regularly updated data for this purpose, which allow a rational selection of proportional factors. Tables 1 and 2 contain the results of such an estimation based on engineering practice [10] which lead to a relatively easy computation of estimates of the total manufacturing costs, and of the total general expense. As shown by the detailed derivation in Tables 1 and 2, the two relationships may be written as

$$(TMC) = 0{\cdot}192A_{\mathrm{T}} + 0{\cdot}15D_{\mathrm{S}} + C_{\mathrm{RM}} + C_{\mathrm{u}} \qquad (1)$$

and

$$(TGE) = 0{\cdot}05A_{\mathrm{T}} + 0{\cdot}023D_{\mathrm{S}} + 0{\cdot}1D_{\mathrm{T}}. \qquad (2)$$

Thus, the total product cost per annum may be written as

$$D_{\mathrm{T}} = (TMC) + (TGE) = 0{\cdot}242A_{\mathrm{T}} + 0{\cdot}173D_{\mathrm{S}} + 0{\cdot}1D_{\mathrm{T}} + C_{\mathrm{RM}} + C_{\mathrm{u}} \qquad (3)$$

which is an implicit relationship, requiring information on the cost of equipment, raw materials and utilities. These costs being rather sensitive to the nature of the product and to process operating conditions, simplification is possible only if C_{RM} and C_{u} are expressed as some approximate

Table 1. Typical ranges and selected values of factory manufacturing costs

Fixed charges (typical values)	*Selected value*	*Direct production costs (typical values)*	*Selected value*	*Plant overhead costs (typical values)*	*Selected value*
depreciation on A_T (0·05–0·1A_T)	0·067A_T*	raw materials (0·1–0·51D_S)	C_{RM}	items listed above (0·5–0·7 of total expenses for operating labour, supervision and maintenance) (0·05D_S + 0·03A_T)	
taxes (0·01–0·04A_T)	0·015A_T	operating labour (0·05–0·2D_S)	0·09D_S		0·05D_S
insurance (0·004–0·01A_T)	0·01A_T	direct supervisory and clerical labour (0·1–0·2D_S)	0·01D_S		0·03A_T
rent (0·08–0·1 of rented property value)	0	maintenance and repairs (0·06A_T)	0·06A_T		
		operating supplies (0·15 of maintenance and repairs)	0·01A_T		
		patents (0–0·06D_S)	0		
		utilities (0·1–0·2D_S)	C_U		
Total:	0·092A_T	Total:	0·07A_T + 0·1D_S + C_{RM} + C_U	Total:	0·5D_S + 0·03A_T
Total manufacturing costs = 0·192A_T + 0·15D_S + C_{RM} + C_U					

* Based on depreciation over 15 years

fractions of D_T. Experience in constructing chemical plants indicates that $C_{RM} \cong 0{\cdot}2D_T$ and $C_u \cong 0{\cdot}15D_T$; hence Equation 3 may be simplified to

$$D_T \cong 0{\cdot}440A_T + 0{\cdot}3145D_S. \tag{4}$$

Further simplification can be introduced when standard construction materials are used. Then, $A_T = A_S$; $D_T = D_S$ and Equation 4 is simplified to $D_S \cong 0{\cdot}642A_S$. Under such conditions

$$D_T = 0{\cdot}269A_T + 0{\cdot}124A_S + 1{\cdot}11\,(C_{RM} + C_u) \tag{5}$$

becomes the basic cornerstone of a preliminary cost estimation procedure, requiring the estimation of four fundamental cost components: the total plant costs, the cost of raw materials and the cost of utilities. Notice that costs associated with standard and special construction appear as two distinct components, allowing the computation of the effect of deviations from standard construction techniques.

Table 2. General expenses

Administrative		*Distribution and selling*		*Research and development*		*Financing*	
items listed above	0·02D_S	items listed above	0·05D_T	items listed above	0·05D_T	interest	0·04A_T
(0·15 of operating labour, supervision, and maintenance)	0·003D_S 0·01A_T	(0·02–0·2D_T)		(0·02–0·05D_T)		(0·03–0·06 of A_T + working capital)	
Total general expenses = 0·05A_T + 0·023D_S + 0·1D_S							

