1-1-1993

Process Plants, Costs of Scaled-up Units

Donald S. Remer
Harvey Mudd College

Lawrence H. Chai
Harvey Mudd College

Recommended Citation

Remer, D.S. and Chai, L.H. "Process Plants, Costs of Scaled-up Units." Encyclopedia of Chemical Processing and Design, ed., McKetta, J. J., Marcel Dekker, Inc., 44, 14-39, 1993.

Phadke, P. S., and Kulkarni, P. D., "Estimating the Costs and Weights of Process Vessels," *Chem. Eng.,* April 11, 1977.
Richardson Engineering Services, Inc., *Process Plant Construction Estimating and Engineering Standards,* Vol. IV and V, P.O. Box Y, Solana Beach, CA 92075.

Other Sources

Chilton, C. H., "Six-Tenths Factor Applies to Complete Plant Costs," *Chem. Eng.,* April 1950.
Dickens, S. P., and Douglas, F. R., "Off-Site Investment and Working Capital," *Chem. Eng. Prog., 56*(12), December 1960.
Hand, W. E., "From Flow Sheet to Cost Estimate," *Petroleum Ref.,* September 1938.
Hirsch, J. H., and Glazier, E. M., "Estimating Plant Investment Costs," *Chem. Eng. Prog., 56*(12), December 1960.
Lang, H. J., "Simplified Approach to Preliminary Cost Estimates," *Chem. Eng.,* June 1948.
Williams, L. F., "Capital Cost Estimating from the View Point of Process Plant Contractor," *Cost Engineer, II*(1), January 1972.

M. B. DESAI

Process Plants, Costs of Scaled-up Units

(see also Process Equipment Cost articles)

Introduction

Engineers must often make a quick ballpark cost estimate of a new plant before the detailed design stage. One easy way of obtaining such an estimate is to base it on a known cost for the same type of plant, with the ratio of the capacities of the known and proposed plants raised to exponent R. This method, referred to as the 0.6 power-factor model, was first applied to equipment cost estimates in 1947 [20] and to plant costs in 1950 [8]. The range of R factors for plants is much wider than for equipment.

This predesign cost-estimating approach is especially useful for performing sensitivity analyses, for which a high degree of accuracy is not required. Equipment and plant costs are still being estimated by means of this method, and operating costs can be estimated via a variation of it.

Values for R for several hundred different types of plants and processes are presented in this article. Such values are difficult to find. These represent a thorough compilation of published R factors. Values vary with plant type and process. The most appropriate provides the most accurate estimate.

Cost Versus Capacity Relationship

Equation (1) expresses the relationship between facility cost and capacity:

$$\frac{C_2}{C_1} = \left(\frac{S_2}{S_1}\right)^R \qquad (1)$$

Here, C_1 and C_2 are the costs and S_1 and S_2 are the corresponding capacities (i.e., sizes) for a particular process plant or process.

An R value can be determined by plotting cost estimates for several different operating capacities, as shown in Fig. 1. The slope of the best line through the points is R, which can also be calculated from two points via Eq. (2):

$$R = \frac{\ln C_2/C_1}{\ln S_2/S_1} \qquad (2)$$

With more than two points, calculate R by a least-squares regression analysis. A plot of the ratios on log-log scale produces a straight line, as shown in Fig. 2 for values of R from 0.2 to 1.1. With R known, how much it will cost to scale up a plant or process can be determined via Eq. (1) or Fig. 2.

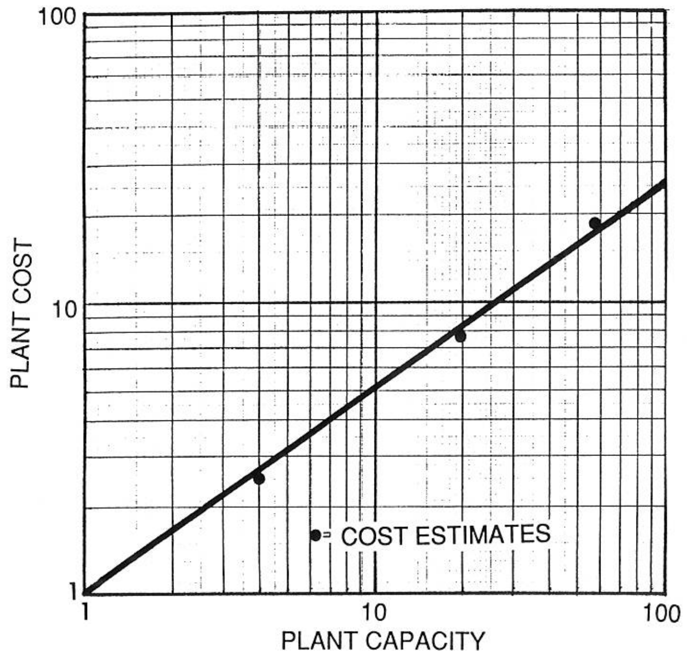

FIG. 1 Method for obtaining the cost-capacity exponent R.

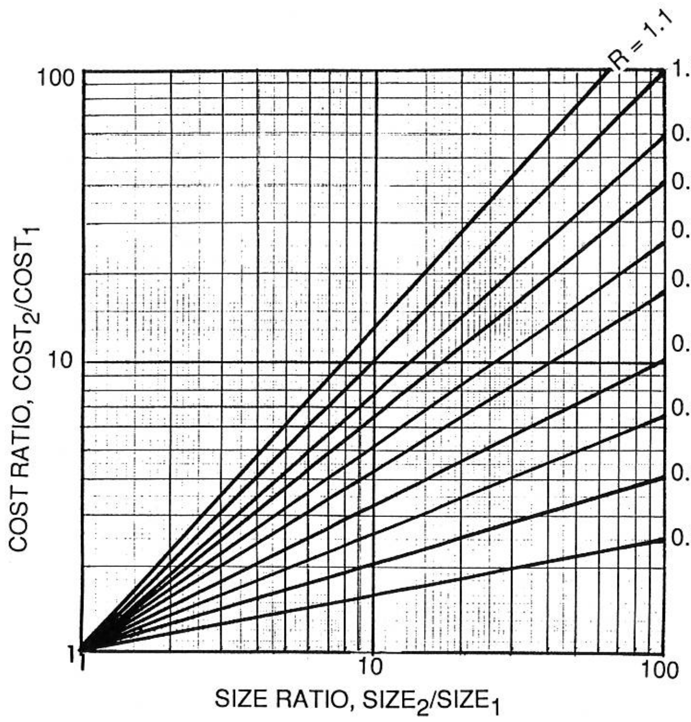

FIG. 2 Plant cost ratio versus plant size ratio for two orders of magnitude.

The cost ratios for doubling or tripling the size of a plant or process, as a function of R, are presented in Table 1 and can be calculated by means of Eq. (1). A rule of thumb says that, with $R = 0.6$, doubling the size of a plant hikes cost by 50% and tripling its size boosts cost by 100%. In the chemical process industries, average values of R fall between 0.6 and 0.7.

