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CAPITAL COEFFICIENTS AS ECONOMIC PARAMETERS: THE PROBLEM OF INSTABILITY

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The issue of fixed versus variable coefficients is generally settled by faith rather than fact. This is easy to understand. Few can doubt the possibility of producing most products in a variety of ways, but it will be some time before there is sufficient information for a comprehensive quantitative appraisal of the importance of variability. Furthermore the importance of substitution and the methods appropriate for dealing with it can be judged only in relation to a specific model in a given temporal context. While the evidence is fragmentary, the search for empirical capital coefficients for the dynamic input-output model has yielded some insight into the problem of variability in technique of production in disaggregated schema. The purpose of this paper is to outline and discuss some problems posed by the variability of productive methods in the implementation of a dynamic input-output model.

The search for empirical capital coefficients has focused attention on the problems of variability to a far greater extent than studies of input flows on current account. There are reasons, both in the types of data used and in the theoretical structure of the model, which explain the greater apparent variability of capital requirements. Input coefficients were derived primarily from census information. Thus interplant differences in input-output ratios were automatically obscured in the aggregation of inputs and outputs for all plants in an industry. In the absence of analogous over-all coverage of stocks of capital goods, capital coefficients were de-

Note: This paper draws upon a number of studies of capital requirements conducted at the Harvard Economic Research Project. The author wishes to acknowledge the contributions of the various members of the Project who participated in these studies, particularly Mrs. Carol Cameron and Mrs. Helen Kistin. Both of them played major roles in the analysis of capital requirements in the chemical industries. Mrs. Cameron also shouldered major research responsibility in the follow-up studies of unbalanced expansions and of capital requirements in carbon black production. However, the conclusions based on these studies which are presented in this paper are those of the author.

rived from descriptions of small samples of individual plants. Where more than one plant was covered, interplant differences in fixed asset-output ratios and by inference in technique became apparent. Were the input-output flow ratios studied on the same basis, similar variation might well be observed.

In inferring industrywide coefficient matrices from individual plant input structures, the various plant coefficients are viewed as a distribution of which the industrywide coefficients constitute an output-weighted mean. When dealing with the substitution question, it is important to remember that dispersion among plants does not in itself imply instability of the industrywide coefficients over time. To understand the stabilities of flow and capital coefficients over time, it is necessary to examine the pattern in which the distribution of component techniques changes.

It is at this point that the basic theoretical characteristics of flow and capital coefficients must be examined. In the dynamic input-output model, two aspects of input structure are distinguished: ratios of time rates of input to time rates of output, or flow coefficients, and ratios of stocks of goods to time rates of output, or capital coefficients. A thorough description of a productive process should include stock-flow and flow-flow relationships both for so-called current account inputs and for capital inputs. Thus it should include inventory as well as input flow coefficients and capital replacement flow as well as fixed capital coefficients. Every input has both a stock and a flow characteristic. The usual stress on the stock aspect of fixed capital and the flow aspect of current account inputs rests on the relatively high ratio of stock to flow in the former, and the low ratio in the latter.

Since stock and flow relationships describe different aspects of a given technique, in general, both are affected by technical change. Except in special cases, a new technique means both new capital coefficients and new flow coefficients. But a change in technique and hence a change in the flow coefficients requires investment in new capital goods. The capital cost of changeover coupled with the durability of old capital provides an important stabilizing element for flow coefficients. By and large, flow coefficients can only change in step with the rate of investment in new capital goods and hence their revision is hampered by the inertia of old capital stocks. The new technique is introduced only gradually as capacity is expanded or old capital goods are replaced with new capital goods. Only when a new technique entails drastic savings in flows that are sufficient to offset the cost of replacing old capital will this inertia be overcome quickly. The larger the capital stock requirements per unit of capacity, the greater the inertia to be overcome.

Capital coefficients themselves are not stabilized by the inertia of old capital. It may seem paradoxical that capital requirements tend to stabilize input coefficients while capital coefficients themselves do not partake of the stabilizing influence. This is related to the orientation of the model. In each industry, total input flows are generated by current account requirements of *all* the producing units and by additions to stock required for the *expansion* of capacity. Hence input coefficients should reflect all technologies in use, and capital coefficients only the techniques employed in the newest sector of the industry. Essentially, input coefficients are average; capital coefficients are incremental.

To recapitulate: While, at any given time, input coefficients are representative of a wider range of techniques than capital coefficients, they tend to be relatively stable because of their "moving average" property. Capital coefficients are more sensitive, describing technical characteristics of the incremental portion of the industrial capacity picture only. Furthermore capital coefficients in dynamic input-output models describe prospective rather than "sunk" investment. Hence they are not subject to the technological inertia which characterizes the great bulk of industrial capacity at any given time. Since previous technological commitments impose little restriction on the choice of techniques in the incremental sector of capacity, technical investment parameters must reflect many known technical possibilities including newly discovered techniques. Thus it is reasonable to expect that variability of techniques will be a much more pressing problem in the prediction of new capital requirements than it was in dealing with flow coefficients; and it may prove wise to use a technical model of capital requirements which differs radically from the fixed coefficient matrix used for flows.

