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MARKET GROWTH, ECONOMIES OF SCALE, AND PLANT SIZE IN THE CHEMICAL PROCESSING INDUSTRIES*

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What factors determine the size of new industrial plants? This study uses data on 22 chemical products to test alternative models of capacity expansion, including the Manne model and a "scale frontier" model. The empirical results strongly support the scale frontier model: the size of new plants increased along a time trend that was unrelated to market concentration, market growth, or the magnitude of investment scale economies. Entrants typically built smaller plants than incumbents, but all firms built plants closer to the technological frontier when small plants carried a higher relative cost penalty.

INTRODUCTION

IN INDUSTRIES with plant-level economies of scale, do firms undertake larger capacity expansions when industry growth is more rapid? Do new entrants tend to build smaller plants than incumbents? More generally, what factors influence the size of new plants and shifts in optimal plant size over time? This paper explores these issues and tests alternative models of capacity expansion.[1]

The analysis is based on a data sample covering 22 chemical products over a period of roughly 25 years. The sample includes a total of 422 plants that were constructed during the coverage period. The chemical industry provides an excellent focus for the empirical analysis, given the availability of plant capacity and engineering data and the existence of well-documented economies of scale at the plant level.

Two alternative models of capacity expansion are tested. The first is the classic model of capacity expansion originally developed by Alan Manne [1967]. This model, based on a trade-off between scale economies and capacity holding costs, implies that the optimal policy is to expand with a fixed cycle time between investment dates, so that expansion sizes are directly proportional to market growth. The alternative model, which has never been clearly formalized in the literature, suggests that although economies of scale are in principle available up to very large plant sizes, at any given point in time the maximum feasible scale is limited by technological constraints. With

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[1] This paper focuses on the *size* of new plants; related papers (Gilbert and Lieberman [1987], Lieberman [1987]) examine the *timing* of capacity expansion decisions.

technical progress over time, these constraints are gradually lifted, thereby allowing the construction of larger-scale plants.

The paper is organized as follows. Section I discusses the Manne model and its implications regarding the scale and timing of new plant capacity. Section II discusses the scale frontier model. Section III describes the data sample and the variables used in the empirical tests. Section IV tests the Manne and the scale frontier models. Section V considers a series of factors that might be expected to influence the movement of the scale frontier. A concluding section summarizes the empirical findings and appraises the models and the validity of their underlying assumptions.

I. MANNE MODEL

The classic model of capacity expansion with investment economies of scale is Manne [1967]. The model gives the cost minimizing investment policy for a single firm that must build new plants to service a growing demand. Given the assumptions of the model, the optimal policy is to allow a constant cycle time between investment dates. This implies that the capacity of each new plant equals the incremental demand growth between investment dates.

The assumptions of the basic model are as follows:

(1) Demand grows at a constant linear rate of G units per year.[2] Assuming a time interval of T years between successive expansions, plant size equals GT.

(2) The firm is required to service all demand—backlogs and deficits are not permitted.[3]

(3) The firm cannot adjust price to change the quantity demanded. Moreover, there is no price or quantity competition among producers.

(4) All expansions take the form of new plants—expansion of existing plants is not permitted.

(5) Capital investment costs are an exponential function of plant size, i.e.,

$$C(GT) = c_0(GT)^{\alpha}, \qquad \alpha < 1 \tag{1.1}$$

where $C(GT)$ represents the total plant investment cost, GT is the capacity of the plant, and α is the scale economy parameter. The model assumes that an infinite range of plant sizes are technically feasible, and scale economies are characterized by the parameter α over the entire range.[4]

(6) Plants have an infinite economic life (or equivalently, are replaced by an identical plant at the end of their life).

[2] The model yields similar results if demand growth is geometric (Srinivasan [1967]) or stochastic (Manne [1961]; Giglio [1970]).

[3] Allowing for backlogs and deficits leads to an increase in the optimal plant size and cycle time; however, the constant cycle time policy remains optimal. See Manne [1961] and Erlenkotter [1967].

[4] The exponential function provides a reasonably accurate representation of scale economies in many industries, at least within the range of existing plant sizes. See Haldi and Whitcomb [1967], and Chilton [1960].

(7) Operating costs (labor and materials) are constant per unit of output and independent of plant size. In other words, scale economies arise only in fixed investment costs. The average variable cost curve is horizontal up to the full production capacity of the plant.
(8) The opportunity cost of capital is constant at interest rate r.