TABLE 1 Cost Ratios for Increasing the Size of a Plant as a Function of Exponent *R*

	Cost Ratios for Size Multiples			
R Value	2 Times	3 Times	5 Times	10 Times
0.2	1.15	1.25	1.38	1.58
0.3	1.23	1.39	1.62	2.00
0.4	1.32	1.55	1.90	2.51
0.5	1.41	1.73	2.24	3.16
0.6	1.52	1.93	2.45	3.98
0.7	1.62	2.16	3.09	5.01
0.8	1.74	2.41	3.62	6.31
0.9	1.86	2.69	4.26	7.94
1.0	2.00	3.00	5.00	10.00
1.1	2.14	3.35	5.87	12.59

Equation (1) can be modified to take inflation into account. This is done by multiplying the capacity ratio by the ratio of cost indexes, as in Eq. (3):

$$\frac{C_2}{C_1} = \left(\frac{S_2}{S_1}\right)^R \frac{I_2}{I_1} \tag{3}$$

Here, I_1 and I_2 are cost indexes for particular years.

Among the indexes available for adjusting the costs of process plants are the *Chemical Engineering* (CE) plant cost index, Marshall and Swift (M&S) equipment cost index, Nelson refinery index, and *Engineering News Record* (ENR) index. The first three are shown in the frontmatter of each volume of this encyclopedia. Some cost indexes are also available for other countries [7].

Scale-up Factors

For this article, a plant or process is defined as a self-sufficient entity that includes auxiliary facilities and utilities. In Table 2 are R values for many different types of processes and plants in the chemical process industries, including gas plants and polymer processes and biotechnology plants, as well as power, effluent treatment, drinking water and refrigeration facilities, and utilities. Some miscellaneous R values are also presented.

When there is more than one R value for the same process, they are listed in chronological order—as with chlorine, for example. Also indicated in the tables are the ranges over which the R values apply and the units of the values, if these are known. When the R values in one source have been obtained from an earlier source, the original source is cited. If plant size ranges in the original source are given in tons/day, the ranges were multiplied by 365 to convert them to tons/year.

Some discrepancies can be found in the published factors. These may have been caused by variations in plant definition, scope, and size. Some of the data in the original sources cover a smaller range than what is now standard. For example, a new ammonia plant would probably not be built smaller than 1,000 ton/day, and 1,500 ton/day is more common. Also, processes and technology have changed, and governments now dictate expenditures for environmental control and safety that were not required in earlier plants.

It is not always clear how the earlier exponents were arrived at or what was included in the estimate. Some of the articles referenced are quite old. For example, the exponent for TNT (trinitrotoluene) comes from an article written by Chilton in 1950 [8], but the data he used to arrive at the exponent goes back to 1945. The original wartime process was composed of multiple units. In newer plants, the reactors are continuous-flow stirred-tank or tubular, which are better controlled, higher yielding, and lower costing [2]. For all these reasons, the more recent R values should be selected.

TABLE 2 Exponential *R* Values for Estimating the Costs of Several Hundred Processes

Product	Process	Size Range	Unit[a]	Exponent	Reference
Chemical Plants and Process					
Acetaldehyde	Ethylene			0.70	13
Acetaldehyde	Ethylene	25–100	1,000 t/year	0.70	21
Acetaldehyde				0.70	3
Acetaldehyde	Ethylene	2–84	1,000 ton/year	0.41	10
Acetic acid		2–20	1,000 ton/year	0.68	12
Acetic acid	Methanol	3–50	1,000 t/year	0.68	21
Acetic acid	Methanol	2–64	1,000 ton/year	0.59	10
Acetone		20–200	1,000 ton/year	0.45	12
Acetone	Propylene	3–50	1,000 t/year	0.45	21
Acetone	Propylene	9–300	1,000 ton/year	0.55	10
Acetylene	Natural gas	4–37	1,000 ton/year	0.73	4
Acetylene				0.75	9
Acetylene	Natural gas			0.70	13
Acetylene		1–91	1,000 ton/year	0.73	15
Acetylene				0.75	17
Acetylene				0.73	16
Acetylene		3–30	1,000 ton/year	0.65	12
Acetylene	Natural gas or petrochemical source	2–150	1,000 t/year	0.70	21
Acetylene				0.68	3
Acetylene	Hydrocarbons	3–45	1,000 ton/year	0.65	10
Acrylic fiber		4–20	1,000 t/year	0.69	21
Acrylic fiber	Acrylonitrile	3–24	1,000 ton/year	1.02	10
Acrylonitrile		20–200	1,000 ton/year	0.65	12
Acrylonitrile	Acetylene, hydrogen cyanide	10–500	1,000 t/year	0.60	21
Acrylonitrile				0.60	3
Acrylonitrile	Acetylene, hydrogen cyanide	16–261	1,000 ton/year	0.60	10
Adipic acid		5–50	1,000 t/year	0.53	21
Alkyl benzene (linear)		10–120	1,000 t/year	0.70	21
Alkyl benzene (linear)		9–150	1,000 ton/year	1.07	10
Alkylation		2–30	1,000 barrel/day	0.60	12
Alkylation				0.60	3
Alkylation, large plants				0.60	14

Alkylation, small plants				0.67	14
Alum (liquid)		7–37	1,000 ton/year	0.71	4
Alum (liquid)		7–350	1,000 t/year	0.71	21
Alumina	Bauxite	10–400	1,000 t/year	0.66	21
Alumina	Bauxite	34–365	1,000 ton/year	0.54	10
Aluminum	Alumina	20–200	1,000 t/year	0.76	15
Aluminum				0.76	16
Aluminum	Alumina	25–200	1,000 t/year	0.80	21
Aluminum	Alumina	37–300	1,000 ton/year	1.00	10
Aluminum ingot		15–139	1,000 ton/year	0.90	8
Aluminum sulfate	Alum	9–37	1,000 ton/year	0.71	4
Aluminum sulfate		10–500	1,000 t/year	0.71	21
Ammonia	Natural gas	37–110	1,000 ton/year	0.63	4
Ammonia	Blast furnace gas	37–110	1,000 ton/year	0.53	4
Ammonia				0.70	13
Ammonia	Steam-reformed synthesis gas			0.74	9
Ammonia	Steam-methane reforming	37–1,095	1,000 ton/year	0.72	15
Ammonia				0.88	17
Ammonia				0.72	16
Ammonia		20–400	1,000 ton/year	0.53	12
Ammonia				0.71	3
Ammonia	Gas, air	212–800	1,000 ton/year	0.58	10
Ammonia (anhydrous liquefied)	Steam reforming of naphtha	30–330	1,000 t/year	0.70	21
Ammonia (anhydrous liquefied)	Steam reforming of natural gas	30–330	1,000 t/year	0.70	11
Ammonia (anhydrous liquefied)	Partial oxidation of natural gas	30–330	1,000 t/year	0.70	11
Ammonia (anhydrous liquefied)	Naphtha	30–330	1,000 t/year	0.70	11
Ammonia (anhydrous liquefied)	Fuel oil	30–330	1,000 t/year	0.70	11
Ammonia (anhydrous liquefied)	Coal	30–330	1,000 t/year	0.70	11
Ammonia (synthetic)		47–420	1,000 ton/year	0.81	8
Ammonia, alone				0.90	14
Ammonia, and nitric acid or urea				0.98	14
Ammonia, and other products				0.95	14
Ammonia, most complete				1.02	14
Ammonium nitrate		18–110	1,000 ton/year	0.65	4
Ammonium nitrate				0.54	9