In an immediate sense, the variety of alternative productive methods makes it difficult to derive unique capital coefficients which correctly predict actual requirements per unit of capacity in a given expansion. The problem of variability appears most commonly in one of the following four forms: problems of choice among alternative processes, among variants within major processes, among varieties and grades of a given commodity produced, and choice among expansions in the form of new plants, balanced additions, and the various kinds of unbalanced additions. At least the first three forms of variation are closely interrelated. The distinction between interprocess and intraprocess variability is based on engineering definitions of process. Economically the distinction can be reduced to a matter of industrial classification. The same can be said of the distinction between product and product grade. Frequently differences among or within processes are correlated with differences in product grade, and the choice among process alternatives is conditioned by grade requirements rather than by cost economies in a particular industry. For example the choice between woolen and worsted yarn systems makes a marked difference in the types and costs of equipment required per pound or per dollar value of output. Value of cotton spinning and weaving equipment per pound will vary by five or more times, depending on the quality of output. Variation per dollar of output is smaller but still appreciable since machinery, raw material, and labor costs constitute different proportions of total product value for different grades. The choice between electric furnace and open hearth steelmaking is conditioned primarily by grade rather than immediate cost considerations. Investment in electric generating capacity per unit consumed depends on the time distribution of loads over the day.

Variability of Capital Requirements in the Chemical Industries

These are just a few random instances of the relation between capital requirements and product grade. The interrelationships among different types of variability are illustrated somewhat more systematically by the results of the Harvard Economic Research Project studies of capital requirements in the chemical industries. Of roughly seventy chemical products for which records of World War II expansion of capacity in the form of new plants or balanced additions were available, ten were represented by more than one process, separately identifiable in engineering terms. This does not imply, of course, that there were technological alternatives for only ten products, but rather that the choice among alternatives was not unique for these ten products. In the case of at least four of these ten, synthetic rubber, carbon black, ethyl alcohol, and oxygen, the choice of process is known to be determined primarily by the qualitative characteristics desired for the product.

In a few cases, material was available for comparing total equipment costs per unit of capacity within groups of plants producing similar products by nominally identical processes.[1] The range of variation within three processes is shown in Tables 1, 2, and 3.

Table 1 shows total equipment costs per unit of capacity for four new plants producing synthetic rubber, "Buna S."

TABLE 1

Equipment Costs per Unit of Capacity, Synthetic Rubber, Buna S

Plant	*Approximate Size Index*	*Equipment Cost per Ton per Year*
A	100	$60
B	100	93
C	200	65
D	250	55

Equipment cost per ton per year in these plants varied from $55 to $93. One might expect part of this variation to be accounted for by differences in the sizes of the plants in question. For this reason an index of plant size (capacity) was constructed with each plant's capacity expressed as a percentage of that of the smallest plant. While for plants B, C, and D unit cost varied inversely with plant size, the cost per unit of A, the smallest plant, was almost as low as that of D, the largest.

Total costs (equipment plus construction) per unit of capacity for ten new gas furnace process carbon black plants are presented in Table 2, together with their respective size indexes.[2] Obviously the range in unit equipment costs of roughly 400 per cent cannot be explained entirely in terms of differences in plant size. Even among plants of identical capacity, equipment costs vary by more than 100 per cent. Some increase in homogeneity was attained by singling

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[1] These are all World War II expansions covered by applications for certificates of necessity, which are requests for accelerated amortization privileges on new facilities for federal tax purposes. They usually contain detailed descriptions of the costs of the facilities in question.

[2] Carbon black is a fine bulky carbon obtained as soot by the direct impingement of a burning flame on a metal surface. Nowadays it is used primarily in the manufacture of natural and synthetic rubber. Different grades of black, varying in size and surface area of carbon particles, produce different properties in rubber.

There are two major processes for producing carbon black: the channel and the furnace process. Channel and furnace blacks differ in their properties. Only the furnace process is discussed in the present paper. In this process, differences in grade are achieved by varying the time rate at which fuel is fed to the furnace and by the degree of fuel combustion.

A more elaborate analysis of investment in carbon black during the postwar period is discussed below.

TABLE 2

Equipment Costs per Unit of Capacity, Carbon Black Plants, Gas Furnace Process

Plant	*Approximate Size Index*	*Equipment Cost per Pound per Year*
E	100	$0.032
F	100	0.084
G	200	0.053
H	250	0.030[a]
I	325	0.028
J	325	0.033[a]
K	550	0.053[a]
L	550	0.020[a]
M	600	0.022[a]
N	650	0.052[a]

[a] Plants producing SRF (semi-reinforcing furnace) grade black—one of the standard grades.

TABLE 3

Equipment Costs per Unit of Capacity, Sulfuric Acid and Oleum, Contact Process

Plant	*Approximate Size Index*	*Equipment Cost per Ton per Year*
O	100	$12
P	100	6
Q	175	9
R	200	9
S	300	7
T	400	8

out a group of plants producing a particular grade, although the grade information furnished on World War II certificates of necessity was not very reliable. There was also reason to believe that the special influences of wartime conditions affected the ratios.

Equipment cost per unit of capacity for plants making sulfuric acid and oleum from sulfur by the contact process behaved somewhat more systematically, although even in this case not all the variability is easily explained.

In Table 3, two plants, Q and R, are balanced additions[3] rather than new plants. Althohgh O and P are approximately equal in size, the unit equipment cost of P was only half that of O, and was lower than that of any of the larger plants.

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[3] Balanced additions are defined as comprising substantially identical equipment but possibly different construction items than new plants.