3. Cost estimation via factorial method

While the estimation of the total plant cost can be carried out by a number of techniques known in the cost-estimation literature, the factorial approach proposed originally by Lang [11, 12] has several important advantages: it is cheap and requires a minimum expenditure of engineering time. The method uses *experimentally* known major equipment cost/plant-item ratios and yields an approximation to the capital investment by multiplying the basic equipment cost and an appropriate factor; in the instance of fluid processing plants the Lang multiplication factor is roughly 4·8 for fixed-capital investment and about 5·7 for total capital investment. Although individual industries may be characterized by somewhat different factors, they do not become obsolete, as pointed out by Bach [13] in contrast to unit cost data. Furthermore, certain improvements in accuracy have been achieved by various modifications, such as the so-called 'work-category' technique [13, 14] where Lang factors are used to estimate the cost of each major expenditure category (e.g., delivered equipment, erection of equipment, delivered instruments, etc.; see pp. 156 and 158 of [13] for further details). The total direct cost is then computed as the sum of the major categories. A comprehensive list of Lang factors for the estimation of installed process equipment costs by Clerk [15] and Gallagher [16] facilitates the required computations which also allow for differences in materials of construction, an important consideration for electrochemical processes. The fundamental relationship in employing Lang factors may be written as [16]

$$C_i = L_i L_o C_o. \tag{6}$$

The use of Lang factors is illustrated in the Appendix using a specific example.

The factorial method can easily be combined with the estimation of capacity adjustment and indirect costs. The former is based on the widely used exponential relationship

$$C_1/C_2 = (P_1/P_2)^n \tag{7}$$

where P denotes plant capacity and C plant cost. Unless P_1 and P_2 are order(s) of magnitude apart, Equation 7 yields historically reliable estimates. Much has been written about the correct numerical value of n, its range being 0·38–0·9 [17, 18]; existing plant data in a particular industry are the most reliable source of its value. Indirect costs may be estimated [19] as

Table 3. Estimation of the total plant cost via Lang's method [11, 12]. Steps in determining the total plant cost from delivered equipment costs

Step	*Item*	*Cost ratio (fluids plant)*
1	C_1, cost of process equipment delivered to the site	–
2	C_2, installed cost of equipment (includes foundations, supports, chutes, vents, insulation, and ventilation)	$C_2 = 1{\cdot}43C_1$
3	C_3, installed cost of equipment and piping	$C_3 = 1{\cdot}60C_2$
4	C_4, total construction cost of plant (includes material and labour costs for yard improvements, buildings, building services, process equipment and piping, electrical installations, and service facilities including insurance and taxes on labour and premium time, if any)	$C_4 = 1{\cdot}50C_3$
5	C_5, total overhead costs (includes contingency, field office expense including temporary construction, engineering expense and the engineer's and contractor's fees)	$C_5 = 0{\cdot}38C_4$
6	C_6, total estimated cost of plant	$C_6 = C_4 + C_5$ $= 4{\cdot}74C_1$

$$IC = aC_i^{0\cdot882} \tag{8}$$

where the coefficient *a* is a function of the annually adjusted Marshall and Stevens index [20] reported periodically in the literature (in 1953, e.g., $a = 1\cdot68$ and in 1973 $a = 1\cdot81$; for an electrolytic plant the IC/C_i ratio was between 0·27 and 0·33 in 1973, for a 2–10M$ size).

The factorial technique has some disadvantages, such as lack of precision (a fault common to all economic estimation techniques), the relating of service facilities solely to equipment costs and the assumption of the same cost indices for all plant components. The technique may underestimate by about 30% and overestimate by about 20% actual plant costs [21] in extreme cases. In spite of these shortcomings, the Lang factor method is regarded as a highly useful tool in plant design and it has particular merits when the plant is made up of several different unit processes. It is therefore particularly useful for those electrochemical processes which constitute *one* component of a large chemical installation.

Table 3 summarizes the typical steps involved in arriving at the common Lang factor of about 4·8 for fluid-processing plants.

4. The application of the factorial technique to the design of an industrial scale electrochemical process

As an illustration of the factorial design technique, consider cost estimation for an industrial-scale rotating bipolar (RBE) cell, whose laboratory prototype has been thoroughly studied recently [8, 22, 23]. Although this cell has not yet attained industrial application, it was chosen in preference to a known electrochemical technology where detailed economic design data, which may be obsolescent, are not readily and fully available in the literature. The approach can, however, be applied to other cell types in principle and would require only specific modifications of certain cost components. As shown by Nadebaum [8] the RBE cell with wiper blades has potential in metal recovery, electro-organic synthesis and other areas, and as such, it serves as a good illustrative example.

