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SCHMOOKLER REVISITED

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Abstract

This paper replicates the pioneering cross-sectional analyses of Jacob Schmookler for a comprehensive set of finely subdivided manufacturing industries. Invention patents originating from 443 U.S. corporations were classified by specific industries of use. The correlations between using industry investment and the number of linked capital goods inventions, although not as high as those obtained by Schmookler for a small subset of industries, were nevertheless substantial. The link between demand-pull and the flow of capital goods inventions was at least as strong for inventions sold across industry lines as for those that represented internal processes to their originators. For industrial materials, the relationship between demand-pull (measured by using industry purchases or value added) and the flow of inventions was much weaker, though still significant. Consistent with Schmookler's theory, inter-industry differences in technological opportunity have a significant impact on the specific industrial locus of inventive activity.

DEMAND-PULL AND TECHNOLOGICAL INVENTION: SCHMOOKLER REVISITED

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Revised Version

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During the 1950s and 1960s, quantitative research on the economics of invention was spurred by awareness that technical change was a primary source of the rapid economic growth achieved by industrialized nations. A leader in this effort was Jacob Schmookler, whose analysis of patent statistics [2] [4] provided the first demonstration that inventive activity is responsive to the pull of demand. The motivation now is different but no less compelling: a decade of retarded productivity growth makes it imperative to understand the forces governing the rate of technical advance. This paper retests Schmookler's demand-pull hypothesis with a new and more comprehensive data set.

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Use is made here of aggregated data collected under the Federal Trade Commission's Line of Business program. A determination has been made that the results do not disclose individual company data. The conclusions drawn are the author's and not necessarily those of the Commission.

I. The Schmookler Hypotheses

Schmookler's main contention, contrary to the prevailing emphasis on changes in scientific and technological knowledge, was that demand played a leading role in determining both the direction and magnitude of inventive activity. His basic underlying premises were two: (1) That the ability to make inventions is widespread, flexible, and responsive to profit-making opportunities; and (2) That the larger an actual or potential market is, the more inventive activity will be directed toward it, partly because the profitability of invention rises with market size, all else equal, and partly because chance encounters between inventive talent and a problem needing solution are more frequent, the more productive activity there is devoted to meeting some demand. In his most comprehensive work [4, Chapter VIII], Schmookler took into account the undeniable importance of differences in knowledge by observing that firms in certain industries (e.g., chemicals, electronics, and machinery) had comparative advantage at making inventions by virtue of the access to rich and growing scientific and technological knowledge bases in their fields of specialization.[1] However, these knowledge bases were highly adaptable, he argued, and so the applications to which they were put depended upon relative profitability, which in turn depended upon demand. Invention then flowed through a kind of input-output matrix from knowledge-rich originating industries to high-demand using industries.

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[1] For a critique of Schmookler emphasizing the role of technological opportunity, see [3].

Although there were other (i.e., time series) tests supporting his simpler demand-pull hypotheses, the main confirmation of Schmookler's theory of the relative roles of demand-pull and technological opportunity came from analyses of patenting for various industry cross-sections. His prime focus was on capital goods inventions, measured by the number of U.S. patents linked by Patent Office sub-class codes to particular industrial end uses. The more investment there was in a using industry, Schmookler claimed, the more patented capital goods inventions directed toward that industry's needs one should observe. The source of those inventions could be the using industry, other industries that specialize in supplying capital goods, or independent (i.e., non-corporate) inventors. Schmookler's patent counting methodology made no distinction among sources, but that was viewed as unimportant; what mattered was the pull of using industry demand. His cross-sectional sample covered up to 23 using industries, including petroleum refining, synthetic fibers, glass, sugar, tobacco, railroads, diverse textile and apparel industries, and several lumber and paper products industries. For a variety of time periods extending from 1936 to 1950, Schmookler found that the greater using industry capital investment was, the larger the number of relevant capital goods invention patents from all sources was. The associations were strong, with r^2 values ranging between 0.85 and 0.92, and in logarithmic form, the estimated regression coefficients were insignificantly different from 1.0, implying essential linearity of the demand-pull relationship.