Given the validity of these assumptions, choice of the optimal plant size involves trading off scale economies in capital investment against the cost of holding greater idle capacity during the early life of the plant. (In the absence of scale economies, expansion would take place in infinitely small increments.) The firm's optimal policy is to allow a constant cycle time between investment dates. If demand growth is arithmetic, this cycle time T, is given implicitly by the formula (Manne [1967]):

$$(1.2) \qquad \alpha = \frac{rT}{e^{rT}-1}$$

where α is the scale economy parameter and r is the interest rate. While this formula must be solved numerically, Freidenfelds [1981, p. 82] shows that:

$$(1.3) \qquad t = 2(1/r)(1/\alpha - 1)$$

provides a good approximation for the optimal cycle time between expansions.

A key result of the model is that this cycle time is independent of the growth rate of demand. This implies that the optimal plant size is proportional to the demand growth rate. The constant cycle time result is fairly robust to changes in the assumptions regarding demand growth or the nature of investment scale economies; it holds if demand grows at a constant geometric rate (Srinivasan [1967]), or if the investment cost function is characterized by an initial fixed cost plus a variable cost per unit of capacity (Freidenfelds [1981, pp. 73–81]).[5]

Optimal plant size equals optimal cycle time multiplied by G, the market growth rate faced by the firm. Unfortunately, data on output and output growth at the individual firm level are not publicly available. Thus, for the empirical work it is necessary to assume that the firm obtains some fraction of total industry output growth. If this fraction depends on the firm's pre-expansion share of industry capacity, the firm's output growth rate can be represented as:

$$(1.4) \qquad g = Q(\Delta Q/Q)S^{b_1}$$

where Q total is industry output and S is the capacity share of the firm.

New entrants have an initial capacity share of zero, so it is necessary to assign them some positive fraction of industry output growth. This is done by

[5] Although the model yields a unique optimum cycle time, the total discounted cost function is relatively flat over a wide range in the vicinity of the optimum. This means that deviations from the optimum cycle time (within a reasonable range) have only a small impact on total discounted costs.

arbitrarily setting S for new entrants equal to $1/(N+1)$, where N is the number of firms in the industry, and including an entry dummy to correct for the average bias introduced by this procedure. The firm's output growth thus becomes:

$$g = Q(\Delta Q/Q)S^{b_1}E^{b_2} \tag{1.5}$$

where E is the entry dummy.

Combining equations (1.3) and (1.5), the optimal plant size, K', is approximately equal to:

$$\begin{aligned} K' &\approx gt \\ &\approx 2Q(\Delta Q/Q)S^{b_1}E^{b_2}(1/r)(1/\alpha-1) \end{aligned} \tag{1.6}$$

Taking logs one obtains:

$$\begin{aligned} \log K' \approx c+\log Q+\log(\Delta Q/Q)+b_1\log S+b_2\log E \\ -\log r+\log(1/\alpha-1) \end{aligned} \tag{1.7}$$

A regression conforming to this specification for the Manne model is tested empirically in section IV. The model predicts a negative regression coefficient for the interest rate ($\log r$), and positive, unitary coefficients for market size ($\log Q$), market growth ($\log \Delta Q/Q$), and the degree of investment scale economies ($\log(1/\alpha-1)$).

II. SCALE FRONTIER MODEL

Several studies have noted that while scale economies are available in principle up to very large plant sizes, the construction of ever-larger plants typically requires the solution of numerous technical problems (Levin [1977]; Hughes [1971]; Cowing [1974]; Pearl and Enos [1975]; Hollander, [1965]; Sultan [1975]). In effect, there is a moving "scale frontier" that defines the largest economically feasible plant that can be constructed at any point in time. Technical progress in many capital intensive industries has taken the form of pushing out this scale frontier to exploit potential scale economies.

In a production function framework, movement in the scale frontier can be modeled as scale-augmenting technical change. Empirically, however, it is typically difficult to distinguish scale-augmenting change from other forms of non-neutral technical change (Lau and Tamura [1972]; Diamond, McFadden and Rodriguez [1978]; Sato [1970]). Consequently, the production function approach has not been particularly fruitful in this area, and the interpretation of results is often arbitrary.