Variability of Capital Requirements with Grade of Product and Scale of Plant

To appraise the relative importance of the various factors contributing to intraprocess variability in capital requirements, a more detailed study of capital requirements per unit of capacity in carbon black production was undertaken. For this study, a group of oil furnace plants built during the period 1950–1951 was chosen since these were described in greater detail on certificates of necessity than most of the World War II expansions. By this time most of the carbon black expansions were oil furnace process. The gas furnace process, most common among World War II expansions, was only scantily represented, and there was only one expansion in channel black.

The procedure adopted was as follows: First, the array of capital-to-capacity ratios for all plants in the sample was examined (Table 4). The coefficients are presented in terms of total cost broken

TABLE 4

Capital Coefficients for Carbon Black, Based on New Plant Current Certificates, Oil Furnace Process

				Investment Required per Pound per Year		
Plant	*Firm*[a]	*Grade of Product*[b]	*Capacity per Year (mill. lbs.)*	*Construction*	*Equipment*[c]	*Total Cost*
1	A	FEF HAF	44	$0.006	$0.029	$0.035
2	A	FEF HAF	50	0.005	0.038	0.043
3	B	HAF	24	0.022	0.057	0.079
4	C	HAF	32	0.015	0.074	0.088
5[d]	D	HAF	35	0.021	0.050	0.071
6	E	HAF	36	0.014	0.037	0.051
7	C	HAF	40	0.009	0.048	0.057
8	B	HAF (or SAF)	50	0.014	0.041	0.055
9	F	HAF	72	0.010	0.036	0.046
10[e]	G	SAF	15	0.036	0.124	0.160

[a] Actual company names have been concealed, but plants of the same producing firm are designated by the same letters.

[b] There are different grades of oil furnace black: FEF—fast extruding furnace black—has large particle size. HAF—high abrasion furnace black—has medium particle size. SAF—super abrasion furnace black—has small particle size.

[c] Total equipment cost includes engineering service cost.

[d] Coefficients for this plant are based on actual costs.

[e] This plant was actually a completely new entire producing unit for a new grade of product at an already existing plant.

Note: Capital coefficients are based on estimated costs found in current certificates of necessity granted for carbon black expansion, 1950–1952. Component parts may not equal totals because of errors of rounding.

down into equipment and construction costs. The standard deviation of each set (total, equipment, and construction) of coefficients was computed as a measure of variability.[4]

An attempt was then made to reduce variability by eliminating the effect of differences in grade. This was done in each of two ways: first by limiting the sample to plants producing a single grade (HAF blacks), and second by converting coefficients for FEF and SAF blacks to an HAF basis using typical ratios of capital requirements for these grades supplied by engineers.[5] The effect of increasing the homogeneity of the sample can be observed in Table 5.

TABLE 5

Average Total Coefficients for New Oil Furnace Carbon Black Plants, Showing Effect of Grade on Variability

	Mean Coefficient (1)	*Standard Deviation* (2)	*Coefficient of Variation* (2) ÷ (1) (3)
	(dollars per pound per year)		
All plants, unadjusted for grade:[a]			
Total cost	$0.069	$0.034	0.49
Construction	0.015	0.009	0.60
Equipment	0.053	0.027	0.51
HAF plants only:[b]			
Total cost	0.064	0.015	0.23
Construction	0.015	0.005	0.33
Equipment	0.049	0.012	0.24
All plants, adjusted to HAF grade:[c]			
Total cost	0.063	0.015	0.24
Construction	0.014	0.006	0.43
Equipment	0.049	0.013	0.27

[a] Based on 10 plants: 2 combined FEF and HAF plants, 7 HAF plants, 1 SAF plant.

[b] Based on 7 HAF plants.

[c] Based on 10 plants, all adjusted to HAF grade.

Both adjustments for grade differences reduced interplant variation in the ratio of total capital to capacity by 51 per cent, variability in equipment cost to capacity by a little more than that

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[4] See Table 5.

[5] The author wishes to thank Alan F. Beede and C. A. Stokes of Godfrey L. Cabot, Inc. for their cooperation in this matter.

amount, and variability in construction cost to capacity by somewhat less—about 45 and 28 per cent for the elimination of non-HAF plants and the adjustment to HAF grade respectively.

These observed results are consistent with theoretical expectations. That grade accounts for a lower proportion of variability in construction than in equipment costs is to be expected since specific site conditions explain a relatively large proportion of variability in this category.[6] The findings confirm the general thesis that differences in product grade are important in explaining variability of capital requirements.

The next stage in the carbon black study was the investigation of the contribution of scale to coefficient variation. For this purpose least squares lines of regression of the ratio of total capital to capacity on plant size were computed for HAF plants, and also for all plants, adjusted to an HAF basis. In each case the standard error of estimate about the line was computed and compared to the respective standard deviation. The difference between the standard error of estimate and the standard deviation, divided by the standard deviation, measures the proportion of variability (after the elimination of grade differences) which is explained by the scale factor. In both cases the proportion of remaining variability explained by scale was (0.015 – 0.010)/0.015 or 33 per cent.

Summary

In summary then it was possible by means of adjustment for interplant differences in product quality and scale to reduce the standard deviation of the ratios of total capital to capacity from 0.034 to about 0.010, or from about 49 per cent to about 16 per cent.

The evidence just presented is fragmentary in relation to the total economic picture. It would be premature to crystallize the impressions of interplant variability of capital requirements based on experience with this single product. Provided that this is borne in mind, it is useful to consider what more general findings of this sort would imply for the prediction of expenditures on capital goods in the dynamic input-output model.