To isolate the role of technological opportunity, Schmookler turned to a different sample of large corporations' patents classified by _industry of origin_. Since roughly three-fourths of business enterprises' patented inventions comprise new or improved products sold to others and only a fourth are internally-used processes, a classification of patents by industry of origin is quite different from one by industry of use. The question arises, is there a difference in the statistical relationship between patents classified by industry of origin and some index of demand, e.g., total inventing corporation sales, as compared to a classification by industry of use and a demand index (e.g., for capital goods inventions, user investment)?[2] Breaking his corporate sample into 14 broad industry classes, Schmookler found that the relationship between patenting and origin industry sales was essentially linear, as it had been for patenting and using industry investment. However, the association was much weaker, with r^2 values on the order of 0.43 -- half the levels obtained for the industry of use analyses. This difference Schmookler attributed to the intervening role of technological opportunity differences: firms in industries with rich knowledge bases originated many more inventions per million dollars of sales than less favorably disposed firms, causing the overall sales - patent origination correlation to deteriorate. Yet when differences in opportunity

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[2]From the perspective of a technology-originating industry, sales measures the purchases of its products. For industries _using_ capital goods, investment measures the purchases of those goods.

were aggregated out by flowing inventions through to using industries, regardless of origin, strong correlations demonstrated the pervasive force of demand-pull.

In essence, then, Schmookler's case for the relative importance of demand-pull rested upon three empirical results: (1) the linearity of the relationship between demand, as measured by new capital investment, and the flow of capital goods inventions to investing industries; (2) the strong correlations between those two indices; and (3) the much weaker correlations between counts of patents assigned by industry of origin and indices of demand or industry size.

Among the various possible limitations of these tests by Schmookler, two deserve emphasis. First, the sample of industries chosen for his investment - capital goods patent analysis was small and perhaps not representative. "Older" industries such as apparel, lumber, and paper-making were over-represented; and the number of patents included in the analysis totalled only 6 to 8 percent of all U.S. patents issued to individuals and domestic corporations during the late 1940s and early 1950s. Second, the sample of patents classified by industry of origin was quite different from the use-oriented sample, covering a much larger fraction of all patents, but excluding unaffiliated inventor and small-firm patents. The sample of origin industries was also much broader and defined at higher levels of aggregation. A new sample makes it possible to retest the Schmookler hypotheses while substantially avoiding these problems.

II. The New Data

As part of a broader effort to estimate the technology flows matrix first proposed by Schmookler, a sample of 443 large U.S. corporations was drawn. For reasons only peripherally related to the research reported here, these were the corporations covered by the Federal Trade Commission's 1974 Line of Business survey. An attempt was made to identify all the U.S. invention patents originating from U.S. resident inventors and issued to the 443 enterprises between June 1976 and March 1977. Some 15,112 patents, or 61 percent of all patents issued to U.S. industrial corporations during that period, were identified in this way. They comprised the basic working sample.

The printed specification of each individual patent was examined by a team of four Northwestern University students (an organic chemist, a chemical engineer, an electrical engineer, and a "utility infielder") to determine the nature of the invention (e.g., internal process vs. capital good product vs. material product), the industry(ies) in which the invention originated, and the industry(ies) in which use of the invention was anticiated.[3] The industry code system upon which these assignments were made tracked closely the FTC Line of Business codes and included a total of 245 manufacturing categories, usually defined at the four- or three-digit S.I.C. Level. Assignments according to industry of use were based upon information patent applicants provided to show the "utility" of

[3]For further methodological details, see [8].

their inventions. Roughly 7.4 percent of the sample inventions had consumer goods uses only, and another 34 percent had uses too broad to associate with any identifiable subset of using industries.[4] These were excluded from the sample analyzed here. Only the 8,875 inventions coded as having one, two, or three specifically identifiable industries of use remain. Classifications according to industry of origin were based upon information concerning the nature of the inventions, the patent-receiving corporations' product structures, and the specific activities undertaken at laboratories and plants near which the relevant inventors resided. With each specific-use patent coded as to both industry of origin and industry(ies) of use, both sides of Schmookler's two-way classification were available for the same set of inventions. Thus, the dual-sample problem of his research was avoided.

Our sample, however, covers only a subset of all industrial corporations. To analyze the forces affecting industrial invention, it was necessary to inflate the sampled patents so that their totals corresponded to the relevant inventive output of the U.S. industrial corporation universe. This was done by estimating for each origin industry i the fraction w_i of that industry's sales accounted for by companies included in our sample and then inflating each patent from industry i by $1/w_i$. Among the 245 industries, these sales coverage ratios w_i ranged from 0.06 to 0.99, with a value added weighted average of 0.61.

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[4] On this problem, see the letter Schmookler wrote to Robert Baldwin, quoted in [4, p. 91].