There have been few attempts to model the scale frontier phenomenon theoretically. One notable exception is Levin [1978] who considers the effects of scale-augmenting technical change on barriers to entry and market structure. Levin assumes that the rate of advance depends solely on the research expenditures of each individual firm; different results would apply if the rate of advance is determined by the collective expenditures of all firms in the industry or by the research activities of outside firms. Levin's work thus raises an important (but empirically unresolved) question: is movement in the scale frontier exogenously determined, or is it influenced by endogenous factors such as R & D spending and market concentration?

While prior studies have documented the scale frontier phenomenon, they have failed to evaluate the mechanisms that advance the frontier. The rate of advance may be a function of time, or of investment in new capacity, or of resources devoted to process improvement. Given this lack of knowledge regarding the mechanisms that shift the scale frontier, we initially model the frontier as a simple geometric time trend. Let $K_{i,t}$ be the scale frontier at any time t, and b_0 be the rate of advance. The moving frontier can then be represented as:

$$(2.1) \qquad K_{i,t} = ce^{b_0 t} K_{i,t_0}$$

$$(2.2) \qquad \log K_{i,t} = c' + b_0 t + \log K_{i,t_0}$$

This formulation assumes that all firms will build their new plants at the prevailing scale frontier. Such behavior is consistent with cost minimization in a constrained version of the Manne model, where maximum feasible plant size is less than the optimal plant size given by the unconstrained model. However, even if the range of feasible plant sizes extends beyond the Manne optimum, competitive price adjustment may force all firms to build frontier-scale plants.

Furthermore, there are a number of reasons why firms may choose to build plants of less than frontier scale. New entrants may lack the construction and operating expertise needed to build and run frontier-scale plants and thus may opt for smaller, more proven designs. Entrants may build relatively small plants to avoid generating excess capacity that could trigger industry price cutting or retaliation by market incumbents. Entrants and vertically-integrated incumbents may simply lack outlets to market the entire output of large-scale plants.

Thus, one might expect plants of less than frontier size to be constructed by new entrants, or by incumbent firms facing marketing constraints. However, the extent of deviation from the frontier should depend upon the relative cost penalty associated with small scale plants. With a larger cost penalty, all plants would be built closer to the frontier.

These factors suggest the following more general formulation:

$$(2.3) \qquad \log K_{i,t} = c' + b_0 t + b_1 \log K_{i,t_0} + b_2 \,\textit{ENTRY} + b_3 \log CDR_i + \varepsilon$$

where $K_{i,t}$ represents the size of plants actually constructed, K_{i,t_0} is a benchmark plant size for year t_0, *ENTRY* is a dummy variable defined for new entry, CDR represents the relative cost disadvantage of small scale plants,

TABLE I
LIST OF PRODUCTS INCLUDED IN DATA SAMPLE

Acrylonitrile (1959–82)
Aniline (1961–82)
Ammonia (1960–82)
Bisphenol A (1959–82)
Caprolactam (1962–82)
Cyclohexane (1956–82)
Ethylene (1964–82)
Ethylene Glycol (1960–82)
Formaldehyde (1962–82)
Isopropyl Alcohol (1964–82)
Maleic Anhydride (1959–82)
Methanol (1957–82)
Nylon Fibers (1954–82)
Phenol (1959–82)
Phthalic Anhydride (1955–82)
Polyester Fibers (1954–82)
Polyethylene-LD (1958–82)
Polyethylene-HD (1958–82)
Styrene (1958–82)
Urea (1962–82)
Vinyl Acetate (1960–82)
Vinyl Chloride (1962–82)

and ε is a random error term. This is the regression specification tested empirically in section IV. We expect $b_0 > 0$ if new plant sizes increased over time, $b_2 < 0$ if entrants built smaller plants than incumbents, and $b_3 > 0$ if firms built plants closer to the scale frontier when small plants carried a relatively greater cost penalty.

III. DATA SAMPLE AND COMPUTATION OF VARIABLES

The data sample used in this study covers the 22 chemical products listed in Table I. There are approximately 20 years of coverage for each product. The sample includes 422 chemical plants. The sample is limited to new "greenfield" plants; expansions of existing facilities are excluded.[6]

The data on new plant capacity were collected from annual issues of the *Directory of Chemical Producers* published by SRI International. Annual data on total industry output of each product were obtained from annual issues of *Synthetic Organic Chemicals.* Engineering estimates of investment scale economies and unit production costs over a range of plant sizes were obtained from the 1976 issue of the *SRI Process Economics Program Handbook.* Additional data on R&D expenditures were obtained from

[6] The sample is a subset of a larger dataset on the chemical industry collected by the author. The sample includes plants for all products in the larger dataset for which engineering data on plant-level scale economies could be obtained.