The principle of the cell is shown in Fig. 1, while Fig. 2 illustrates one possible industrial-size cell using the RBE concept. The cost components, taken into account in the factorial design, are assembled in Table 4, where each specific item in the three major cost categories (i.e., direct costs, auxiliary costs and indirect costs) is considered by

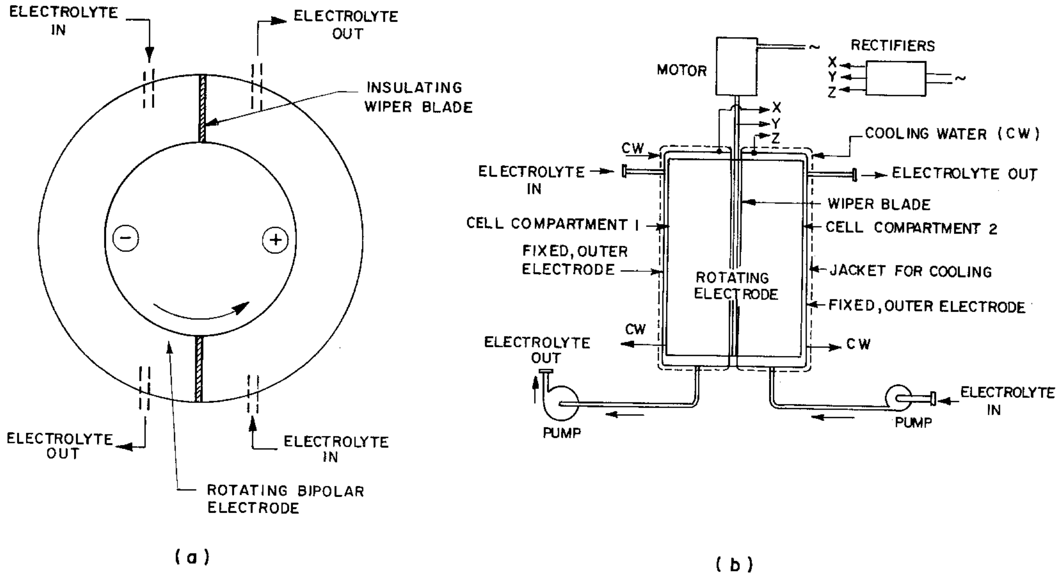

Fig. 1. The rotating bipolar cell. (a) Illustration of the principle; (b) sketch of the apparatus.

Table 4. Determination of the total plant cost (factors have been chosen from [10, 13, 24, 25])

Item	*RBE cell (per cell)*	*Cell motor (per cell)*	*Pumps (per pump)*	*Rectifier* (per total installation)*
Direct costs				
base cost of delivered item (no special materials or machining)	C_c	C_m	C_p	C_r
cost of item constructed from special alloy (excluding electrodes and special machining)	x_cC_c	C_m	x_pC_p	C_r
cost of special machining and electrode materials (incl. installation)	C_e	–	–	–
equipment erection, testing	$0{\cdot}1C_c$	$0{\cdot}10C_m$	$0{\cdot}10C_p$	$0{\cdot}10C_r$
delivered instrument cost	$0{\cdot}3C_c$	$0{\cdot}15C_m$	$0{\cdot}05C_p$	$0{\cdot}15C_r$
instrument installation	$0{\cdot}05C_c$	$0{\cdot}04C_m$	$0{\cdot}01C_p$	$0{\cdot}04C_r$
building, frames, supports	$0{\cdot}2C_c$	0	$0{\cdot}10C_p$	$0{\cdot}10C_r$
piling	$0{\cdot}05C_c$	0	0	0
foundations, sewers, drains	$0{\cdot}25C_c$	0	$0{\cdot}05C_p$	$0{\cdot}10C_r$
electrical	$0{\cdot}25C_c$	$0{\cdot}25C_m$	$0{\cdot}20C_p$	$0{\cdot}25C_r$
insulation	$0{\cdot}05C_c$	0	0	$0{\cdot}05C_r$
painting	$0{\cdot}10C_c$	$0{\cdot}02C_m$	$0{\cdot}05C_p$	$0{\cdot}02C_r$
piping	$0{\cdot}60x_cC_c$	0	$0{\cdot}30x_pC_p$	0
Total direct costs for each item	$(1{\cdot}35 + 1{\cdot}6x_c)C_c + C_e$	$1{\cdot}56C_m$	$(0{\cdot}56 + 1{\cdot}3x_p)C_p$	$1{\cdot}81C_r$
Total direct costs for plant with *n* cells	$n(1{\cdot}35 + 1{\cdot}6x_c)C_c + nC_e + 1{\cdot}56nC_m + n(0{\cdot}56 + 1{\cdot}3x_p)(C_{p_1} + C_{p_2})1{\cdot}81C_r$			
Auxiliary costs				
auxiliary components (includes land, offices, warehouses, laboratories, transportation and utilities facilities, electrical installations, outside lines, yard improvements, etc. Assumes grass roots plant)		$0{\cdot}27 \times$ (total direct costs of standard plant)		
Indirect costs				
construction overhead (includes field and home office, supervision, engineering, insurance, etc.)	$0{\cdot}15$			
contractors fees	$0{\cdot}07$	$0{\cdot}37 \times$ (total direct costs + auxiliary costs of standard plant) $= 0{\cdot}27$ total plant, standard construction		
contingencies	$0{\cdot}15$			
Total plant costs (A_T)†	$n(3{\cdot}53 + 1{\cdot}6x_c)C_c + nC_e + 2{\cdot}75nC_m + n(1{\cdot}97 + 1{\cdot}3x_p)(C_{p_1} + C_{p_2}) + 3{\cdot}19C_r$			
Total plant cost assuming standard const. (A_S)	$5{\cdot}13nC_c + nC_e + 2{\cdot}75nC_m + 3{\cdot}27n(C_{p_1} + C_{p_2}) + 3{\cdot}19C_r$			