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Ammonium nitrate		20–300	1,000 ton/year	0.65	12
Ammonium nitrate	Ammonia, nitric acid	15–300	1,000 t/year	0.65	21
Ammonium nitrate				0.59	3
Ammonium nitrate	Ammonia (prilled)	66–434	1,000 ton/year	0.65	10
Ammonium phosphate				0.68	13
Ammonium phosphate				0.68	3
Ammonium sulfate		37–110	1,000 ton/year	0.65	4
Ammonium sulfate				0.68	13
Ammonium sulfate		30–300	1,000 ton/year	0.73	12
Ammonium sulfate	Ammonia, sulfuric acid (crystallized)	22–400	1,000 ton/year	0.67	10
Aromatics		3–365	1,000 ton/year	0.40	10
Aviation gasoline		44–493	1,000 ton/year	0.88	8
Benzene				0.61	9
Benzene				0.61	3
Benzene	Toluene, H_2 (Detol)	20–365	1,000 ton/year	0.73	10
BTX extraction	Reformer streams, e.g., Udex			0.70	13
Butadiene	Butylenes	16–164	1,000 ton/year	1.02	8
Butadiene		5–400	1,000 ton/year	0.65	4
Butadiene				0.59	9
Butadiene	Butane			0.70	13
Butadiene	Butylene			0.70	13
Butadiene		5–300	1,000 ton/year	0.65	15
Butadiene				0.65	17
Butadiene		20–200	1,000 ton/year	0.68	12
Butadiene	Butane; butylene	4–365	1,000 ton/year	0.63	10
Butanol		10–200	1,000 ton/year	0.40	12
Butanol	Propylene	11–365	1,000 ton/year	0.48	10
Butanol	Butylene	2–40	1,000 ton/year	0.69	10
Butyl alcohol	*n*-butanol	4–350	1,000 ton/year	0.55	4
Butyl alcohol				0.55	9
Butyl alcohol		0.4–350	1,000 ton/year	0.55	15
Butyl alcohol				0.55	17
Butyl alcohol		2–30	1,000 ton/year	0.78	12

Butyl alcohol				0.50	3
Caprolactam	Cyclohexane, NH_3 (ammonium sulfate by-product)	19–150	1,000 ton/year	0.52	10
Carbon black		0.4–55	1,000 ton/year	0.53	15
Carbon black		20–200	1,000 ton/year	0.70	12
Carbon black				0.70	3
Carbon black	Aromatic oils; gas	16–365	1,000 ton/year	0.67	10
Carbon fibers		0.4–2	1,000 ton/year	0.85	10
Carbon tetrachloride	Propane, Cl_2 (perchlorethylene by-product)	5–58	1,000 ton/year	0.48	10
Catalytic polymerization				0.70	17
Catalytic polymerization of refinery gas		7–80	1,000 ton/year	0.66	8
Caustic		4–300	1,000 ton/year	0.38	4
Caustic				0.35	9
Caustic				0.38	17
Caustic				0.40	3
Cement				0.86	16
Cement		140–6,850	Barrels/day	1.00	10
Chlorine	Electrolytic	5–300	1,000 ton/year	0.38	4
Chlorine	Electrolytic			0.35	9
Chlorine		4–292	1,000 ton/year	0.62	15
Chlorine				0.38	17
Chlorine				0.62	16
Chlorine		20–200	1,000 ton/year	0.45	12
Chlorine	Brine electrolysis			0.83	5
Chlorine				0.40	3
Chlorine	Electrolytic			0.75	14
Chlorine		3–350	1,000 ton/year	0.44	6
Chlorine	NaCl brine (electrolysis; caustic soda by-product)	37–365	1,000 ton/year	0.47	10
Chlorine/caustic	NaOH			0.69	13
Clay treating	Contact			0.53	14
Clay treating	Percolation, including regeneration			0.55	14

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
CO and CO_2 removal from hydrogen				0.74	17
CO and CO_2 removal from hydrogen				0.74	14
Coke-oven gas separation				0.82	17
Coke-oven gas separation				0.82	14
Coking (delayed)				0.58	9
Coking (delayed)		2–50	1,000 barrel/day	0.38	12
Coking (delayed)				0.45	3
Coking (delayed)		3–58	1,000 barrel/day	0.42	10
Coking (delayed) of petroleum		102–657	1,000 ton/year	0.73	8
Coking (fluid bed)		3.8–71	1,000 barrel/day	0.64	10
Coking (fluid)		3–50	1,000 barrel/day	0.42	12
Coking (old data)				0.72	14
Coking (recent)				0.81	14
Coking only				0.72	17
Cooling towers				0.64	14
Cracking	Ortho flow; general; air-lift Thermofor catalytic cracking (TCC)	1–65	1,000 barrel/day	0.49	10
Cracking	Hydro; fluid catalytic cracking (FCC)	2–76	1,000 barrel/day	0.53	10
Cracking	Visbreaking	1–65	1,000 barrel/day	0.54	10
Cracking	Thermal	2–68	1,000 barrel/day	0.65	10
Cracking (catalytic)	Thermofor	33–584	1,000 ton/year	0.71	8
Cracking (catalytic)		135–1,132	1,000 ton/year	0.81	8
Cracking (catalytic)	Topping feed preparation, gas recovery, polymerization	270–5,658	1,000 ton/year	0.88	8
Cracking (catalytic)	Air-lift Thermofor catalytic cracking	2–40	1,000 barrel/day	0.55	12
Cracking (catalytic)	Fluid	2–50	1,000 barrel/day	0.70	12
Cracking (catalytic)	Orthoflow	2–50	1,000 barrel/day	0.55	12
Cracking (catalytic)				0.55	3
Cracking (catalytic)				0.83	14