Compustat; and data on process patents were collected from *Chemical Abstracts*.[7]

The products in the sample are all homogeneous, commodity-type chemicals or related products. Production capacities of all products are well defined; chemicals with production processes involving significant joint products have been excluded, as have those where production capacity can be switched from one product to another in response to shifts in market demand. Unit variable costs for any given plant tend to be relatively constant up to the level defined by its full production capacity.

Output was often consumed captively in firms' downstream operations, but for all products at least 25 percent of industry output was sold through arms-length channels. All products in the sample demonstrated positive net output growth from the earliest year of coverage through at least 1975. Thus, the sample represents products with growing demand, although in a few cases output declined after 1975.

Dependent variable

The sample consists of one observation for each new plant built during the coverage period for each product in Table I. The dependent variable, K_{ijt}, equals the total announced initial capacity of a new plant to produce product i constructed by firm j during year t.[8] Capacity is measured in thousands of pounds per year. K_{ijt} was converted to logarithms.

Independent variables

The following independent variables were used in the regressions. All variables except the time trend and entry dummy were converted to logarithms.

Time trend ($\textsc{time}_t$). The last 2 digits of the observation year were used as a time trend.

Total industry output. Q_{it} is the total physical volume of output of product i (measured in thousands of pounds) produced by all firms in the industry during the observation year t in which expansion took place.

Growth rate of industry output. $\textsc{grow}_{it}$ is the percentage increase in industry output over the three years prior to and including the expansion year, measured in thousands of pounds. ($\textsc{grow}_{it} = (Q_{it} - Q_{it-3})/Q_{it-3}$). Since all variables were converted to logarithms, $\textsc{grow}$ is defined only for observations with positive market growth.

[7] A detailed appendix describing the data and sources is available from the author.

[8] The mean value of K_{ijt} obviously varies across industries. To control for industry effects, the regressions in Table II were also run with the dependent variable scaled to represent plant size as a fraction of total industry output (K_{ijt}/Q_{it}) and plant size relative to the SRI benchmark ($K_{ijt}/K76_i$), with the output and benchmark variables omitted from the right-hand-side of the regressions. The results for the remaining variables were very similar to those reported in Table II.

Capacity of "typical" new plant in 1976. K76$_i$ is the benchmark plant size used by SRI. SRI estimates the cost of plants constructed at both one-half and twice this benchmark size. According to SRI, "these (benchmark) capacities are representative of sizes for competitive U.S. plants which might be built today (1976)."

Extent of scale economies in capital investment costs. SCALE_i equals $(1/\alpha_i - 1)$, where α_i is the scale economy exponent for the product, based on SRI estimates. A larger value of SCALE implies more extensive scale economies.

Cost disadvantage ratio of small scale plants. CDR_i equals the average total unit cost of a small scale plant (one-half benchmark scale) divided by the average total unit cost of a large scale plant (twice benchmark scale), based on SRI engineering estimates. *CDR* is based on *total* production costs rather than capital investment costs alone. *CDR* is distinct from SCALE primarily because of differences across products in the magnitude of capital costs as a percent of total production costs.

Entry dummy. ENTRY_{ijt} was set equal to 1 if the plant was built by a firm that had not previously produced product *i*.

TABLE II
REGRESSION ANALYSIS OF NEW PLANT SIZE†
Dependent Variable: K_{ijt}

Model:	1 *Manne*	2 *Scale Frontier*	3 *Combined*
constant	−1.1	−5.49	−5.39
	(−3.1)	(−8.6)	(−7.3)
r_t	0.280		0.297
	(1.7)		(2.0)
SCALE_i	−1.41		−0.191
	(−10.1)		(−1.0)
Q_{it}	0.540		0.178
	(11.1)		(3.0)
GROW_{it}	−0.182		0.010
	(−3.0)		(0.2)
SHARE_{ijt}	0.089		0.231
	(1.3)		(3.6)
ENTRY_{ijt}	−0.459	−0.512	−0.498
	(−4.8)	(−5.7)	(−5.7)
TIME_t		0.087	0.073
		(10.4)	(6.6)
$K76_i$		0.767	0.698
		(16.8)	(8.4)
CDR_i		1.84	1.58
		(2.1)	(1.7)
R^2	0.531	0.594	0.619
No. of Obs.	392	392	392

† All variables except TIME and ENTRY are in logarithms. Plants built during periods of negative growth are excluded. Numbers in parenthesis are t-statistics.

