1-1-1993

Process Equipment, Cost Scale-up

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Obtaining corporate approval for new equipment or estimating detailed costs for a new plant often require that ball-park costs be calculated quickly for different types of hardware during both predesign and design phases. One easy method of developing such estimates is to base them on a known cost for the type of equipment and the ratio of the capacities for the known equipment and the desired equipment, raised to a factor R. This method, often referred to as the 0.6 power factor model, was first applied to equipment cost estimates by Williams in 1947 and then to plant costs by Chilton in 1950.

Determination of *R* Values

The relationship between cost and capacity is given by the equation

$$\frac{\text{cost}_2}{\text{cost}_1} = \left(\frac{\text{size}_2}{\text{size}_1}\right)^R$$

A plot of the ratios on a log-log scale produces a straight line. R values for equipment have a larger range than for entire process plants, for which the values tend to be averaged out by the large variety of equipment.

R Values

The tables in this article summarize R values for many types of equipment. Individual equipment cost information can be used to generate a more accurate cost estimate for an entire plant rather than using a single R value for the entire facility. The R factor cost-estimating approach is especially useful when doing a "sensitivity analysis," for which a high degree of accuracy is not required.

Through an extensive literature search, R values were found for the different types of equipment listed here:

General equipment, Table 1
Heat exchangers, Table 2
Fluid-moving equipment (blowers, compressors, fans, and pumps), Table 3
Tanks, vessels, and towers, Table 4
Environmental equipment, Table 5
Nonequipment (including catalysts/chemicals, engineering procurement fees, labor, services, and utilities), Table 6

When multiple R values for the same process were found, as was the case for filters, we list them in chronological order. Also shown are the ranges over which the values are applicable and the units for the values when known. When we found that a more recent source obtained all their R values from an earlier source, the original source is cited, if it could be located.

In looking at some of the R cost factors, some discrepancies in published factors are apparent as a result of variations in definition, scope, and size. Technology has also advanced over time, making it cheaper to produce larger machinery now than in years past. In addition, new regulations dictate expenditures for environmental control and safety not included in earlier equipment.

TABLE 1 General Equipment

Equipment	Size Range	Exponent	Reference No.
Absorber and mist eliminator		0.90	10
Aerobic digester	0.2–40 million gal/day	0.14	2
Agitators, carbon or stainless steel	1–30 hp	0.54	3
Agitators, propeller		0.50	7
Agitators, turbine		0.30	7
Agitators, surge tank		0.50	10
Agitators, propeller		0.50	4
Agitators, turbine		0.30	4
Air compressors		0.28	7
Air driers		0.56	7
Ball mills		0.75	7
Blenders, twin-cone, 304 stainless steel	60–600 ft^3	0.57	3
Blenders		0.78	7
Blenders, double cone rotary, carbon steel	50–250 ft^3	0.49	14
Blenders, solid mixing		0.55	1
Catalyst sifter		0.55	10
Cation-exchange column		0.73	13
Centrifuges, horizontal basket		1.16	7
Centrifuges, vertical basket		1.00	7
Centrifuges, bird solid bowl		0.38	7
Centrifuges, sharpless super D		0.68	7
Centrifuges, solid bowl, carbon steel	10–100 hp drive	0.67	14
Centrifuges, basket type		1.00–1.25	4
Centrifuges		0.80	1
Centrifuges	40–60 in.	0.71	2
Civil works		0.65	9
Clarifier	0.1–100 million gal/day	0.98	2
Construction		0.61	9
Converters		0.90	10
Conveyors, belt, 12 in. width		0.80	12
Conveyors, belt, 18 in. width		0.85	12
Conveyors, belt, 24 in. width		0.90	12
Conveyors, screw, 4 in. diameter		0.90	12
Conveyors, screw, 12 in. diameter		0.83	12
Conveyors, screw, 20 in. diameter		0.73	12