Cracking (catalytic), complete refinery				0.85	17
Cracking (catalytic), only				0.78	17
Cracking (hydro)	With compression	2–30	1,000 barrel/day	0.50	12
Cracking (thermal)		51–767	1,000 ton/year	0.62	8
Cracking (thermal)		37–208	1,000 ton/year	0.48	8
Cracking (thermal)		2–40	1,000 barrel/day	0.70	12
Cracking (thermal, two-coil)				0.79	14
Cracking (thermal, also reforming)				0.51–0.70	14
Cracking (topping and thermal)		172–5,658	1,000 ton/year	0.60	8
Cracking (two coil crude oil)		88–1,716	1,000 ton/year	0.82	8
Cracking, only	Thermal			0.51	17
Cyclohexane				0.70	13
Cyclohexane		20–200	1,000 ton/year	0.50	12
Cyclohexane				0.60	3
Cyclohexane				0.70	22
Cyclohexane	Benzene, H_2	15–365	1,000 ton/year	0.49	10
Desalting crude oil				0.60	14
Desulfurization (catalytic, old)				0.80	14
Desulfurization of gases				0.41	14
Desulfurization of gasoline (catalytic)		5–25	1,000 ton/year	0.81	8
Desulfurizing	Hydrotreating	2–46	1,000 barrel/day	0.64	10
Desulfurizing	Sweetening	5–56	1,000 barrel/day	0.57	10
Desulfurizing	Gas oil desulfurization	3–31	1,000 barrel/day	0.78	10
Detergent alkalate	*n*-Paraffin	2–183	1,000 ton/year	0.64	10
Dicyandiamide		7–37	1,000 ton/year	0.43	4
Diethanolamine	Ethylene oxide, ammonia	2–26	1,000 ton/year	0.64	10
Dimersol, ethylene	Dimerization	1–11	1,000 ton/year	0.64	10
Distillation	Vacuum			0.80	17
Distillation	Vacuum flash			0.64	17
Distillation	Atmospheric	20–500	1,000 barrel/day	0.90	12
Distillation	Vacuum	20–500	1,000 barrel/day	0.70	12
Distillation	Vacuum (old data)			0.80	14
Distillation	Vacuum (recent)			0.57	14
Distillation	Vacuum flash (old data)			0.64	14
Distillation	Vacuum flash, large units			0.32	14

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Distillation	Vacuum flash, small units			0.41	14
Distillation	Vacuum	18–600	1,000 barrel/day	0.73	10
Distillation	Atmospheric	18–560	1,000 barrel/day	0.87	10
Distillation of crude oil	Vacuum flash	84–2,700	1,000 ton/year	0.58	8
Distillation of lube oil	Vacuum	17–730	1,000 ton/year	0.60	8
Dimethyl terephthalate	Grass-roots plant	33–365	1,000 ton/year	0.51	10
Ethane	Petroleum	10–190	Million std ft^3/day	0.65	10
Ethanol	Synthetic	1–100	1,000 ton/year	0.60	4
Ethanol	Synthetic			0.60	9
Ethanol	Ethylene by direct hydration or ethyl sulfuric acid			0.72	13
Ethanol	Synthetic	3–200	Million gal/year	0.60	15
Ethanol	Synthetic			0.60	17
Ethanol		2–20	1,000 ton/year	0.73	12
Ethanol	Synthetic			0.70	3
Ethylene	Refinery gas	12–70	1,000 ton/year	0.67	8
Ethylene		11–370	1,000 ton/year	0.71	4
Ethylene				0.58	9
Ethylene	Refinery gases or hydrocarbons			0.71	13
Ethylene		20–800	1,000 ton/year	0.72	15
Ethylene				0.71	17
Ethylene		20–200	1,000 ton/year	0.83	12
Ethylene				0.58	3
Ethylene	Refinery gases or hydrocarbons			0.71	22
Ethylene				0.86	14
Ethylene	Gas, naptha, gas oil, others	20–700	1,000 ton/year	0.85	10
Ethylene dichloride				0.71	13
Ethylene dichloride				0.71	3
Ethylene glycol				0.70	3
Ethylene glycol	Ethylene oxide	22–700	1,000 ton/year	0.59	10
Ethylene oxide				0.79	9
Ethylene oxide	Direct oxidation of ethylene			0.67	13

				0.67	13
Ethylene oxide				0.78	17
Ethylene oxide		20–200	1,000 ton/year	0.78	12
Ethylene oxide				0.78	3
Ethylene oxide	Ethylene	18–292	1,000 ton/year	0.80	10
Ethylene oxide (including glycol-manufacturing facilities)		2–100	1,000 ton/year	0.78	4
Fischer-Tropsch				0.79	1
Fischer-Tropsch (complete)				0.77	14
Flue gas desulfurization, catalytic oxidation	2.5% Sulfur coal			0.73	5
Flue gas desulfurization, catalytic oxidation	3.5% Sulfur coal			0.75	5
Flue gas desulfurization, double alkali	3.5% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.73	5
Flue gas desulfurization, double alkali	3.5% Sulfur Eastern coal, 90% SO_2 removal			0.74	5
Flue gas desulfurization, double alkali	7.0% Sulfur Eastern coal, 90% SO_2 removal			0.72	5
Flue gas desulfurization, lime slurry	2.5% Sulfur coal			0.72	5
Flue gas desulfurization, lime slurry	3.5% Sulfur coal			0.69	5
Flue gas desulfurization, lime slurry	3.5% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.74	5
Flue gas desulfurization, lime slurry	7.0% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.76	5
Flue gas desulfurization, lime slurry	3.5% Sulfur Eastern coal, 90% SO_2 removal			0.75	5
Flue gas desulfurization, lime slurry	7.0% Sulfur Eastern coal, 90% SO_2 removal			0.76	5
Flue gas desulfurization, lime slurry	0.8% Sulfur Western coal, 90% SO_2 removal			0.73	5
Flue gas desulfurization, lime slurry	0.8% Sulfur Western coal, 0.5 lb $SO_2/10^6$ Btu			0.72	5
Flue gas desulfurization, limestone slurry	2.5% Sulfur coal			0.72	5

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Flue gas desulfurization, limestone slurry	3.5% Sulfur coal			0.69	5
Flue gas desulfurization, limestone slurry	Rosebud coal, 90% sulfur removal			0.75	5
Flue gas desulfurization, limestone slurry	3.5% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.74	5
Flue gas desulfurization, limestone slurry	7.0% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.76	5
Flue gas desulfurization, limestone slurry	3.5% Sulfur Eastern coal, 90% SO_2 removal			0.74	5
Flue gas desulfurization, limestone slurry	7.0% Sulfur Eastern coal, 90% SO_2 removal			0.76	5
Flue gas desulfurization, limestone slurry	0.8% Sulfur Western coal, 90% SO_2 removal			0.75	5
Flue gas desulfurization, limestone slurry	0.8% Sulfur Western coal, 0.5 lb $SO_2/10^6$ Btu			0.73	5
Flue gas desulfurization, MgO slurry	2.5% Sulfur coal			0.69	5
Flue gas desulfurization, MgO slurry	3.5% Sulfur coal			0.69	5
Flue gas desulfurization, MgO slurry	3.5% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.67	5
Flue gas desulfurization, MgO slurry	3.5% Sulfur Eastern coal, 90% SO_2 removal			0.68	5
Flue gas desulfurization, MgO slurry	7.0% Sulfur Eastern coal, 90% SO_2 removal			0.71	5
Flue gas desulfurization, sodium solution	2.5% Sulfur coal			0.72	5
Flue gas desulfurization, sodium solution	3.5% Sulfur coal			0.70	5
Flue gas desulfurization, Wellman Lord	3.5% Sulfur Eastern coal, 1.2 lb $SO_2/10^6$ Btu			0.66	5
Flue gas desulfurization, Wellman Lord	3.5% Sulfur Eastern coal, 90% SO_2 removal			0.66	5