Real interest rate. The real interest rate, r_t, was estimated as the BAA long-term corporate bond rate, minus the expected rate of inflation. The expected inflation rate was taken as a five-year moving average of changes in the GNP deflator, with linearly declining weights over the period.

Firm's share of total industry capacity. $SHARE_{ijt}$ is firm j's share of total industry capacity for product i, prior to construction of the new plant. For new entrants, SHARE is set equal to $1/(N+1)$, where N is the number of firms in the industry prior to entry.

Several additional explanatory variables are defined in section V.

IV. EMPIRICAL TEST OF MANNE AND SCALE FRONTIER MODELS

Table II reports regression results comparing the Manne and scale frontier models. The Manne model (in the form represented by equation (1.7)) is estimated in regression 1. The model performs quite poorly in describing the size of plants in the sample. The key parameters of the model—r, SCALE, and GROW—have signs opposite to those predicted. The regression coefficients imply (rather perversely) that lower interest rates, more rapid market growth, and more extensive scale economies led firms to build comparatively *smaller* plants.

Other coefficients in regression 1 are more consistent with expectations. Plant size was positively related to total market size. This is largely a scaling effect, reflecting the fact that low unit value chemicals (e.g., fertilizers) tend to have large tonnage markets and are also produced in large tonnage plants. The SHARE coefficient in regression 1 is positive but small—on average a doubling of market share induced only a 6% increase in new plant size.[9]

In the test of the scale frontier model (regression 2), the coefficients generally conform to predictions and are all highly significant. The TIME coefficients reveal that the size of new plants increased at an average rate of about 8% per year across all products in the sample. Thus, there is clear evidence of a shifting "scale frontier."

The benchmark plant size, $K76$, appears highly significant, although its coefficient is below unity. It is likely that this downward bias results from "errors" in the benchmark estimates.[10]

ENTRY appears uniformly negative and significant, confirming that new plants built by entrants were substantially smaller than those built by incumbents. The coefficients imply that, on average, entrants' plants were only about 60% as large as incumbents' plants.[11] Entrants were an important

[9] The coefficient in regression 3 is somewhat larger, implying a 17% increase in plant size for each doubling of share. A detailed analysis of the time intervals between capacity expansions by a given firm (including incremental expansions) revealed that larger firms tended to expand more frequently, rather than in larger absolute increments. The Manne model predicts identical inter-expansion cycle times for all firms.

[10] Deviations between the SRI estimates and the "true" scale frontier in 1976 biases the K76 coefficient downward.

[11] Entrants' relative plant size equals e^{b_2}, where b_2 is the coefficient of the ENTRY dummy.

source of new plants, accounting for about half of the new plants in the sample.

Although entrants built smaller plants than incumbents, their plant size decisions were sensitive to the cost penalty of small scale operation, as recorded by *CDR*. Entrants' plant scale was closer to that of incumbents (and in general, all new plants were built closer to the prevailing scale frontier) when *CDR* was large. As a rough guide, the *CDR* coefficients imply that each 1% differential in unit production cost between small and large scale plants led to about a 2% increase in the average size of new plants relative to the SRI benchmarks.

Regression 3 includes the variables from both models. The scale frontier parameters are highly significant and retain the expected signs. In contrast, the two key variables of the Manne model, *SCALE* and *GROW*, are statistically insignificant, and the interest rate, *r*, continues to carry the "wrong" sign. Thus, the empirical evidence strongly supports the *SCALE* frontier model. The size of new plants increased over time, remarkably independent of changes in market growth, interest rates, or the extent of static scale economies.[12]

The poor performance of the Manne model indicates that at least one of the model's underlying assumptions is invalid. One obvious candidate is the assumption that an infinite range of plant sizes is technically feasible. In their planning study, Erlenkotter and Manne [1968] found that technical limits on the size of fertilizer plants in the 1960s virtually determined the optimal plant size. This finding appears to have held more generally for a wide range of chemical products over a relatively long period of time.

V. FACTORS AFFECTING THE RATE OF SCALE ADVANCE

The results in Table II document significant increases in plant size over time. To supplement these results, a series of additional variables and interaction terms were tested to identify factors influencing the rate of advance of the scale frontier and the relative size differential between entrants' and incumbents' plants. The interaction terms were computed by multiplying *TIME* and *ENTRY* by various interaction variables described below.