* In power production, rectifier cost will be zero.

† Total plant costs = total direct costs + auxiliary costs + indirect costs.

$$A_T = \text{total direct costs} + \text{total direct costs} \,|_{x_c,x_p=1} + 0{\cdot}27A_S$$

which can be evaluated by noting that

$$A_S = (1{\cdot}27/0{\cdot}73)\ \text{total direct cost} \,|_{x_c,x_p=1}.$$

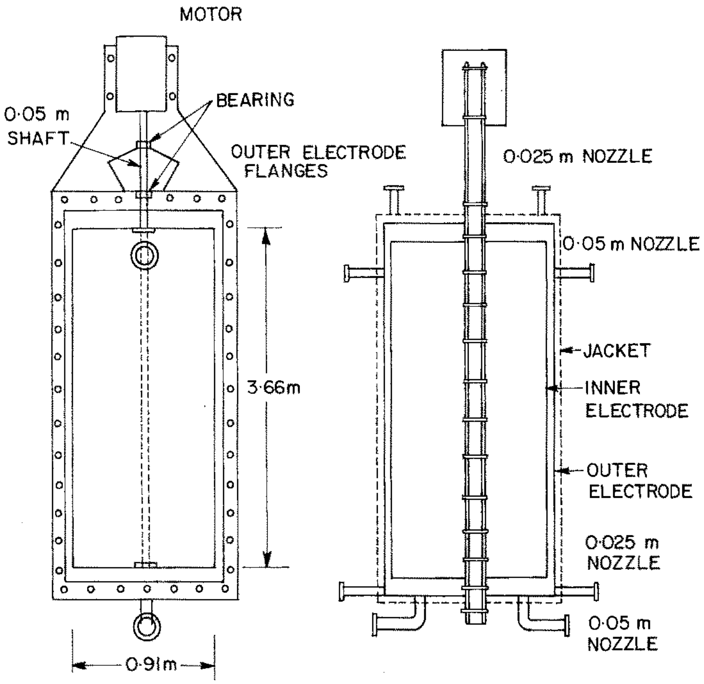

Fig. 2. An industrial-scale rotating bipolar cell envisaged for the purpose of economic analysis.

its associated Lang factor. In this manner, the contribution of the pertinent physical equipment (cell, motor, pumps, rectifier) to the overall cost can systematically be estimated, by summing the individual column entries. The result of this summation is the total plant cost, shown at the bottom of Table 4. If special alloys are used, the alloy cost coefficients must also be taken into account and the formula written for A_T is employed; with standard construction materials, these coefficients are unity and the formula written for A_S applies. Tables 5 and 6 contain typical alloy cost coefficient data for computing A_T (the 1973 prices may be updated by appropriate cost indices published regularly in technical journals such as *Chemical Engineering*). The numerical estimation of A_T and A_S has now been reduced to an appropriate estimation of base costs of delivered equipment; this step is illustrated in the Appendix for the RBE cell.