First of all the wide range of interplant variation suggests that it is not safe to infer capital coefficients from expenditure information on one or two expansions without considerable supplementary technical information and an over-all knowledge of the industry's pecul-

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[6] See "Capital Coefficients for the Chemical Industries," Harvard Economic Research Project, hectographed, 1952.

iar characteristics.[7] Second, the fact that a sizable proportion of variability can be traced to identifiable factors, such as grade and plant size, suggests that the problem may be brought under control through elaboration of the model to take explicit account of these items. Thus it would seem feasible to express capital requirements in each industry as functions of the sizes of units to be built and some index of product grade. Many other studies of capital-to-capacity relationships have shown that it is feasible to derive production functions in terms of more than one product dimension.[8]

The problem for prediction is not so much the difficulty in elaborating the capital-to-capacity relationship itself. The more elaborate relationship is generally a by-product of the derivation of the coefficients in any case. The more difficult problem is that of predicting what the actual sizes of plants to be built and the distribution of product grades will be.

Perhaps surprisingly, the former, i.e. the prediction of plant size, is apt to be considerably more difficult than the latter. Economic theory of the firm tells us that, given the demand for the product and the production function, the optimum plant size is determined, provided of course that production costs vary systematically with plant size. In fact, however, plants of different sizes continue to be built simultaneously in a given industry despite strong apparent economies (or diseconomies) of scale. This is because, within a broad range dictated by over-all economic considerations, size of plant is influenced strongly by specific site conditions and other local factors. Information about these factors is generally very detailed and too cumbersome to encompass in a general interindustry model.

The best that can be done with the scale problem at this stage is to base capital coefficients on an estimate of average size of plant to be constructed in any given expansion. This may involve some bias where capital coefficients are nonlinear functions of scale. However, it will guard against the more serious danger of inferring coefficients from the observation of abnormally large or

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[7] With respect to variability, the use of accounting data in the derivation of capital coefficients may have some advantage provided that the firms are large and technological change is not great. At least they provide broader coverage than a single expansion; but of course there are other drawbacks.

[8] See, for example, Wassily W. Leontief, *et al.*, *Studies in the Structure of the American Economy*, Oxford, 1953, Chaps. 7, 8, 10, and 11, and "Preliminary Approximation of Output Capacity of U.S. Petroleum Refineries," hectographed, Rice Institute, Dept. of Economics, 1952.

small plants. A further contribution to the solution of this problem may be forthcoming as an outcome of research on the problem of resources in the interindustry context currently under way.

The grade problem is somewhat more hopeful since the distribution of grades to be produced is often closely related to the distribution of industries consuming the product. In carbon black, the grade requirements depend primarily on the amounts of natural and synthetic rubber produced and on the proportions of the various kinds of tires to be made.[9] Exploratory work indicated the feasibility of relating load factors in electric public utilities to the industrial distribution of demand for power.[10] Similarly it should be possible to estimate grade requirements for such industries as steel, petroleum, and nonferrous metals from a knowledge of their customer industries.

The method suggested is essentially one of introducing additional product dimensions in the first round, i.e. in the relationship of an industry's capital requirements to the distribution of demand by its immediate customers. In some cases where the grades of consuming industries' outputs have important effects on capital requirements in the producing industry, it should be possible to extend the grade interrelationships to the second round or further. This is equivalent to the suggestion that greater stability be sought through a finer industrial classification, a classification in which, for example, FEF carbon black comes from a different industry than HAF black, and "Buna S" from a different industry than "Thiokol."[11] Use of grade parameters as an alternative to disaggregation is a device like the process service industry.[12] The choice of one method of elaboration instead of another is a matter of expediency. Use of grade parameters may be helpful in maintaining process identity for the study of technological change.

The estimation of grade or quality requirements, or disaggregation, in industries selling directly to consumers is likely to be most difficult. To include final demand industries in such a scheme would require a more detailed description of the bill of goods.

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[9] Satisfactory estimates of requirements by grade were made on this basis during World War II. These are described in the unpublished records of the War Production Board.

[10] See Judith Balderston, "Notes on Alternative Methods of Predicting Capacities of Electric Public Utilities," Harvard Economic Research Project, hectographed, 1952.

[11] These are two different types of synthetic rubber.

[12] For a discussion of process service industries, see Mathilda Holzman, "Problems of Classification and Aggregation," *Studies in the Structure of the American Economy.*

There is no reason why the introduction of grade parameters, or the disaggregation process, should not be approached piecemeal as the necessary relationships are developed industry by industry. This is an area in which it will be possible to integrate special insights in particular industries into the general economic picture.

The moral implicit in the foregoing discussion is that estimates of such complex dynamic elements as fixed capital accumulation are not cheap. Furthermore it is interesting to note that the introduction of price substitution or, on a general equilibrium level, optimum programming does not solve the sort of operational problem which has been stressed thus far. Not all variability can be reduced to price substitution within a given industry. To the extent that choices among processes, as well as among variants of the same process, are conditioned by special characteristics of resource or product specifications, the improvement of estimates can best be accomplished through refinement of classification. Introduction of grade parameters would require not only the elaboration of process descriptions but also the description of the special limiting relationships between process and output characteristics. Thus, without prejudging the importance of price substitution, supplementary technical relationships or equivalent disaggregation should be introduced within the fixed coefficient framework.