TABLE 1 *(continued)*

Equipment	Size Range	Exponent	Reference No.
Conveyors		0.65	1
Cooling towers		0.60	4
Crushers, cone		0.85	7
Crushers, gyratory		1.20	7
Crushers, jaw		1.20	7
Crushers, pulverizers		0.35	7
Crystallizers, growth		0.63	7
Crystallizers, forced circulation		0.58	7
Crystallizers, forced batch		0.62	7
Crystallizers, vacuum batch, carbon steel	500–7,000 ft^3	0.37	14
Crystallizers		0.65	4
Driers, pan		0.69	7
Driers, rotary vacuum		0.55	7
Driers, drum		0.62	7
Driers, drum, single vacuum	10–100 ft^2	0.76	14
Driers, drum, single atmospheric	10–100 ft^2	0.40	14
Driers		0.45–0.50	4
Driers, drum		0.38	1
Driers, rotary		0.80	1
Driers, spray		0.22	1
Driers, spray		0.71	13
Driers	15–400 ft^2	0.71	2
Economizers		0.80	10
Ejectors		0.45–0.55	4
Ejectors, steam jet		0.52	1
Electrics		0.70	9
Evaporators, long tube, cast iron, copper heating surfaces		0.49	12
Evaporators, long tube, rubber-lined and lead construction		0.55	12
Evaporators, agitated, falling film		0.55	7
Evaporators, forced circulation		0.70	7
Evaporators, vertical tube		0.53	7
Evaporators, horizontal tube		0.53	7
Evaporators, jacketed vessel		0.50	7
Evaporators		0.50	9
Evaporators, installed, horizontal tank	100–10,000 ft^2	0.54	14

TABLE 1 *(continued)*

Equipment	Size Range	Exponent	Reference No.
Evaporators, conventional		0.55	4
Evaporators, forced circulation		0.70	4
Extruders, double screw, stainless	50–160 mm diameter	1.30	3
Extruders, single screw, stainless	2–6 in. diameter	1.09	3
Extruders, single screw, stainless	6–12 in. diameter	2.60	3
Filters, pressure leaf, cast iron, 2 in. spacing		0.63	12
Filters, pressure leaf, cast iron, 4 in. spacing		0.60	12
Filters, rotary vacuum, carbon steel and wood (less motors)		0.67	12
Filters, plates and press		0.58	7
Filters, pressure leaf, wet		0.49	7
Filters, pressure leaf, dry		0.44	7
Filters		0.60–0.65	4
Filters		0.57	1
Fluid bed calciners		0.60	10
Fluid bed dryers		0.60	10
Furnace heaters		0.70	9
Furnaces, process		0.85	6
Furnaces		0.80–0.85	4
Furnaces, process heaters		0.78	1
Gas holders (without foundations)		0.75	12
Generation of electricity		0.75	4
Grinders		0.65	4
Heaters, direct fired		0.85	6
Hoists		0.81	10
Instrumentation		0.60	9
Insulation and painting		0.65	9
Kettles, cast iron, jacketed	250–800 gal	0.27	14
Kettles, glass lined, jacketed	200–800 gal	0.31	14
Mills, ball		0.65	7
Mills, rollers		0.65	7
Mills, hammers		0.85	7
Mixers, propellers		0.58	7
Mixers, turbine		0.30	7
Motors, squirrel-cage, drip proof, 40°C		0.84	12
Motors, squirrel-cage, splash proof, 50°C		0.84	12
Motors, wound rotor, 40°C		0.66	12

TABLE 1 *(continued)*

Equipment	Size Range	Exponent	Reference No.
Motors		0.80	9
Motors, squirrel-cage, induction 440 V, explosion proof	5–20 hp	0.69	14
Motors, squirrel-cage, induction 440 V, explosion proof	20–200 hp	0.99	14
Motors		0.90–1.00	4
Package plants		0.75	9
Piping		0.70 0.90	9
Reactors, glass lined, jacketed (without drive)	50–600 gal	0.54	14
Reactors, stainless steel, 300 psi	100–1,000 gal	0.56	14
Reactors		0.65–0.70	4
Reactors	50–4,000 gal	0.74	2
Reactors (agitated)		0.45–0.50	4
Refrigeration units		0.70	4
Refrigeration units		0.72	1
Screens, vibrating single		0.56	7
Screens, vibrating double		0.58	7
Screens		0.58	10
Separators, centrifugal, carbon steel	50–250 ft^3	0.49	14
Separators, cyclone	20–8,000 ft^3/min	0.64	2
Size reduction equipment		0.60	1
Slakers, lime		0.57	10
Sludge drying beds	0.04–5 million gal/day	1.35	2
SO_2 absorbers		0.60	10
SO_2 reduction units		0.55	10
Soot blowers		1.00	10
Stabilization ponds	0.01–0.2 million gal/day	0.14	2
Steam ejectors		0.54	3
Steam generation		0.80	4
Structural steel		0.65	9
Tank heaters, steam coil		0.38	7
Tank heaters, immersions		0.88	7
TCA scrubbers		0.80	10
Trays		1.00	6
Trays, bubble cup, carbon steel	3–10 ft diameter	1.20	14
Trays, sieve, carbon steel	3–10 ft diameter	0.86	14
Turbines		0.70	9
Turboblowers, 3,500 rpm, 16 oz pressure		0.50	12
Waste heat boilers		0.67	10