Flue gas desulfurization, Wellman Lord	7.0% Sulfur Eastern coal, 90% SO_2 removal			0.68	5
Formaldehyde				0.55	9
Formaldehyde		2–30	1,000 ton/year	0.55	12
Formaldehyde				0.55	3
Formaldehyde	Hydrocarbons, aqueous	2–68	1,000 ton/year	0.55	10
Formaldehyde	Methanol	16–365	1,000 ton/year	0.66	10
Formaldehyde (100%)		9–37	1,000 ton/year	0.56	4
Gas dehydration (field practice)				0.61	14
Gas processing	Recovery of light ends			0.52	10
Gas treating alone		13–250	1,000 std ft^3/day	0.75	10
Gas treating with liquids fractionation		20–610	1,000 std ft^3/day	0.75	10
Gas-cycling plants				0.69	14
Glycerin (synthetic)				0.67	13
Glycol		2–20	1,000 ton/year	0.75	12
Glycol	Ethylene, Cl_2	2–43	1,000 ton/year	0.79	10
Hydrochloric acid		2–30	1,000 ton/year	0.68	12
Hydrochloric acid				0.68	3
Hydrochloric acid	Salt, H_2SO_4 (Na_2SO_4 by-product)	2–330	1,000 ton/year	0.69	10
Hydrochloric acid (anhydrous 99.5%)		4–7	1,000 ton/year	0.60	4
Hydrochloric acid (water white)		18–47	1,000 ton/year	0.60	4
Hydrocyanic acid		4–8	1,000 ton/year	0.52	4
Hydrodesulfurization (recent)				0.57	14
Hydrodesulfurization of gases				0.75	14
Hydrofluoric acid		2–20	1,000 ton/year	0.70	12
Hydrofluoric acid	CaF_2, H_2SO_4	2–142	1,000 ton/year	0.72	10
Hydrofluoric acid (anhydrous)		4–18	1,000 ton/year	0.68	4
Hydrogen cyanide				0.71	9
Hydrogen cyanide				0.82	17
Hydrogen cyanide				0.71	3
Hydrogen cyanide	Propane, ammonia	1–42	1,000 ton/year	0.70	10
Hydrogen peroxide		20–200	1,000 ton/year	0.75	12
Hydrogen peroxide				0.75	3
Hydrogen peroxide	Isopropylene alcohol, O_2	15–365	1,000 ton/year	0.73	10

TABLE 2 *(continued)*

Product	Process	Size Range	Unit^a	Exponent	Reference
Hydrogen sulfide removal				0.55	14
Hydrogen sulfide removal from natural gas		8–365	1,000 ton/year	0.33	8
Hydrogenation stalls, vapor or liquid				0.32	14
Hydrotreating	Desulfurizing	2–40	1,000 barrel/day	0.65	12
Hypersorption		10–5,110	1,000 ton/year	0.42	8
Hypersorption				0.43	17
Hypersorption				0.43	14
Isomerization		2–40	1,000 barrel/day	0.65	12
Isomerization		18–50	1,000 barrel/day	0.64	10
Isoprene		14–150	1,000 ton/year	0.55	12
Isoprene	Propylene, methanol, O_2	18–365	1,000 ton/year	0.49	10
Isopropanol		3.8–120	Million gal/year	0.60	4
Isopropanol				0.60	9
Isopropanol				0.60	17
Isopropanol				0.60	3
Isopropanol	Propylene	20–263	1,000 ton/year	0.73	10
LP gas recovery in refineries				0.70	14
Lube		3–34	1,000 barrel/day	0.59	10
Lubricating oil manufacture				0.89	14
Magnesium	Ferrosilicon	4–33	1,000 ton/year	0.62	8
Maleic anhydride		4–9	1,000 ton/year	0.61	4
Maleic anhydride	Benzene	9–220	1,000 ton/year	0.48	10
Melamine	Dicyandiamide	5–55	1,000 ton/year	0.70	4
Methanol		0.018–110,000	Million ton/year	0.75	4
Methanol				0.83	9
Methanol	Natural gases			0.71	13
Methanol		5–100	Million gallon/year	0.83	15
Methanol				0.83	17
Methanol		20–250	1,000 ton/year	0.60	12
Methanol	Coal			0.79	5
Methanol				0.71	3
Methanol	Methane, CO, H_2	12–200	100,000 ton/year	0.78	10

Methyl chloride	Methanol			0.72	13
Methyl isobutyl ketone		7–40	1,000 ton/year	0.64	10
Natural gasoline		51–1,351	1,000 ton/year	0.51	8
Natural gasoline				0.51	17
Natural gasoline				0.73	14
Nitric acid		18–110	1,000 ton/year	0.55	4
Nitric acid				0.56	9
Nitric acid		20–200	1,000 ton/year	0.60	12
Nitric acid				0.58	3
Nitric acid				0.93	14
Nitric acid	Ammonia	18–365	1,000 ton/year	0.59	10
Nitric acid (50–60%)		37–365	1,000 ton/year	0.66	15
Oxoalcohols		20–200	1,000 ton/year	0.75	12
Oxoalcohols	Olefins, CO, H_2	18–365	1,000 ton/year	0.74	10
Paraxylene		2–20	1,000 ton/year	0.55	12
Paraxylene	(Crystallization)	2–40	1,000 ton/year	0.61	10
Peterson sulfuric acid towers				0.73	1
Peterson sulfuric acid towers				0.73	17
Peterson sulfuric acid towers				0.73	14
Phenol		13–110	1,000 ton/year	0.75	12
Phenol				0.75	3
Phenol	Benzene; toluene	9–365	1,000 ton/year	0.68	10
Phenol	Cumene	36–365	1,000 ton/year	0.72	10
Phosphoric acid				0.58	9
Phosphoric acid		2–20	1,000 ton/year	0.60	12
Phosphoric acid				0.60	3
Phosphoric acid	Phosphate rock, H_2SO_4	2–153	1,000 ton/year	0.56	10
Phosphoric acid (54% including concentration)		18–110	1,000 ton/year	0.63	4
Phosphoric acid (as P_2O_5)				0.66	13
Phosphorus	Phosphate rock, electricity, coke	36–365	1,000 ton/year	1.06	10
Phthalic anhydride		20–150	1,000 ton/year	0.70	12
Phthalic anhydride	Naphthalene; *o*-xylene	21–365	1,000 ton/year	0.72	10
Polymerization		4–50	1,000 barrel/day	0.58	12
Polymerization		3–44	1,000 barrel/day	0.61	10
Polymerization, large plants				0.91	14