Capital Requirements for Balanced and Unbalanced Expansions

Before speculating further on methods for dealing with variability in capital-to-capacity relationships, it might be well to discuss the other forms of variability noted, namely the balance problem and, finally, process substitution. Three major types of expansion can be distinguished: new plants, balanced additions, and unbalanced additions. Balanced additions are defined as expansions at the site of existing capacity which require essentially the same amount (and kinds) of equipment expenditures as new plants but not necessarily a full complement of construction expenditures. Unbalanced expansions add less than a full complement of both equipment and construction. Hence one would expect unbalanced expansions to be cheaper than balanced and balanced cheaper than new plants, per unit of capacity. Operationally it is sometimes difficult to distinguish between unbalanced expansions of capacity and conversions to new products or grades because of the necessarily rudimentary descriptions of product at this stage in the development of primary data. Given full information, it would be reasonable to deal with conversions as a special form of unbalanced expansion.

If there were a clear ranking of new plants and balanced and unbalanced additions according to cost per unit of expansion, one would expect that the opportunities for expansions of each type would be filled successively in ascending order of unit cost of product for each type. As in Ricardian rent theory, all the possibilities of unbalanced expansions would be absorbed first, then those of balanced expansions, and finally, if necessary, those of new plants. If the options for each type were marketable, one would expect them to be valued at differential cost of expansion. However, study of the problem reveals that decisions as to type of expansion are complicated by dynamic expectational considerations which seem to belie conclusions based purely on short-run cost considerations.

Despite this last complication, it is essential to the understanding of this form of capital cost variability to consider the mechanisms whereby opportunities for unbalanced expansions are created. The possibility of expanding capacity with less than a full complement of capital items implies a situation of initial imbalance in existing plants. Such imbalance is created in three ways: (1) purposive creation of initial imbalance with an eye toward future growth, (2) partial changeover for cost reduction, and (3) process conversions.

Imbalance Because of Expectations of Future Growth

The rationale for the creation of initial imbalance is to be found in definite or indefinite expectations of future expansion. In the light of such anticipations it pays to build in extra capacity in those items where there are striking economies of scale or where initial installation of excess capacity is cheap relative to the cost of adding to these facilities in the future. If future expansion is contemplated, it is cheaper to build in extra plumbing and wiring during initial construction than to add to them at a later date. When there are large economies of scale in process or storage units, it is wise to install larger units in anticipation of future expansion rather than to install additional small ones at some future date.

The possibility of taking advantage of such economies of scale in equipment is limited, however, by efficiency losses in operating certain types of equipment units at rates substantially below capacity. For this reason most of the initially designed imbalance is limited to excess construction items, such as land improvements and utilities rather than to equipment, while excess equipment is

TABLE 6

Percentage Distribution of Equipment Expenditure for Balanced and Unbalanced Additions, by Major Industries of Origin

	Plants Handling Liquids and Solids		*Plants Handling Liquids*	
	Mean for Balanced Additions (30 plants)	*Mean for Unbalanced Additions (31 plants)*	*Mean for Balanced Additions (14 plants)*	*Mean for Unbalanced Additions (13 plants)*
Process equipment:				
SIC 3443	9	12	12	12
SIC 3559	27	37	26	39
SIC 3567	5	3	3	2
SIC 3569	3	3	5	8
SIC 3585	5	5	5	...
Total process equipment	49	60	51	61
Piping:				
SIC 3591 and 3592	14	8	21	8
Electrical:				
SIC 361	7	4	6	9
Auxiliary equipment:				
SIC 3561	5	9	9	12
SIC 3563	2	7	1	1
SIC 3564	2	2	...	...
SIC 3821	3	1	4	1
Total auxiliary equipment	12	19	14	14
Other	19	9	10	7

... indicates less than 0.5.

Note: Percentages may not total 100 because of rounding.

Source: Averages for balanced additions were obtained from *Capital Coefficients for the Chemical Industries*, Harvard University Economic Research Project, Appendix VI, Table IV.

generally confined to storage and process piping capacity.[13] This is borne out by a study of the distribution of capital expenditures for expansions of various degrees of balance in the chemical industries. The cost patterns of the expansions reflect, indirectly,

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[13] Process piping is an engineering term which refers to valves, pipes, and fittings for the network of piping which serves the various chemical processing equipment units directly. Process piping is to be distinguished from plumbing and sewerage lines, which connect the plant as a whole to outside supply and disposal facilities. The latter are generally classed with construction rather than equipment. In practice the distinction between process piping and other piping is often difficult to make.

the initial state of balance of the plants' capacities. However, the initial condition of a plant relative to any given expansion may be the cumulative result of many successive additions to a new plant, and provisions for still further anticipated growth may be built into an addition to capacity as well as into a new plant.

Table 6 compares the percentage distribution, by SIC industry of origin and by broad functional groupings, of equipment expenditures for balanced and unbalanced expansions. Since balanced expansions are defined in terms of the similarity of their equipment distributions to those of new plants, new plants and balanced additions are lumped together in this comparison.[14] Expansions were grouped by type of process, but it was not possible to maintain identical product mixes for the averages being compared.

Table 6 reveals that expenditure on process equipment is a smaller proportion of total equipment expenditure in balanced than in unbalanced expansions, while relative expenditures on piping are higher in the former. This is in accord with theoretical expectations outlined above. Expectations of higher expenditures on electrical installations in balanced additions are not borne out unequivocally. This may be due in part to difficulties in classification of expenditures by industry of origin. It is almost impossible to distinguish operationally between expenditures for electrical work which belong with equipment and those which are classified under construction. The above discussion of the advantage of overbuilding in electrical categories would of course cover the total of equipment and construction expenditures of these items.