One important design parameter of any electrolytic cell is its geometric configuration; in the case

Table 5. Cost of the RBE cell per unit area with special materials of construction (1973 prices)

		Cell fabrication technique ($ m^{-2})	
Metal	*Alloy cost coefficient* *(x_c)*	*Conventional* *6 m length* *0·175 m radius*	*Mass production* *(labour = 30% conventional)* *6 m length* *0·12 m radius*
carbon steel	1·0	250	96
stainless steel 410	2·10	525	200
405	2·25	550	220
304	2·75	700	270
316	3·0	750	300
310	3·25	800	310
nickel alloys: monel	4·0	1000	380
inconel	4·5	1100	430
nickel	4·5	1100	430

Table 6. Investment cost of plant directly associated with the RBE cell (1973 prices)

Metal	*Alloy cost coefficient* (x_c)	*Plant cost* ($ m^{-2})	
		Conventional *6 m length* *0·175 m radius*	*Mass production* *(labour = 30% conventional)* *6 m length* *0·12 m radius*
carbon steel	1·0	1013	393
stainless steel 405	2·25	1383	537
316	3·0	1605	624
nickel alloy: monel	4·0	1901	739
nickel	4·5	2049	797

of RBE cell, the relative magnitudes of the rotating electrode radius and electrode length, as well as their combined effect on the cell cost per unit electrode area. Using the factorial technique this relationship is established for the RBE cell as shown in Fig. 3. It is seen that long reactors would be expected to be more economical than shorter reactors of the same radius; moreover, the cell cost per unit area is minimal at a cell radius close to 17·5 cm. Cells of radii larger than 30 cm and less than 10 cm will be considerably more expensive although such limits would depend somewhat on cell design and construction. If the design cell length is constant, varying the radius will result in cost distributions as depicted in Fig. 4; the position of the minimum total cost depends on the specified cell length (for a six metre long cell, the optimal radius is about 17 cm). At low radii labour costs are much higher than the cost of materials but with increasing radius, they gradually decrease relative to the cost of materials.

The sensitivity of the estimated costs to their specific components can also be computed with relative ease, using the factorial technique. As an illustration, consider the variation of the cell cost with the cost of labour, since the latter is very

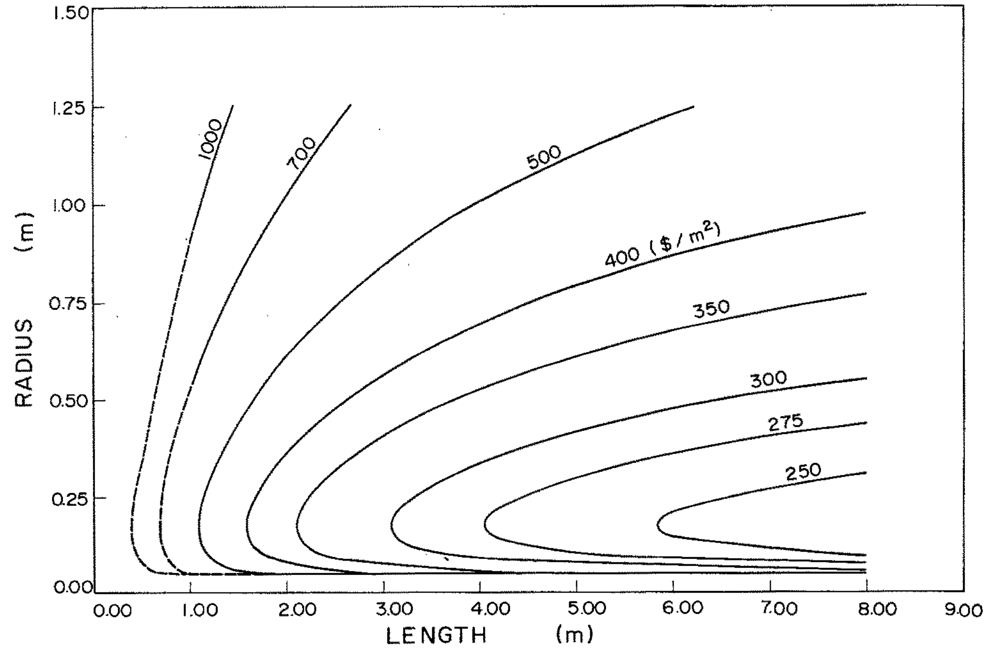

Fig. 3. The effect of the cell geometry on the cost contour lines (standard construction using carbon steel).