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Polymerization, small plants				0.73	14
Propane deasphalting		2–40	1,000 barrel/day	0.65	12
Propane deasphalting	Propane liquid extraction of vacuum distilled crudes	2–56	1,000 barrel/day	0.61	10
Propane dewaxing		2–30	1,000 barrel/day	0.45	12
Propane dewaxing	Propane addition, filtration, stripping of diesel, etc., oils	2–52	1,000 barrel/day	0.47	10
Propylene		3–30	1,000 ton/year	0.70	12
Propylene oxide	Chlorohydrin	25–60	1,000 t/year	0.90	21
Pulp: acid sulfite	Bleached with recovery	8–200	1,000 t/year	0.78	21
Pulp: acid sulfite	Bleached without recovery	8–200	1,000 t/year	0.86	21
Pulp: alkaline chemical (sulfite, sulfate, Kraft)	Softwood, bleached including recovery, as air dry pulp	8–200	1,000 t/year	0.87	21
Pulp: alkaline chemical (sulfite, sulfate, Kraft)	Unbleached nonintegrated	8–300	1,000 t/year	0.62	21
Pulp: alkaline chemical (sulfite, sulfate, Kraft)	Bleached nonintegrated	8–60	1,000 t/year	0.62	21
Pulp: chemomechanical	Cold caustic soda	8–65	1,000 t/year	0.70	21
Pulp: chemomechanical	Bleached	65–160	1,000 t/year	1.00	21
Pulp: ground wood	Unbleached	8–200	1,000 t/year	0.71	21
Pulp: semichemical	Bleached with recovery	8–65	1,000 t/year	0.72	21
Pulp: semichemical	Unbleached	65–160	1,000 t/year	1.00	21
Refinery, complete		9–120	1,000 barrel/day	0.86	10
Refinery, complete (including catalytic cracking)		281–5,658	1,000 ton/year	0.75	8
Refinery, large				0.67	14
Refinery, small				0.57	14
Reforming (catalytic)		2–50	1,000 barrel/day	0.60	12
Reforming (catalytic)				0.61	3
Reforming (catalytic)				0.62	14
Reforming, distillation		2–62	1,000 barrel/day	0.63	10
Soap		2–7	1,000 t/year	0.23	21
Sodium bicarbonate	Soda ash or NaOH; CO_2	28–153	1,000 ton/year	0.65	10
Sodium carbonate	Solvay process	60–200	1,000 t/year	0.55	21

Sodium carbonate (soda ash)	NaCl, CO_2 (Solvay)	36–365	1,000 ton/year	0.74	10
Sodium chlorate		15–60	1,000 t/year	0.66	21
Sodium hydroxide	Electrolysis of brine	3–300	1,000 t/year	0.38	21
Sodium hydroxide purification	Ammonia	14–120	1,000 ton/year	0.48	8
Solvent dewaxing				0.76	17
Solvent dewaxing		0.3–5	1,000 barrel/day	0.68	12
Solvent dewaxing				0.68	3
Solvent dewaxing				0.82	14
Solvent dewaxing of lube oil		230–3,431	1,000 ton/year	0.74	8
Solvent extraction				0.73	14
Solvent extraction of lube oil		34–548	1,000 ton/year	0.68	8
Solvent extraction of lube oil		1–13	1,000 barrel/day	0.66	10
Solvent extraction or treating				0.67	17
Sour gas treating	With sulfur recovery and liquids fractionation	20–615	1,000 std ft^3/day	0.84	10
Styrene		18–110	1,000 ton/year	0.53	8
Styrene		2–100	1,000 ton/year	0.68	4
Styrene				0.68	9
Styrene		4–200	1,000 ton/year	0.68	15
Styrene				0.68	17
Styrene		20–200	1,000 ton/year	0.80	12
Styrene	Benzene, ethylene	20–400	1,000 t/year	0.67	21
Styrene				0.67	3
Styrene				0.65	14
Styrene	Benzene, ethylene, steam	19–365	1,000 ton/year	0.56	10
Sulfur		3–30	1,000 ton/year	0.65	12
Sulfur	H_2S			0.65	3
Sulfur	H_2S			0.64	14
Sulfur	H_2S, package plants			0.40	14
Sulfur	H_2S-containing gas	2–78	1,000 ton/year	0.71	10
Sulfuric acid	Contact, smelter gas	15–215	1,000 ton/year	0.91	8
Sulfuric acid	Contact, sulfur	7–256	1,000 ton/year	0.63	8
Sulfuric acid	Contact	18–365	1,000 ton/year	0.70	4
Sulfuric acid	Contact			0.67	13
Sulfuric acid	Contact			0.62	9
Sulfuric acid	Contact			0.64–0.66	17
Sulfuric acid	Chamber			0.60	17

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Sulfuric acid				0.90	17
Sulfuric acid				0.67	16
Sulfuric acid		20–500	1,000 ton/year	0.65	12
Sulfuric acid				0.65	3
Sulfuric acid	Contact			0.66	14
Sulfuric acid	Akylation acid			0.89	14
Sulfuric acid	Sulfur	35–365	1,000 ton/year	0.56	10
Sulfuric acid (100%)		37–365	1,000 ton/year	0.67	15
Sulfuric acid, general				0.78	14
Sweetening		2–30	1,000 barrel/day	0.65	12
Thiourea dioxide		1–4	1,000 ton/year	0.64	10
Titanium dioxide		4–37	1,000 ton/year	0.61	4
Titanium dioxide	Rutile ore, H_2SO_4	7–102	1,000 ton/year	0.89	10
TNT		91–303	1,000 ton/year	1.01	8
Toluene diisocyanate	Phosgene	4–32	1,000 ton/year	0.64	10
Topping				0.64	14
Topping (atmospheric crude oil)		95–1,898	1,000 ton/year	0.62	8
Topping (old data)				0.58–0.67	14
Topping (recent)				0.62	14
Topping of crude oil		28–1,460	1,000 ton/year	0.52	8
Urea		37–110	1,000 ton/year	0.70	4
Urea				0.59	
Urea		37–91	1,000 ton/year	0.67	15
Urea		20–200	1,000 ton/year	0.70	12
Urea				0.68	3
Urea				0.93	14
Urea	Ammonia, CO_2	20–365	1,000 ton/year	0.64	10
Vinyl acetate		30–300	1,000 ton/year	0.65	12
Vinyl acetate				0.65	3
Vinyl acetate	Ethylene	20–365	1,000 ton/year	0.65	10
Vinyl chloride		20–200	1,000 ton/year	0.80	12
Vinyl chloride				0.80	3
Vinyl chloride	Ethylene, Cl_2 or HCl	27–365	1,000 ton/year	0.88	10
Visbreaking		3–40	1,000 barrel/day	0.60	12