Table 7 gives a comparison of various types of construction costs for new plants, balanced additions, and unbalanced additions. This shows that new plants involve relatively more construction expense than balanced additions,[15] and balanced additions relatively more than unbalanced additions. Within the construction cost category, new plants tend to cost more than balanced additions, and balanced additions more than unbalanced additions, in nonbuilding as compared with building construction items. The subdivision of nonbuilding construction into utilities and land improvement yields

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[14] A detailed description of this study of balanced and unbalanced additions is on file at the Harvard Economic Research Project.

[15] There is danger of circularity in comparing construction expenditures in new plants and balanced additions since they are defined as identical with respect to equipment but not to construction expenditures. Hence one may be tempted to place a plant in one category rather than another on the basis of its construction outlays. This pitfall was avoided by supplementary checks on initial capacity at the site.

TABLE 7

Median and Mean Ratios of Construction and Equipment Expenditures to Total Cost in New Plants, Balanced and Unbalanced Additions

	Median Expenditure Ratios[a]			*Mean Expenditure Ratios*[a]		
	New Plants	*Balanced Additions*	*Unbal. Additions*	*New Plants*	*Balanced Additions*	*Unbal. Additions*
Ratio to total plant cost of expenditure for:						
Equipment	0.72	0.79	0.97	0.69	0.77	0.84
Construction	0.28	0.21	0.03	0.31	0.23	0.16
Building construction	0.17	0.15	0	0.20	0.16	0.13
Nonbuilding construction	0.11	0.06	0	0.11	0.07	0.03
Ratio to total construction cost of expenditure for:						
Building construction	0.61	0.73	1.00[b]	0.62	0.67	0.78[b]
Nonbuilding construction	0.39	0.32	0	0.38	0.33	0.22[b]
Ratio to total nonbuilding construction cost of expenditure for:						
Land improvement	0.19	0.01	0.19[c]	0.33[d]	0.10[e]	0.41[c]
Utilities	0.71	0.99	0.81[c]	0.64[d]	0.89[e]	0.59[c]
Miscellaneous	0.10	0	0	0.03[d]	0.01[e]	0

[a] All ratios exclude "Service."

[b] Based on twenty-seven plants.

[c] Based on eleven plants.

[d] Based on forty-five plants.

[e] Based on twenty-nine plants.

Note: Groups of median ratios may not total 1.00 due to the small number of entries.

Source: Median ratios for new plants and balanced additions were obtained from *Capital Coefficients for the Chemical Industry*, Harvard Economic Research Project, 1952, Appendix VI, Table XI.

ratios contrary to expectation; expenditures on land improvement in unbalanced expansions and those on utilities in balanced additions are inexplicably high. This may possibly be a result of poor data and classification difficulties in this particular cost area, which notably lacked descriptive detail.

There may be some objection to the use of the terms balanced and unbalanced expansions in this context. If the general hypothesis concerning initial imbalance is correct, then *all* expansions, properly speaking, will be unbalanced, some in one and others in another direction. A new term is needed to describe these different kinds of expansion. The evidence just presented was, by and large, consistent with the thesis concerning initial imbalance, but explicit standards by which to judge the balance of particular plants are extremely difficult to find. If truly balanced plants are rarely built, absence of blueprints for them is quite understandable.

Unbalanced Expansion Induced by Technological Change and Process Conversion

Technological change is a second reason for unbalanced expansions. Two aspects of the relationship between technological change and unbalanced expansions should be distinguished. First, technological changes are often introduced through unbalanced additions to existing plant, additions of particular items which change productive methods, or replacements of parts of the existing capital stock. Second, the innovation process creates imbalance by increasing productivity in certain areas of the productive process but not in others. Thus a particular plant may find itself with bottlenecks which must be eliminated before full advantage can be taken of the innovation, or which can be eliminated, should additional capacity be desired.

The importance of innovation in generating unbalanced expansions is illustrated by a detailed tabulation of unbalanced expansions in the carbon black industry during the Korean emergency (1950–1951) and during World War II. The sample covered was not chosen selectively, but included all unbalanced expansions in gas and oil furnace black for which certificates of necessity were available (see Table 8).

The itemization of equipment purchases and changeovers gives a clue to the characters of the individual expansions. Of the eleven expansions described, all but three include direct innovational expenditure: four plants introduced secondary collection facilities, a feature that has become workable only quite recently. Two of the

TABLE 8

Characteristics and Costs of Unbalanced Expansions for Carbon Black, Oil and Gas Furnace Processes