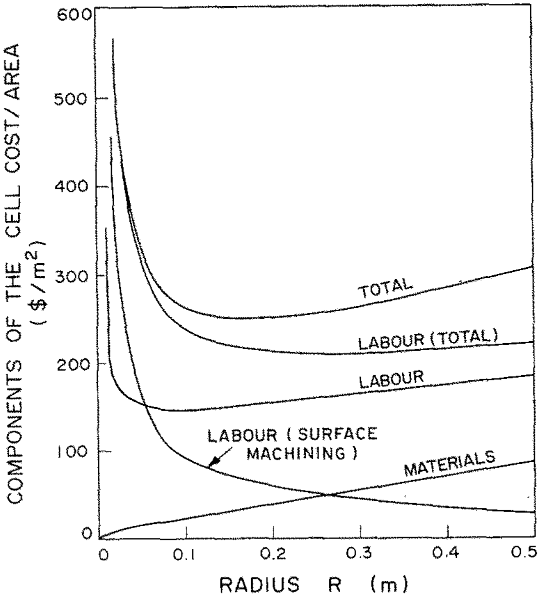

Fig. 4. The variation of the major cost components per unit area with cell radius (special labour defined as that required for machining of electrode surface and wiper blades; length of cell =6 m).

sensitive to cell geometry. Fig. 5 shows clearly the effect of the labour cost component; the smaller the fractional labour cost the larger the cell size for a specified total expenditure, allowing a more profitable investment over a certain period of time. A reduced labour requirement will also result in a modified optimal geometry.

In the second example of sensitivity analysis the variation of the cell cost with materials of construction is taken. Using the data in Tables 5 and 6 the relative contribution of cell costs to the cost of electrochemical production of a chemical may be estimated at various electric current flows. Fig. 6 shows that conventionally constructed nickel-clad cells would cost about 4·5 times as much as mass produced carbon-steel cells, although the product cost will increase only by a factor of 1·8. The circle on line 4, corresponding to the production of chlorine and sodium hydroxide via a conventional diaphragm cell process, serves as reference for comparison with an existing major electrochemical technology. The negative slope of the cost lines also makes it clear that unless an expensive chemical is produced, the current density should be relatively high.

A further application of the factorial technique could be the study of production alternatives where conventional electrolytic, RBE-based and non-electrolytic production paths could be compared; this exercise is beyond the scope of this paper. A more detailed economic analysis would require a

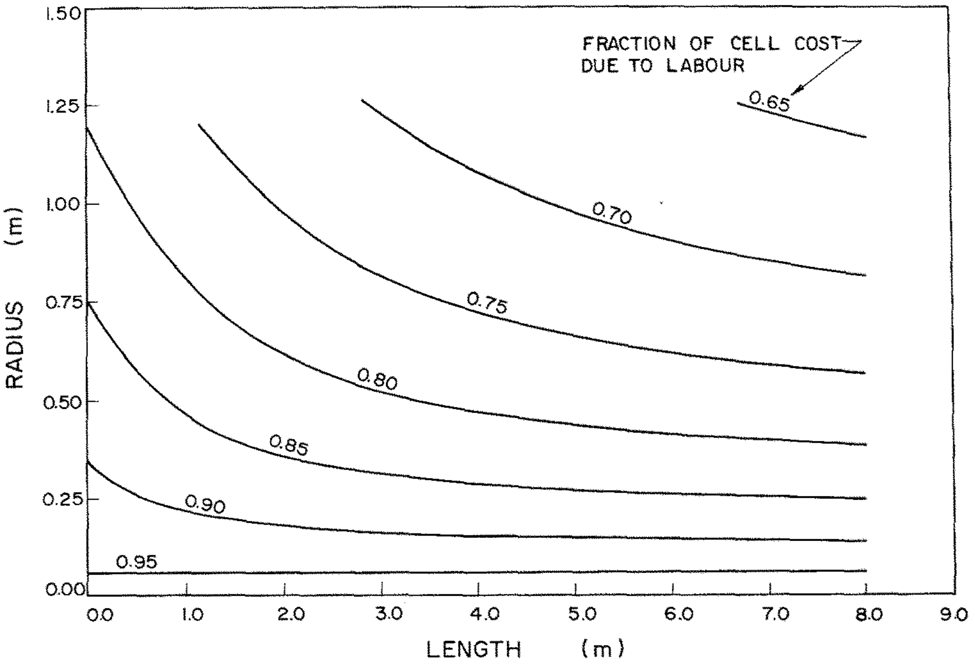

Fig. 5. The effect of labour costs on the cell cost.