Water-gas				0.81	1
Water-gas				0.81	17
Water-gas manufacture				0.81	14
Water-gas shift conversion				0.69	17
Water-gas shift conversion				0.69	14
Gas processes					
Air, nitrogen, liquid		27–1,716	1,000 ton/year	0.66	10
Argon	Air, liquefied	1–17	1,000 std ft^3/h	0.89	10
Argon, hydrogen, liquid		0.4–15	1,000 ton/year	0.66 (estimated)	10
Carbon dioxide		18–110	1,000 ton/year	0.67	4
Carbon dioxide				0.72	10
Carbon dioxide, liquid		34–400	1,000 ton/year	0.72	10
Hydrogen	Natural gas	1–10	Million std ft^3/day	0.57	4
Hydrogen	Natural gas	10–50	Million std ft^3/day	0.68	4
Hydrogen				0.80	13
Hydrogen	Refinery gases	0.5–10	Million std ft^3/day	0.64	15
Hydrogen		20–200	1,000 ton/year	0.70	12
Hydrogen				0.75	3
Hydrogen		0.5–20	1,000 std ft^3/day	0.56	6
Hydrogen	Methane; partial oxidation; reforming	6–200	1,000 ton/year	0.65	10
Hydrogen, steam hydro				0.72	14
Natural gas (liquefied)	Tealarc process	365–8,000	1,000 ton/year	0.68	10
Natural gas (synthetic)	Coal	2–1,000	Million std ft^3/day	0.75	10
Oxygen		7–365	1,000 ton/year	0.56	4
Oxygen				0.64	9
Oxygen				0.71	13
Oxygen		0.4–548	1,000 ton/year	0.72	15
Oxygen				0.59	17
Oxygen				0.70	17
Oxygen				0.72	16
Oxygen				0.68	3
Oxygen				0.65	14
Oxygen	Air (liquefied)	14–365	1,000 ton/year	0.59	10
Oxygen (low purity)		11–548	1,000 ton/year	0.47	8
Oxygen (low purity)		27–438	1,000 ton/year	0.59	8
Oxygen (low purity)		11–694	1,000 ton/year	0.57	8

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Oxygen (low purity)				0.58	1
Oxygen (small)				0.47	17
Oxygen, liquid		200–1,100	1,000 ton/year	0.37	10
Polymer processes					
Cis-polybutadiene				0.67	13
GR-S copolymer		252–164	1,000 ton/year	0.82	8
GR-S synthetic rubber				0.63	14
Polycarbonate		8–146	1,000 ton/year	0.79	10
Polyethylene		2–20	1,000 ton/year	0.65	12
Polyethylene	Ethylene	16–365	1,000 ton/year	0.65	10
Polyethylene (high pressure)		3–90	1,000 ton/year	0.67	4
Polyethylene (high pressure)				0.90	9
Polyethylene (high pressure)				0.70	13
Polyethylene (high pressure)				0.67	17
Polyethylene (high pressure)				0.71	3
Polyethylene (low pressure)		3–70	1,000 ton/year	0.90	4
Polyethylene (low pressure)				0.67	9
Polyethylene (low pressure)				0.70	13
Polyethylene (low pressure)				0.90	17
Polyethylene (low pressure)				0.69	3
Polyisoprene (including manufacture of the monomer)				0.74	13
Polypropylene		2–20	1,000 ton/year	0.70	12
Polypropylene				0.70	3
Polypropylene	Propylene	16–365	1,000 ton/year	0.62	10
Polypropylene	Gas, naphtha, gas oil	16–365	1,000 ton/year	0.74	10
Polystyrene	Styrene	5–112	1,000 ton/year	0.53	10
Polyvinyl chloride (PVC)		2–20	1,000 ton/year	0.60	12
Polyvinyl chloride (PVC)	Ethylene, Cl	6–237	1,000 ton/year	0.82	10
Biotechnology processes					
Brewing				0.60	18
Ethanol	Fermentation	1–105	Million gallon/year	0.90	10
Fructose, crystalline		4–57	1,000 ton/year	0.64	10
Fructose, syrup		59–365	1,000 ton/year	0.64	10

Single-cell protein				0.70–0.80	19
Soybean extraction				0.70	1
Soybean extraction				0.70	17
Soybean extraction				0.70	14
Sugar	Sugarcane; operates 120 days/yr	6–30	1,000 t/year	0.41	21
Power plants, effluent treatment, drinking water, refrigeration and utilities					
Activated sludge		1–100	100,000 gal/day	0.84	6
Desalinization	Multistage flash distillation, electrodialysis, reverse osmosis	1–103	Million gal pure water/day	0.89	10
Desalinization	Vertical tube evaporators	8,000–110,000	Million gal pure water/day	0.82	10
Municipal incinerator				0.80	16
Power	Coal	100–1,000	Megawatts	0.88	15
Power	Nuclear	100–4,000	Megawatts	0.68	15
Power	Fossil fuel			0.79	16
Power	Nuclear			0.68	16
Power		0.71–18.5	1,000 kVA	0.75	12
Power		2,000–20,000	Kilowatt-hours	0.88	14
Power	Oil field	20–200	Kilowatt-hours	0.50	14
Power	Refuse to energy	8–630	Megawatts	0.75	10
Power	Cogeneration	5–630	Megawatts	0.75	10
Refrigeration (including auxiliaries)				0.85–0.96	17
Refrigeration (including auxiliaries)				0.85–0.96	14
Refrigeration (no auxiliaries)				0.80–0.82	17
Refrigeration (no auxiliaries)				0.81	14
Refrigeration, centrifugal				0.68	14
Sewage treatment (primary and secondary)				0.75	16
Sewage treatment (primary only)				0.68	16
Steam boiler				0.75	16
Steam boiler (field erected)		50–1,200	1,000 lb/h	0.80	12
Steam boiler (package)		19–720	1,000 lb/h	0.72	12
Steam generation, indoor				0.66	14
Steam generation, large, 1,000 psi				0.81	14

TABLE 2 *(continued)*

Product	Process	Size Range	Unit[a]	Exponent	Reference
Steam generation, large, 200 psi				0.61	14
Steam generation, outdoor				0.61	14
Steam generation, package units				0.61	14
Steam generation, refinery (no auxiliaries)				0.72	14
Wastewater or sewage treatment	Carbon adsorption sewage treatment	0.1–100	1,000 gal/min	0.64	10
Wastewater or sewage treatment	Reverse osmosis	0.1–10	1,000 gal/min	0.79	10
Wastewater or sewage treatment	Demineralization	0.1–11	1,000 gal/min	0.65	10
Water (drinking) preparation	Desalinization	0.1–0.8	1,000 gal/min	0.89	10
Water (drinking) preparation	Standard treatment	0.1–19	1,000 gal/min	0.65	10
Water (drinking) preparation	Pumping, clarification	0.2–100	1,000 gal/min	0.74	10
Water treating				0.91	17
Miscellaneous processes					
Industrial building				0.67	16
Pipelines (cost versus diameter squared)				0.72	14
Public housing project			Number of rooms	0.75	16
Steel	Integrated	150–4,000	1,000 t/year	0.65	21

[a] t/year = metric tons per year.

Exponents tend to be higher if the process involves equipment designed for high pressure or is constructed of expensive alloys. As R approaches 1, cost becomes a linear function of capacity: that is, doubling the capacity doubles the cost. The value of R may also approach 1 if product lines will be duplicated rather than enlarged. Although a small plant may require only one reactor, a much larger plant may need two or more operating in parallel.