The implicit assumptions underlying this inflation approach are that patent coverage for an origin industry is proportional to sales coverage and that the patents of non-sampled corporations are similar, e.g., in use patterns, to those of sampled companies. No independent verification of the second assumption is possible. Concerning the first assumption, it is noteworthy that the weighted average sales coverage ratio of 61 percent is identical to the sampled corporations' 61 percent share of all domestic industrial corporation patents. Thus, the proportionality assumption is correct on average, even though there may be positive or negative inflation errors for individual industries.

The sampling error characteristics of our approach differ significantly from those of Schmookler's. His use-oriented sample included all patents, from large enterprises and small, foreign and domestic, as well as from independent inventors, in the use classes selected for analysis. His sampling of patents linked according to patent classification codes to using industries is exhaustive, but he sampled only a small subset of using industries. Our sample of using manufacturing industries is exhaustive, but we include only a subset of the inventions flowing to those industries, correcting in part for this non-exhaustiveness through origin industry sampling ratio inflation. No correction is made in our sample for the exclusion of inventions made overseas (15 per cent of all U.S. patents in 1940 and 35 percent in 1976) or by independent inventors (20 percent of all 1976 U.S. patents). Both Schmookler's analysis and ours, needless to say, are subject to possible errors in the classification of individual patents' using industries.

The industrial use patents in our sample were divided into two mutually exclusive groups -- materials inventions and capital goods inventions. The latter included originating industry products that became production equipment for some other (using) industry plus process inventions for internal use by the origin industry, but excluding process patents on compositions of matter, since such patents are often used to protect products on which patent protection might otherwise be unavailable. The capital goods part of this dichotomy was designed to replicate as closely as possible the spirit of Schmookler's capital goods invention selection criterion.[5] The capital goods invention sample was further subdivided for some analyses into two components -- processes for internal use by the originating firm and capital goods product inventions for sale across industry lines.

The sum of patented inventions used in the j^{th} industry, each individual patent multiplied by the i^{th} originating industry sampling ratio $1/w_i$, will henceforth be designated PM_j for industrial material inventions and PC_j for capital goods inventions. When an invention had more than one industry of use, it was

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[5]However, Schmookler's classification was not completely faithful to his capital goods use criterion. See [5, pp. 90, 266, and 278]. For instance, his textile dyeing patent classes include azo dye compositions, which we would count as industrial materials. And more importantly, his synthetic fibers industry classes include cellulose derivative compounds that we would classify as material products of the fibers industry, not capital goods processes. These cases appear to be exceptional.

counted fully for each industry to which a prospective use was traced.[6]

Following Schmookler, the preferred measure of demand-pull for capital goods inventions is new capital investment in using industries. Data constraints required that the analysis be limited to manufacturing industries of use only, for which consistent Census statistics are available. Schmookler found that the strongest correlations emerged when patent applications were lagged two years after the year of investment [4, p. 147]. Since it took 19 months on average for a patent application to mature into an issued patent during the mid-1970s,[7] this implies a maximum effect on our patents, whose midpoint issuance date was October 1976, from 1973 capital investment. Investment data for 1972 through 1974 were therefore collected. The investment variable for the j^{th} using industry in year t will be designated I_{tj}. For industrial materials inventions, the preferred measure of demand-pull is using industry material purchases M_{tj}, althoughdata on using industry value added V_{tj} were also gathered.[8]

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[6]Thus, we are implicitly treating inventions as public goods -- an assumption whose logic is analyzed in [8]. Sixty-nine patents obtained by corporations with no patents in the sample period came from a broader three-year sample and were accorded a weight of 10/36.

[7]For a fuller discussion, see [8].

[8]The data were drawn from the U.S. Census of Manufactures for 1972 and from the Annual Surveys of Manufactures for 1973 and 1974.

III. Results

Since 31 manufacturing industries (out of 245) had no assigned capital goods inventions, and 72 were recorded as being users of no industry-specific materials inventions, regressions of patenting on demand-pull indices were run first in untransformed (i.e., additive) variables for all industries,[9] and then (following Schmookler) in logarithms for a restricted sample with non-zero patent use.

In every case, the strongest association was between the relevant patenting variable and 1974 capital investment, material purchases, or value added. In most but not all cases, 1973 lagged variables performed slightly better than 1972 variables. When the lagged variables for all three years were introduced together, the characteristic pattern was for the 1974 variable to be positive and statistically significant and the 1972 and 1973 variables to be insignificant, occasionally with perverse negative signs. When a triangular lag structure with weights of 0.6 for 1974, 0.3 for 1973, and 0.1 for 1972 was imposed, r^2 values were 0.004 to 0.013 lower than with 1974 data alone as the independent variable. The persistently greater explanatory power