TABLE 2 Heat-Exchange Equipment

Equipment	Size Range	Exponent	Reference No.
Air coolers		0.80	6
Air coolers		0.80	4
Air-cooled exchangers, carbon steel (24 ft tube)	300–1,500 ft^2	0.69	3
Air-cooled exchangers, stainless steel (24 ft tube)	300–1,500 ft^2	0.93	3
Exchangers, double pipe, carbon steel	30–1,500 ft^2	0.70	3
Exchangers, conventional		0.65	4
Exchangers, reboilers		0.50	4
Heat exchangers, shell and tube		0.65	6
Heat exchangers		0.65 0.95	9
Heat exchangers, shell and tube, floating head, carbon steel	100–400 ft^2	0.60	14
Heat exchangers, shell and tube, fixed sheet, carbon steel	100–400 ft^2	0.44	14
Heat exchangers, air cooled		0.80	1
Heat exchangers, shell and tube	Small	0.45	1
Heat exchangers, shell and tube	Large	0.75	1
Heat exchangers	500–3,000 ft^2	0.55	2

TABLE 3 Fluid-Moving Equipment

Equipment	Size Range	Exponent	Reference No.
Blowers, centrifugal	1,000–10,000 ft^3/min	0.59	14
Blowers, low head		0.63	1
Blowers	1,000–7,000 ft/min	0.46	2
Blowers		0.68	7
Centrifugal pumps, stainless steel, horizontal		0.70	12
Centrifugal pumps, cast iron, horizontal		0.67	12
Centrifugal pumps, cast iron, vertical		0.98	12
Compressors, process gas and drivers		0.82	6

TABLE 3 *(continued)*

Equipment	Size Range	Exponent	Reference No.
Compressors (including driver and gear)	70–5,000 hp	0.38	3
Compressors, reciprocating		0.75	9
Compressors, turboblowers		0.50	9
Compressors, reciprocating, air cooled, two-stage	10–400 ft^3/min	0.69	14
Compressors, rotary, single-stage, sliding vane	100–1,000 ft^3/min	0.79	14
Compressors		0.80–0.85	4
Compressors, centrifugal		0.40	1
Compressors, reciprocating		0.55	1
Compressors	200–2,100 hp	0.32	2
Fans		0.68	7
Fans, centrifugal	1,000–10,000 ft^3/min	0.44	14
Fans, centrifugal	20,000–70,000 ft^3/min	1.17	14
Pumps, positive displacement, carbon steel		0.70	12
Pumps, centrifugal and drivers		0.52	6
Pumps, reciprocating and drivers		0.70	6
Pumps		0.70–0.90	9
Pumps, reciprocating, horizontal, cast iron (includes motor)	2–100 gal/min	0.34	14
Pumps, centrifugal, horizontal, cast steel (includes motor)	1,000–10,000 gal/min × psi	0.33	14
Pumps, centrifugal		0.40–0.50	4
Pumps, reciprocating		0.60–0.70	4
Pumps		0.50	1
Pumps, centrifugal	10–200 hp	0.69	2

TABLE 4 Tanks, Vessels, and Towers

Equipment	Size Range	Exponent	Reference No.
Pressure vessels, vertical		0.65	6
Pressure vessels, horizontal		0.60	6
Pressure vessels, columns and reactors		0.65–0.70	4
Pressure vessels, tanks		0.60–0.65	4
Pressurized storage tanks, horizontal		0.65	4
Pressurized storage tanks, spherical		0.70	4
Storage tanks	5,000+ gal	0.30	4
Storage tanks	0–5,000 gal	0.65	4
Tanks, stainless steel		0.68	12
Tanks, carbon steel		0.44	12
Tanks, spherical, carbon steel		0.70	12
Tanks, rectangular		0.50	9
Tanks, spherical		0.70	9
Tanks, flat head, carbon steel	100–10,000 gal	0.57	14
Tanks, glass lined, carbon steel	100–1,000 gal	0.49	14
Tanks		0.60–0.65	4
Tanks, storage		0.52	1
Tanks, stainless	100–2,000 gal	0.67	2
Towers, carbon steel (constant diameter)		0.70	12
Towers, carbon steel (constant height)		1.00	12
Towers, packed, stainless	5–36 in. diameter	0.35	3
Towers, packed, stainless	36–100 in. diameter	0.85	3
Towers, bubble cap, carbon steel	36–100 in. diameter	0.86	3
Towers, bubble cap, stainless	36–100 in. diameter	0.52	3
Towers (constant diameter)		1.00	9
Towers (constant height)		0.70	9
Towers, carbon steel	1,000–2,000,000 lb	0.62	14
Towers		0.65–0.70	4
Towers	Under 5 ft diameter	0.35	1
Towers	Over 5 ft diameter	0.70	1
Vessels, process		0.50	1
Vessels and columns		0.65	9