[12] The Manne and scale frontier models ignore changes in factor prices that might influence firms' plant size decisions. In a capital-intensive industry such as chemicals, firms might be particularly sensitive to anticipated changes in plant construction costs. The commonly accepted index of construction costs in the chemical industry is the Plant Construction Cost Index published annually by *Chemical Engineering*. The percentage change in this index (over the 3-year period prior to the observation year) was tested as an explanatory variable in the regressions. This measure proved statistically insignificant. However, the percentage change in plant construction costs, divided by the percentage change in the price index for "chemicals and allied products," proved positive and significant (0.05 level), thus indicating some tendency for firms to build larger plants during periods when construction costs were escalating faster than product prices. However, this relative inflation term added little to the variance in plant sizes explained by the regression model.

TABLE III
SUPPLEMENTARY REGRESSION RESULTS FOR THE SCALE FRONTIER MODEL†
Dependent Variable: K_{ijt}

	4	5	6	7	8
constant	*a*	*a*	*a*	*a*	*a*
$TIME_t$	0.081	0.143	0.112	0.041	0.069
	(6.0)	(5.7)	(8.4)	(1.3)	(2.9)
$TIME_t \times SCALE_i$		−0.146			
		(−2.8)			
Q_{it}		−0.048	−0.070		
		(−0.4)	(−0.6)		
r_t	0.152	0.090			
	(1.2)	(0.7)			
$ENTRY_{ijt}$	−0.481	−0.806	−0.321	−0.174	
	(−5.9)	(−4.8)	(−2.5)	(−1.3)	
$SHARE_{ijt}$		0.109			
		(2.1)			
OIL_{ijt}		0.204			
		(2.0)			
$ICUMCAP_{it}$					0.021
					(0.1)
$FCUMCAP_{ijt}$					0.108
					(2.0)
$PATFOR_{it}$				0.669	
				(2.8)	
$PATUSA_{it}$				−0.233	
				(−0.8)	
$DPAT_{ijt}$				0.239	
				(1.8)	
R^2	0.659	0.671	0.684	0.716	0.630
No. of Obs.	422	422	140[b]	140[b]	201[c]

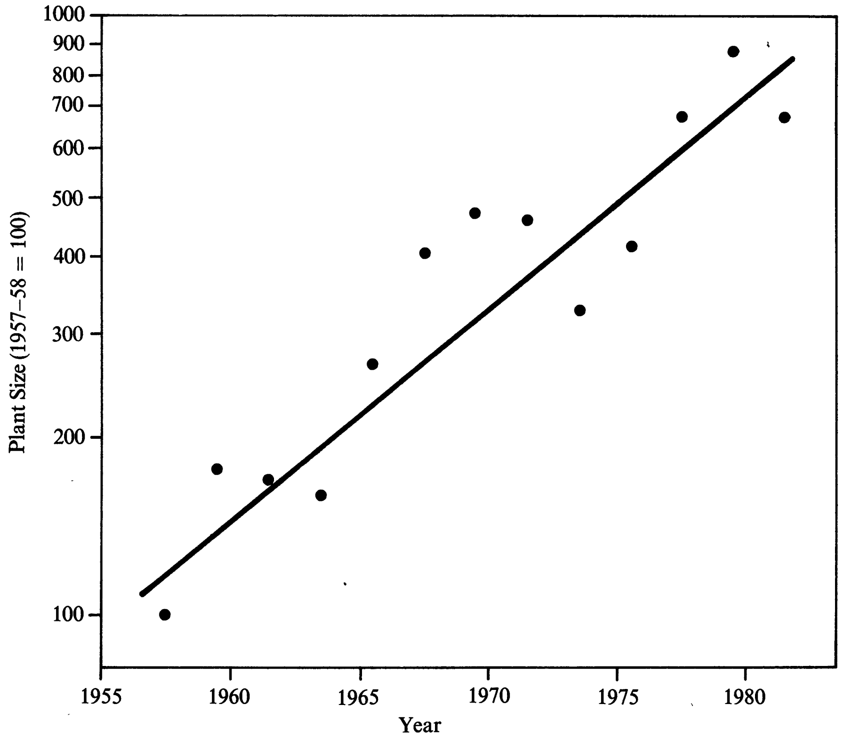
† All variables except TIME, ENTRY, OIL, and the patent measures are in logarithms. Numbers in parenthesis are t-statistics.
[a] Separate constant terms estimated for each product.
[b] Patent data cover only 13 products and are limited to years prior to 1975.
[c] Excludes observations for new entrants.