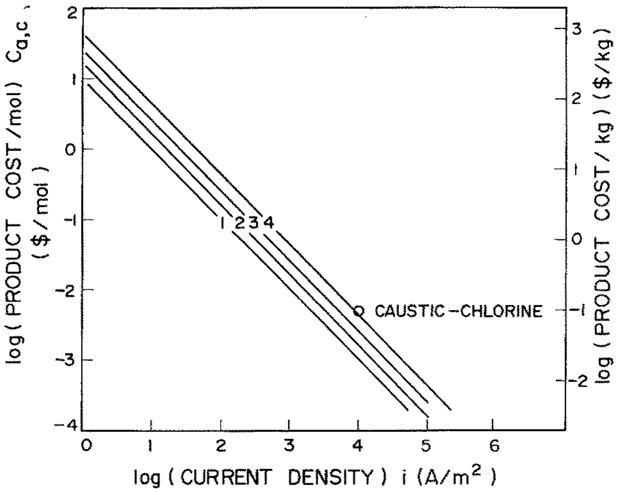

Fig. 6. The portion of cost of a chemical directly attributable to the cell cost [curve 1 mass production, carbon steel ($x_c = 1$); curve 2: mass production nickel-clad ($x_c = 4{\cdot}5$); curve 3: conventional construction carbon steel ($x_c = 1$); curve 4: conventional construction, nickel-clad ($x_c = 4{\cdot}5$)]. Based on a two-electron-transfer cathode process, with a product molar mass of 50 g.

thorough examination of many, somewhat secondary, factors such as the effect of wiper-blade geometry, axial versus circumferential flow in the RBE cell, monopolar versus bipolar operation, electrolyte concentration, cell terminal voltage, electrolyte conductance, and so forth. Such an extension was carried out elsewhere [8] in detail for the case of the RBE cell, and a means of sequentially examining and optimizing the various cell operating variables in order to minimize the product cost was illustrated.

5. Concluding remarks

The factorial cost estimation technique is discussed particularly with a view to exploring the economic viability of novel electrochemical processes where a wide range of applications can be envisaged as an alternative to extensions of conventional technology. The technique is by no means limited to specific cell configurations although certain fabrication, labour and material cost components may vary with electrode shape, material and cell application; in the instance of rectangular (flat) plate electrode cells a higher labour cost component may arise if the electrode length to electrode width ratio was to be increased significantly. Equations 5–8 generally apply, however, inasmuch as specific cost component modifications do not alter the general scheme of the estimation strategy.

Appendix

The use of Lang factors in estimating the total plant cost

Assume that an electrochemical plant design specifies a $100 000 (major) equipment delivery cost, in order to add a further cell assembly to an existing installation. It is supposed that the following Lang factors are representative average values of the various 'work-categories' [13]:

delivered equipment	1·00
equipment erection	0·17
delivered instruments	0·17
instrument installation	0·04
above-ground piping	1·12
underground piping	0·06
structural steel	0·19
building items	0·01
piling	0·06
foundations	0·21
electrical	0·14
insulation	0·19
painting	0·04
yards, roads and site preparation	0·04

L_i = 3·38 (sum of above factors)

Then, the total direct costs will be $C_i = (3{\cdot}38)(100\,000) = \$338\,000$. The indirect costs will be computed (assuming the 1973-based coefficient in

Table 7.

Item and its standard material of construction	L_o	L_i	C_o $
cell; A285 Grade Steel	2·10	2·70	3500
pump; cast steel	1·50	2·85	550
instrument; immaterial	1·00	3·70	1250

Equation 8 as 1·81 $(338\,000)^{0\cdot882} \cong \$136\,000$; hence the total cost of the additional installation is estimated as 338 000 + 136 000 = $474 000.