TABLE 5 Environmental Equipment

Equipment	Size Range	Exponent	Reference No.
Filters, sand	0.5–200 million gal/day	0.82	2
Lagoons, aerated	0.05–20 million gal/day	1.13	2
Particulate scrubbers		0.60	10
Stacks, 24 in. carbon steel		1.00	7
Stacks, 36 in. carbon steel		1.00	7
Stacks, 48 in. carbon steel		1.00	7
Venturi scrubbers		0.60	10
Wastewater or sewage treatment, carbon adsorption	100–100,000 gal/min	0.64	5
Wastewater or sewage treatment, reverse osmosis	100–10,000 gal/min	0.79	5
Wastewater or sewage treatment, demineralization	100–11,000 gal/min	0.65	5

We advise using the more recent R data since it is not always clear how the R values were arrived at or what is included. Moreover, some of the values are rather old.

Average R values and the standard deviation by equipment category are

Values	*Average*	*Standard Deviation*
General equipment	0.68	0.27
Heat-exchange equipment	0.68	0.15
Fluid-moving equipment	0.63	0.19
Tanks, vessels, and towers	0.63	0.15
Environmental equipment	0.82	0.20

Using the average R value of 0.68, the rule of thumb is that doubling the size of a piece of equipment increases the cost by about 60% and tripling the size increases it by about 110%.

TABLE 6 Nonequipment Items

Item	Exponent	Reference No.
Catalysts and chemicals	1.00	9
Engineering and procurement fees	0.45	9
Labor hours	0.25	8
Services	0.38	11
Utilities	0.65	11

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Potential Errors

Traditionally, when a specific value is not known, an R value of 0.6 is often used for equipment and a value of 0.7 for chemical processes. Our study of 200 different chemical processes determined that the average R value for plants is 0.67 [15], which is close to the rule of thumb of 0.7 and also close to our average R value of 0.68, for 75 kinds of equipment. Significant errors may arise, however, if the actual R value is not close to 0.6 or 0.7. For example, if one assumed an R value of 0.6 and the actual value was 0.9, then calculations would be off by 38% if one was scaling up by a factor of 5.

Because we found an average R value of 0.68, it may be better to use 0.68 instead of 0.6 if there are no published values for the equipment of interest. Indeed, the so-called six-tenths rule should probably be called the "seven-tenths rule."

Please note that this estimating method gives only the purchase price of the equipment; additional installation costs for labor, foundations, and construction expenses make the final cost much higher. Installation costs typically vary from 25 to 55% of the purchased equipment cost but may go as high as 90%.

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Process Equipment, Fugitive Emissions, Estimation

(see also Fugitive Emissions, Economics; Emissions, Fugitive)

The U.S. Environmental Protection Agency (EPA) has defined equipment-leak fugitive emissions as emissions from such sources as pumps, valves, flanges, compressors, open-ended lines, pressure relief devices, and sample connection systems. At some plants, 70–90% of the air emissions have been estimated to be the result of fugitive emissions.

Plants must calculate these emissions for reports required by Title III of the Superfund Amendments and Reauthorization Act (SARA Title III) for new source permitting and, in some cases, for state emission inventories. Furthermore, regulatory agencies will base future regulations on the amount of fugitive emissions calculated and on the projected impact of these emissions on the community.

To estimate fugitive emissions, plants can use a variety of methods, including SOCMI factors [developed by EPA as averages for the synthetic organic chemicals manufacturing industry (SOCMI)], leak/no-leak factors, stratified factors, EPA correlation curves, and process-specific curves. Depending on the complexity of the method, testing may be involved. Testing, which consists of screening or bagging (or both) of equipment, can improve the emissions estimates from a plant and provide insight into how to reduce emissions from equipment. Generally, the more detailed and accurate the estimating method selected, the more it costs.

A strategy flowchart developed by the Chemical Manufacturers Association (CMA; Fig. 1) puts the different methods into perspective and summarizes some of the decision criteria. Basically, the approach involves first using the simplest technique, SOCMI emission factors, to estimate emissions