In these regressions, some of which are reported in Table III, separate constant terms were included for each of the products in the sample. These constant terms control for differences across products in mean plant size. Hence the other regression terms reported in Table III reflect changes in plant size over time.

Time trend

To examine the linearity of the time trend, annual time dummies were defined over the sample coverage period. The results, which are graphed in Figure 1, show a fairly steady increase in plant size over time. There is some indication that growth in plant size accelerated in the mid-1960s, slowed in the early 1970s, and accelerated again after 1975. There is no general evidence of a diminishing growth rate over the period.

Figure 1
Average Size of New Chemical Plants, 1957–82[1]



[1] Based on coefficients of dummy variables for each two-year period from 1957 to 1982.

Homogeneity of the time trend across products was tested by allowing each product to have a separate TIME coefficient in the regression. The results revealed statistically significant but relatively small differences across products in the rate of movement of the scale frontier.[13]

Conceivably, these small inter-product differences in the rate of plant size growth might be linked to the extent of scale economies. The more steeply unit investment costs decrease with plant size, the more resources firms might rationally invest to accelerate the rate of scale advance. To test this hypothesis, a multiplicative interaction between TIME and SCALE was included in the regressions. As shown in regression 5, this interaction term proves statistically significant but negative, implying that the rate of scale advance was actually slower for products with greater potential scale economies.

[13] The model was fit in constrained form (regression 4) and also with separate time trend coefficients for each product. Based on this test, the null hypothesis that all the time coefficients are identical was rejected. The F-statistic was 2.1, which exceeds the critical value 1.9[F(21, 375)] required to reject the null hypothesis at the 0.01 level. However, the increase in R^2 was relatively small, from 0.66 to 0.69.

The hypothesis that the rate of increase in plant size was influenced by market concentration was tested by interacting TIME with several alternative concentration measures, including (1) the Herfindahl index of producer concentration, (2) the logarithm of the number of firms, and (3) the logarithm of the number of plants. None of these interaction measures proved statistically significant. Thus, there appears to have been no connection between producer concentration and the rate of scale advance. This suggests that most technological improvements came from outside the firms that ultimately adopted them.

In general, the TIME interactions indicated a surprisingly strong regularity across products in the growth rate of new plant sizes. This suggests that shifts in the scale frontier were based on common underlying advances in chemical engineering technology. The uniformity of the time trend, and its persistence in the regressions despite the inclusion of alternative explanatory variables, is quite striking.

Base industry of firm

Oil companies, which entered the chemical industry in large numbers during the 1960s, are reputed to have built unusually large-scale plants. This scale orientation presumably reflects the importance of scale economies and high-volume operation in their base industry of petroleum refining. Dummy variables were defined for both oil companies (SIC 291) and major chemical companies (SIC 280) in order to determine whether such firms differed from others in their plant scale choices. The oil dummy (OIL) proved statistically significant (0.05 level); its coefficient in regression 5 implies that on average, oil companies built plants about 20% larger than other firms in the sample.

R & D expenditures

In Levin's [1978] model of scale advance, increases in plant scale arise from the R & D expenditures of individual firms. Compustat data on total corporate R & D expenditures are available for many firms in the sample. These data were used to compute company-level R & D to sales ratios which were tested for significance in the regression model. The results failed to show any connection between plant size and company R & D intensity.

Patent applications

Patents are another proxy for technological activity to which the shifting scale frontier might be linked. For thirteen products in the sample, data are available from *Chemical Abstracts* on the number of patent applications pertaining to new or improved production processes filed by US and foreign firms. (These data are described in detail in Lieberman [1987, forthcoming].) Three patent measures were tested in the regressions: (1) the cumulative number of patent applications by foreign firms (PATFOR), (2) the cumulative number of patent applications by US firms (PATUSA), and (3) a dummy variable which registers whether or not the specific firm had filed any process patents for the product in question (DPAT). The results in regression 7 suggest a connection between movements in the scale frontier and cumulative patents by foreign firms. (Patents by foreign firms outnumbered those by US companies by about two to one.) The drop in the time coefficient between regressions 6 and 7 suggests that more than half of the observed increase in plant size may be related to such patent activity. There is also some weak evidence that firms that filed process patents built relatively larger plants.