Large-capacity extrapolations must be done carefully because the maximum size of single-train process plants may be restricted by the equipment's design and fabrication limitations. For example, single-train methanol synthesis plants are now constrained mainly by the size of centrifugal compressors. Costs must also be scaled down carefully from very large to very small plants because much of the equipment (such as computers and instruments) cost about the same regardless of plant size.

Despite these shortcomings, the R factor method represents a fast, easy, and reliable way of arriving at cost estimates at the predesign stage. It is helpful for looking at the effect of plant size on profitability when doing discounted cash-flow–rate of return and payback-period calculations. It is also very useful for making an economic sensitivity analysis involving a large number of variables.

All the R values in Table 2 average 0.67, with a standard deviation of 0.13. The R values for chemical plants and processes alone also average 0.67, with a standard deviation of 0.13. All of the averages are summarized in Table 3. Guthrie's average for 40 plants was 0.64 [12] and Chilton's for 36 plants was 0.68 [8], both of which are close to 0.67. These average values can be used for ballpark estimates when no other data are available.

With an R average of 0.67, doubling the size of a plant increases its cost about 60%, and tripling the size boosts its cost by about 110%, which is close to the 50 and 100% costs by the rules of thumb mentioned earlier. Also, for an R value of 0.67, and a size ratio of 5, the cost triples. Increasing the size by a factor of 10 inflates cost almost fivefold.

Traditionally, when a specific value of R is not known, 0.6 is often used for equipment and 0.7 for chemical processes. However, errors may arise if the actual value is not close to 0.6 or 0.7. Table 4 shows the errors that

TABLE 3 Average R Values Classified by Type of Process Industry from Table 2

Industry	Average R	Standard Deviation
All values in Table 2	0.67	0.13
Chemical plants and processes	0.67	0.13
Gases	0.65	0.10
Polymers	0.72	0.10
Biotechnology	0.67	0.13
Power plants, effluent treatment, drinking water, refrigeration and utilities	0.75	0.10
Miscellaneous	0.70	0.05

TABLE 4 Potential Errors (%) from Using 0.6 or 0.7 as Cost-Capacity Factors

	Actual R Value								
Scaleup	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Error using 0.6									
2 Times	38	23	15	7	0	−7	−13	−19	−24
5 Times	90	62	38	17	0	−15	−28	−38	−47
10 Times	151	100	58	26	0	−21	−37	−50	−60
Error using 0.7									
2 Times	41	38	23	15	7	0	−7	−13	−19
5 Times	124	90	62	38	17	0	−15	−28	−38
10 Times	216	151	100	58	26	0	−21	−37	−50

occur when 0.6 and 0.7 are used instead of actual values. For example, if R is assumed to be 0.7 when it actually is 0.9, the error is 28% for a fivefold scaleup. Thus, it is advisable to use the average value of 0.67 rather than 0.7 if a reliable value is not available.

Application Examples

The first example illustrates using an R factor to estimate the cost of a large plant when the cost of a similar, but smaller, plant is known. A plant that produces 200,000 ton/year of ammonium nitrate was built at a cost of \$7,100,000. Estimate the cost of a similar plant that will produce 350,000 ton/year.

From Table 2, the most recent R value for the plant is 0.65. Via Eq. (1):

$$C_2 = \$7{,}100{,}000 \left(\frac{350{,}000}{200{,}000}\right)^{0.65}$$

$$= \$10{,}200{,}000$$

The second example demonstrates the use of an R factor to calculate the cost of a new high-capacity plant when the cost of an older plant is known. In 1984, a methanol plant was constructed at a cost of \$249,000,000 (that year, the *Chemical Engineering* plant cost index averaged 323). It produces methanol at 6,000,000 ton/year. What will be the cost of building a similar plant in 1990 that will produce 15,000,000 ton/year? The latest available figure for the plant cost index is 357 for December 1989.

From Table 2, the most recent R value for the plant is 0.78. Via Eq. (3),

$$C_2 = \$249{,}000{,}000 \left(\frac{15{,}000{,}000}{6{,}000{,}000}\right)^{0.78} \left(\frac{357}{323}\right)$$

$$= \$562{,}000{,}000$$

Much of this article was excerpted by special permission from *Chemical Engineering,* April 1990, copyright © 1990 by McGraw-Hill, Inc., New York, New York 10020.

References

1. R. S. Aries and R. D. Newton, *Chemical Engineering Cost Estimation,* McGraw-Hill, New York, 1955.
2. G. T. Austin, *Shreve's Chemical Process Industries,* 5th ed., McGraw-Hill, New York, 1984.
3. O. Axtell and J. M. Robertson, *Economic Evaluation in the Chemical Process Industries,* Wiley, New York, 1986.
4. H. C. Bauman, *Fundamentals of Cost Engineering in the Chemical Industry,* Reinhold, New York, 1964.
5. J. H. Black, *Cost Engineering Planning Techniques for Management,* Marcel Dekker, New York, 1984.
6. L. T. Blank and A. J. Tarquin, *Engineering Economy,* McGraw-Hill, New York, 1989.
7. N. Boyd, "Cost and Price Indices," *Eng. Costs Production Economics,* pp. 247–258 (December 14, 1988).
8. C. H. Chilton, "Six Tenths Factor," *Chem. Eng.,* pp. 112–114 (April 1950).
9. J. T. Gallagher, "Rapid Estimation of Plant Costs," *Chem. Eng.,* pp. 89–96 (December 18, 1967).
10. D. E. Garrett, *Chemical Engineering Economics,* Reinhold, New York, 1989.
11. D. W. Green, *Perry's Chemical Engineers' Handbook,* 6th ed., McGraw-Hill, New York, 1984.
12. K. M. Guthrie, *Process Plant Estimating Evaluation and Control,* Craftsman Book Co., Solana Beach, California, 1974.
13. J. E. Haselbarth, "Updated Investment Costs for 60 Types of Chemical Plants," *Chem. Eng.,* pp. 214–215 (December 4, 1967).
14. K. K. Humphreys and P. Wellman, *Basic Cost Engineering,* 2nd ed., Marcel Dekker, New York, 1987.
15. F. C. Jelen, *Cost and Optimization Engineering,* McGraw-Hill, New York, 1970.
16. W. R. Park, *Cost Engineering Analysis,* Wiley, New York, 1973.
17. H. Popper, *Modern Cost Engineering Techniques,* McGraw-Hill, New York, 1970.
18. C. F. Pratten, *Economies of Scale in Manufacturing Industry,* Cambridge University Press, London, 1971.
19. P. F. Stanbury and A. Whitaker, *Principles of Fermentation Technology,* Pergamon Press, Oxford, 1984.
20. R. Williams, "Six-Tenths Factor," *Chem. Eng.,* pp. 124–125 (December 1947).
21. D. R. Woods, *Financial Decision Making in the Process Industry,* Prentice-Hall, Englewood Cliffs, NJ, 1975.
22. J. R. Couper and W. H. Radar, *Applied Finance and Economic Analysis for Scientists and Engineers,* Reinhold, New York, 1986.

DONALD S. REMER
LAWRENCE H. CHAI