The use of Lang factors in estimating installation costs of items constructed of a specific material

Assume that an electrolytic cell assembly with a circulating pump and a recording instrument are to be installed. The cell and the pump are to be made of type 410 stainless steel and the instrument of standard material (its nature does not have to be specified for this computation). Using the Lang factor data of Clerk [15] and Gallagher [16], the information in Table 7 is gathered (the last column contains arbitrarily chosen unit costs).
The estimated total installation cost is, therefore

$$C_i = (2\cdot10)(2\cdot70)(3500) + (1\cdot50)(2\cdot85)(550) + (1\cdot00)(3\cdot70)(1250) = \$26\,821.$$

If all items were made of their respective standard materials of construction (i.e., $L_o = 1\cdot0$ throughout), the same cost would be estimated as

$$C_i = (4)(3500) + (3\cdot7)(550) + (3\cdot7)(1250) = \$20\,660.$$

The L_i/L_o relationships in appropriate tables and figures (e.g. [15, 16]) can be used in similar manner for other equipment items. Note that L_i varies with the numerical value of L_o in each category.

The estimation of base costs of delivered equipment in the design of an RBE cell

Cell and electrodes. The individual costs related to materials, labour requirements and special machining may be expressed as polynomial functions of the rotating electrode radius (R_1) and the electrode length (L) as

$$\begin{aligned}\text{materials cost} = {} & 629R_1^2L + 499R_1^3 \\ & + 43\cdot3R_1^{1\cdot3}L + 40\cdot4R_1^{2\cdot3} \\ & + 96\cdot2R_1 + 92R_1^2 \\ & + 20\cdot4R_1L + 31\cdot6R_1^{2\cdot5} \\ & + R_1^{1\cdot5}L \qquad \text{(A1)}\end{aligned}$$

$$\begin{aligned}\text{labour cost} = {} & 122R_1^2 + 13\cdot3R_1L + 7\cdot9R_1^{1\cdot3} \\ & + 47\cdot5R_1 + 25\cdot5R_1^{0\cdot5} \\ & + 50\cdot3R_1^{1\cdot4}L + 78R_1^{2\cdot4} \\ & + 6\cdot8R_1^{0\cdot7} + 6\cdot35R_1^{1\cdot7} \\ & + 1\cdot3R_1^{0\cdot4} \qquad \text{(A2)}\end{aligned}$$

in dollars. The somewhat tedious procedure required for the development of Equations A1 and A2 had been described elsewhere [8]. The base delivered cost of the cell is computed as

$$C_c = 1\cdot265(\text{material cost}) + 12\cdot65(\text{labour cost}) \qquad \text{(A3)}$$

Similarly, the cost of electrodes for their special machining may be written as

$$C_e = a_cR_1L + 42\cdot0L \qquad \text{(A4)}$$

where the factor a_c depends on the electrode material and may vary from 152 to about 1000 $\$\text{m}^{-2}$.

Rectifier. Assuming silicon diode rectifiers and a total d.c. power requirement of about 2·5 MW in an industrial installation, the rectifier cost is

$$C_r = 0\cdot0362P_{rr}^{0\cdot8} \qquad \text{(A5)}$$

where P_{rr} the total d.c. power requirement is expressed as

$$P_{rr} = n\sum_w V_TI \qquad \text{(A6)}$$

Cell motor. The base cost of the cell motor required to drive the rotating electrode is

$$C_m = 0\cdot124(P_{mc} + P_{mw}) \qquad \text{(A7)}$$

where P_{mc} the power required to overcome fluid frictional forces in the cell compartments is computed as

$$P_{mc} = 0\cdot047G\left(\frac{\rho v^3L}{R_1^2}\right)\left(\frac{2R_1}{G}\right)^{0\cdot4}(Re)_R^{2\cdot6}\ \text{W} \qquad \text{(A8)}$$

and P_{mw} the power required to overcome frictional forces at the wiper blade is computed as

$$P_{\mathrm{mw}} = w\frac{dL\rho v^3}{4gR_1^3}(Re)_{\mathrm{R}}^2\ \mathrm{W} \qquad \text{(A9)}$$

Electrolyte circulation pumps. Assuming centrifugal pumps, the base cost is given as

$$C_{\mathrm{p}} = 320 + 0{\cdot}0875P_{\mathrm{pr}} \qquad \text{(A10)}$$

where P_{pr} is the energy imparted to the electrolyte:

$$P_{\mathrm{pr}} = 0{\cdot}0181R_1\rho v^3L(Re)_{\mathrm{Z}}^{2\cdot 8}/G^3. \qquad \text{(A11)}$$

The cost equations above yield estimates in 1973 dollars. Updating to any later date may be carried out via appropriate cost indices, published regularly in technical journals such as the *Chemical and Engineering News* and *Chemical Engineering*.

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