Plant Number	*Firm*[a]	*Period and Year of Construction*	*Nature of Expansion*	*Grade of Black*[b]	*Increase in Capacity*		*Costs*		
					Millions of Pounds Per Year	*Per Cent of Initial Capacity*	*Con-struction*	*Equip-ment*	*Total Cost*
							(per pound of capacity)		
			A. Conversion from Gas to Oil Furnace Black						
1	A	Current 1950	Conversion of furnace, addition of collection and pelletizing equipment	HAF-FEF	32.00		$0.001	$0.004	$0.005
2	A	Current 1950	Addition of collection and pelletizing equipment subsequent to conversion of furnace	HAF-FEF	57.00		...	0.013	0.013
3	D	Current 1951	Addition of drum magnets, fuel lines, conveyors, screens, mikro-pulverizers, conversion of reactors, oil storage facilities, car spotters, loading system	HAF	10.20	5		0.027	0.027
			B. Recovery Systems						
4	B	Current 1951	Addition of bag filters and pelletizers	FEF	1.50	10		0.158	0.158
5	C	Current 1952	Addition of bag filters and bead machines	HAF-FEF	2.50	2	0.004	0.188	0.192
6	D	Current 1952	Smoke abatement facilities and pelletizers	HAF-FEF	13.00	7	0.002	0.070	0.072
7	C	World War II–1946	Addition of multicyclones, screw conveyors, and insulation	HMF	1.80	10		0.073	0.073

(continued on next page)

TABLE 8 (continued)

					Increase in Capacity		*Costs*		
Plant Number	*Firm*[a]	*Period and Year of Construction*	*Nature of Expansion*	*Grade of Black*[b]	*Millions of Pounds Per Year*	*Per Cent of Initial Capacity*	*Con-struction* (per pound of capacity)	*Equip-ment* (per pound of capacity)	*Total Cost* (per pound of capacity)
			C. Removal of Bottleneck						
8	D	Current 1952	Addition of complete furnace and pelletizing units with auxiliaries	FEF	23.60	25	0.003	0.024	0.027
			D. Miscellaneous Equipment						
8	B	Current 1951	Addition of 15 hopper cars						
10	A	World War II–1945	Addition of pellet mills with dryers, screens, and auxiliaries	SRF	13.16	33	...	0.012	0.012
11	C	World War II–1945	Addition of pelletizers, with conveyors, agitators, motors, and foundations		c				

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[a] Plants of the same firm are designated by the same letter.

[b] Different grades of furnace black are produced from different raw materials. The furnace process using natural gas as a raw material produces grades HMF (high modulus furnace) and SRF (semireinforcing furnace black). These grades were produced in World War II expansions. The furnace process using oil as a raw material produces HAF (high abrasion furnace) and FEF (fast extruding furnace).

[c] No capacity increase was given for this plant. The addition of the pelletizers, conveyors, etc. did not increase capacity but merely made the product in a more useful form.

... indicates less than 0.0005.

World War II expansions introduced pelletizing equipment, pelletizing being a type of product finishing which was new at the time. Three were conversions from one type of fuel to another.[16] The remaining two expansions, 8 and 9, constitute some form of bottleneck removal. The bottlenecks may have been created either by earlier innovational activity or by some other source of initial imbalance. One cannot fail to be impressed by the degree to which technological change colors the unbalanced expansion picture in this industry.

A comparison of the capital cost per unit of capacity for these unbalanced expansions with the capital-to-capacity ratios for new plants in carbon black[17] yields one conclusion which may be surprising: the coefficients for secondary recovery systems show greater cost per unit of capacity than the new plant coefficients. Despite their initial expense, secondary recovery systems are economic because they increase product with no additional raw material or labor cost.

Like the types of innovation already described, conversions increase capacity without requiring a full complement of new capital goods and hence constitute unbalanced expansions. Conversions do not necessarily imply change to a newly discovered process, however. The chief feature distinguishing conversions from other types of unbalanced expansion is that other potentially effective capacity is eliminated by them. The introduction of interindustry or intraindustry conversions into the dynamic input-output model would modify the pattern of irreversibility in investment presently envisaged. Conversions constitute another special form of substitution. To estimate the economic advantage of conversion, one must know not only the technical properties of the processes separately but also the cost of interchanging them. When conversion opportunities are taken into account, capital coefficients of individual industries become dependent on the amount of excess capacity in other industries.

Problems in Predicting the Volumes of Balanced and Unbalanced Expansions

There is as yet no over-all estimate of the relative importance of unbalanced expansions as compared with new plants in the capital picture. There is every indication, however, that unbalanced expansions account for a sizable proportion of capital formation. Of a

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[16] This is a form of process change.

[17] See Tables 2 and 4.

list of some nine hundred World War II expansions in the chemical industries, at least half the number of expansions were unbalanced. Since the capital cost of unbalanced expansions is generally quite different from that of new plants, this problem contributes an important element to variability in capital requirements.

It has been suggested[18] that this particular type of variability can be overlooked safely in predicting costs of expansion for an industry as a whole since imbalances of individual expansions in different directions tend to dovetail, and such dovetailing tends to yield a balanced picture in the aggregate. Reliance on this tendency involves three pitfalls: (1) there is no guarantee that the various types of imbalance will dovetail over any given time span, (2) as was explained above, there is a bias involved in using new plant coefficients to represent truly balanced expansions, and (3) insofar as unbalanced expansions are generated in the technological change process, there will be no tendency for them to balance out, even over the long run.

As in the case of the grade problem, the problem of unbalanced expansion might alternatively be handled through a revision of industrial classification. In dealing with the balance problem, however, a form of vertical rather than horizontal disaggregation is warranted. Instead of dealing with carbon black production—or the production of a particular grade of carbon black—as a single industry, one might subdivide it into a combustion industry, a collection industry, a pelletizing industry[19]—or even into a "piping services to carbon black production" industry, "building services to carbon black" industry, etc. Such a procedure converts the unbalanced expansion problem from a problem of variability of capital requirements per unit addition to capacity to a problem of explaining excess capacity in certain industries.