Cumulative investment experience

A further hypothesis is that growth in plant size is related to the cumulative experience of firms in building and operating new plants, as in a learning-type model. One proxy for experience is cumulative capacity constructed to date. For each product, the plant capacity data were cumulated at both the individual firm level (FCUMCAP), and the industry level (ICUMCAP). These measures were then tested in the regression model. Regression 8 shows the results, where the sample is limited to extant firms. Only the firm-level experience measure proves statistically significant, implying that firm-level learning is relevant. However, the time trend remains large in magnitude, indicating that most of the increase in plant scale must be attributed to factors other than firm-level experience. One interpretation is that more experienced firms simply built plants closer to the technological frontier; this explanation may also account for the size differential between entrants and incumbents. Unfortunately, collinearity between FCUMCAP and SHARE makes it impossible to determine conclusively whether the effect is truly related to cumulative experience or more simply to market share at the time of construction of the plant.

Relative size of entrants' plants

The size differential between entrants' and incumbents' plants was studied in detail by interacting the ENTRY dummy with *CDR*, GROW, TIME, and several market concentration measures, including the Herfindahl index and the logarithm of the number of firms. Of these interaction variables, only *CDR* proved statistically significant; i.e., entrants approached the plant sizes of incumbents only when there was a sizable cost penalty associated with small-scale operation. Rapid growth failed to stimulate entrants to build larger plants; and the size differential between entrants and incumbents failed to diminish over time.

The interaction tests revealed that the relative plant size of entrants was unrelated to market concentration. This casts doubt on the hypothesis (e.g. Scherer, *et al.* [1975, pp. 147–154]) that entrants opt for smaller plants in order to avoid generating overcapacity, which could trigger price cutting and potential retaliation by incumbents. If this were the case, one would observe smaller-scale plants built by entrants in concentrated industries, but not in competitive industries with a large number of firms. The results showed quite clearly that entrants tended to build smaller plants for all products, regardless of seller concentration.

What, then, explains the relative size differential of entrants' plants? One explanation consistent with the results is that without prior production experience, entrants are less capable than incumbents of solving the technical problems which frequently arise during start-up of a state-of-the-art plant. Thus, entrants are more conservative in their technological choices and less likely to take the risks inherent in building plants of frontier scale and beyond. Also, for many firms in the sample, the primary motivation for entry was backward or forward integration; in such cases, plant capacities were often chosen to achieve balance with the firm's other operations. The observed size differentials are consistent with vertical entry occurring as soon as firms' existing upstream or downstream operations reached a threshold size sufficient to permit vertical entry without too severe a cost penalty.

VI. SUMMARY AND CONCLUSIONS

The size of new chemical plants increased more than five-fold over the period from the late 1950s through the early 1980s. This increase in new plant size was unrelated to key parameters of the Manne model; plant sizes were not, in general, influenced by market growth, capital costs, or the magnitude of investment scale economies. Rather, growth in new plant size appears to have been driven by steady technological progress over time.

The rate of change in plant size was independent of market concentration and firm-level R & D expenditures, and only weakly linked to patent applications and firm-level cumulative investment. Plant size decisions were, however, influenced by the slope of the unit production cost curve and whether or not the firm was a new entrant. Entrants built smaller plants than incumbents, but all firms built plants closer to the technological frontier when small plants carried a higher relative cost penalty. The size differential between entrants' and incumbents' plants was not influenced by seller concentration or by the rate of market growth.

The poor performance of the Manne model can be attributed to the lack of validity of one or more of its underlying assumptions. In particular, the assumption that scale economies are available over an infinite range of plant sizes is refuted by the scale frontier results, as well as by engineering data. For most products in the sample, maximum feasible plant size remained below the optimal scale dictated by the Manne model.

These empirical results underscore the limited state of our knowledge regarding economies of scale. Clearly, in many industries, static economies of scale are less important than technological progress leading to shifts in the scale frontier. The standard economic distinction between "static" economies of scale and "dynamic" technical change ignores the fact that in many industries they are closely interrelated. This finding has important implications regarding the effect of scale economies on entry barriers and the process of industry evolution over time.

The empirical results presented here cover only one industrial sector over a relatively brief period. While similar results have been documented for a small number of other industries, the findings may be specific to capital-intensive industries with sizable economies of scale and investment lumpiness, such as materials processing, transportation equipment, and electric power. To understand the scale-frontier phenomenon more fully, it would be useful to have comparative results covering a broader set of industries.

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