This device is useful in emphasizing the over-all economic parallel between interindustrial and intraindustrial imbalance and the relation between imbalance and excess capacity. However, there are additional substantive problems in explaining intraindustrial excess capacity which cannot be eliminated solely by reclassification. Interindustrial excess capacity can be explained partly in terms of changes in the bill of goods which alter the relative demands for the products of various industries. On the other hand

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[18] See "The Economic Impact of the Planned Capacity Expansion in Primary Aluminum, Alumina, and Copper Milling," Bureau of Mines, hectographed, 1952.

[19] These are all stages in carbon black production.

changes in the bill of goods will effect the same change in capacity requirements for all capital goods required in the production of a particular product. A fall in carbon black requirements cuts equally the need for combustion, precipitation collection, and all other services contributing to carbon black output. Whether the problem of plant imbalance is treated directly as variability of capital coefficients or through vertical disaggregation, the same kinds of modifications in the theory of capital purchase, i.e. gearing purchases to future expansion plans rather than a simple accelerator, are required. The treatment of conversions also remains substantially the same in either case. However, provided that vertical disaggregation is effected along engineering process lines, the approach through disaggregation will facilitate the study of technological change in relation to industrial balance. This consideration is important in the choice of industrial classification schema in general as well as in relation to the imbalance picture.

The interdependence of problems of variability and industrial classification cannot be overstressed, both in relation to the quality problem and to process balance. In each case disaggregation was proposed as a device for narrowing a range of indeterminacy in input-output relationships. In disaggregating, however, one should not overlook the possibility that a higher level of accuracy in one direction can be achieved at the expense of greater indeterminacy in another. With a finer industrial classification, one can expect greater precision in the prediction of some factor requirements, but, in other directions, more possibilities of substitution among similar products formerly lumped together. This does not imply that an economic interdependence system is neutral with respect to alternative classifications—that any given change adds a problem here and subtracts one there. On the contrary this discussion is intended to stress the importance as well as the delicacy of the choice of an industrial classification.

Variability of Capital Requirements and Process Substitution

This brings us to the fourth major aspect of the variability problem, process substitution in the orthodox sense. The discussion thus far has pointed up special problems of variability of capital requirements which will not be solved simply by describing a set of alternative processes in place of a single process. These have been problems which do not arise from the specific limitations of a fixed coefficient model. By and large they are problems on an operational level and would remain a plague in almost any general dynamic interdependence scheme.

However, as was noted early in this paper, the choice among alternative processes is more serious in predicting capital requirements than in predicting inputs on current account. The bulk of interprocess switching requires new investment associated with expansion or changeover, and capital coefficients or some counterpart of capital coefficients must describe this element of change in capital stocks. Even with respect to capital coefficients, however, there are some elements in the general equilibrium context which tend to stabilize the relative advantages of alternative processes in the short run. One can expect a certain amount of stability in the structure of relative factor prices conditioned by the inertia of capital structure and thus of input-output relationships in other industries.[20] While the inertia of a given capital structure does not in itself stabilize capital coefficients in its own industry, it indirectly stabilizes capital requirements in other industries by imparting a steadying influence to input structures and hence to prices. Relative price stability, in turn, steadies the relative advantages of a given set of alternative processes, decreasing variability in capital coefficients. Such considerations, however, will not forestall shifts in process advantage in response to sizable changes in the bill of goods or the basic resource position of the economy.

Nor do these stabilizing influences apply to substitutions arising in connection with technological change. Even within a framework of stable factor supply conditions, new processes are always being discovered which can compete successfully with old ones. In order to predict capital expenditures, one must know whether there is a new technology which will govern expansions, and also whether the savings entailed in utilizing the new technique are sufficiently great to warrant replacement of old capacity with new.

There is evidence that the rate at which new methods are developed is sufficiently great in some sectors to render total capital coefficients in error by 50 per cent or more within a few years. The chemical industries are full of examples, particularly in some of the newer products such as nylon and plastics. In such industries, incremental capital coefficients are rendered obsolete at an appallingly rapid rate and the cost advantage of newer processes is often great enough to warrant substantial scrappage of old equipment for changeover purposes as well. Where such radical technical changes occur, the explicit introduction of process substitution into the dynamic input-output model is essential. It is equally im-

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[20] For a discussion of the "inertia of capital structure" see above.

portant that the model absorb a changing roster of process alternatives. These considerations are important not only for improving estimates of capital requirements per unit increase in capacity but also for predicting the volume of capacity which will be replaced. To take realistic account of the process of technological change, it is necessary to relax not only the fixed coefficient assumption but also the simple accelerator theory of capital formation. Research on modification of the dynamic input-output model to take technological change into account is currently under way.

Conclusion

The foregoing account of variability problems in the prediction of capital requirements is by no means comprehensive. The discussion was limited to problems of estimating over-all capital expenditure. The classification and/or substitution problems inherent in establishing breakdowns of capital requirements by industry of origin warrant full treatment on their own. Furthermore the problems of quality and of balance cannot be dealt with independently of the more general problems of classification and product mix, of which they constitute but a single aspect.

A partial review of the problems of estimating capital requirements in a disaggregated scheme is disheartening, but it would be a mistake to evaluate the short-run returns of dynamic input-output models independently of these difficulties. Regardless of the fate of interindustry models, however, someone must deal with these problems in the long-run development of economic knowledge. Judgment as to "where we go from here" is still largely a matter of faith.