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[9]That the regressions have numerous zero-valued dependent variable observations suggests the use of Tobit analysis. However, the nonlinearities implied thereby are inconsistent with both the Schmookler findings and the relationships observed here. As a check on the validity of the full sample OLS regressions, zero-valued observations were deleted. For the analogue of equation 1.1, the regression coefficient was 0.227 and the r^2 was .537. For the analogues of regressions 1.3 and 1.5, the regression coefficients were .00247 and .00627 respectively (differing from their counterparts by less than one standard error), and the r^2 values were .119 and .161.

of 1974 demand-pull indices is a bit surprising, since it implies no lag between the emergence of demand-pull influences and the time when invention occurs (which precedes the filing of a patent application by nine months on average). These results could have occurred by chance, or they may reflect a tendency for corporate inventors to anticipate favorable demand conditions even before they materialize fully. In either event, the results are not appreciably different for any of the three lags or combinations thereof, and the exposition can be simplified by focusing only on the results for 1974 demand-pull variables, which are summarized in Table 1.

Several points stand out. First, in all cases, the relationship between demand-pull indices and associated patent flows is positive and statistically significant, with t-ratios ranging from 5.54 (for equation 1.4) to 17.5 (equation 1.1). Second, the association between capital goods inventions and investment is much stronger than the association between industrial materials inventions and either material purchases or value added (the latter of which unexpectedly has somewhat greater explanatory power). Professor Schmookler evidently chose the best-suited class of inventions for analyzing the role of demand-pull. Third, the r^2 values are at best much lower than those obtained by Schmookler. It is uncertain whether this is so because of sampling or classification errors under our methodology, the shorter time period covered by our data (with less cancelling out of random measurement errors), extraordinary sensitivity to demand-pull influences of the industry and patent

Table 1

Summary of Bivariate Regression Results

Equation	Dependent Variable	Constant	Regression Coefficient and Independent Variable*	r^2	N
1.1	PC_j	-0.8	$+ \underset{(.013)}{0.228}\ I_{74j}$	.544	245
1.2	$\log PC_j$	-0.1	$+ \underset{(.060)}{0.686} \log I_{74j}$	.382	214
1.3	PM_j	7.2	$+ \underset{(.00043)}{0.00278}\ M_{74j}$	.149	245
1.4	$\log PM_j$	-0.5	$+ \underset{(.080)}{0.443} \log M_{74j}$	.153	173
1.5	PM_j	1.4	$+ \underset{(.00087)}{0.00673}\ V_{74j}$	.197	245
1.6	$\log PM_j$	-0.9	$+ \underset{(.092)}{0.588} \log V_{74j}$	.194	173
			WITH CAPITAL GOODS INVENTIONS SUBDIVIDED		
1.7	PCI_j	-0.7	$+ \underset{(.0126)}{0.1719}\ I_{74j}$	.435	245
1.8	PCE_j	-0.2	$+ \underset{(.0031)}{0.0562}\ I_{74j}$	.578	245
			WITH AUTO AND STEEL INDUSTRY OBSERVATIONS DELETED		
1.9	PC_j	-7.7	$+ \underset{(.014)}{0.298}\ I_{74j}$	.651	242
1.10	$\log PC_j$	-0.2	$+ \underset{(.062)}{0.697} \log I_{74j}$	.374	211
1.11	PM_j	6.3	$+ \underset{(.00049)}{0.00334}\ M_{74j}$	.161	242

*Investment, materials purchases, and value added are all scaled in millions of dollars. Standard errors of the regression coefficients are given in parentheses.

class sample chosen by Schmookler,[10] or structural changes over the quarter century separating our samples. Given the broad coverage of our sample, it seems unlikely that the differences can be ascribed solely to origin industry sampling ratio errors. Fourth, logarithmic regressions 1.2, 1.5, and 1.6 reveal that the linear demand-pull relationships observed by Schmookler do not hold up for our sample. Rather, with elasticities in the range of 0.44 to 0.69, appreciable diminishing marginal returns appear to prevail.

To replicate Schmookler's test of the relative roles of demand-pull and technological opportunity, the 1974 sales of sample companies, broken down by individual lines of business, were aggregated to an almost identical industry code structure and level as that assumed in Table 1, and those aggregated origin industry sales S_{74i} were taken as the right-hand side variable in regressions explaining patents P_i classified and aggregated to _industries of origin_. The matching between patents, firms, and industries in this instance is nearly exact, stemming from a link effort exploiting extraordinarily rich data.[11] Owing to the precision of the link, one might expect less "noise" to infiltrate the relationship between origin industry sales and

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[10]That Schmookler's results are not invariant across samples is shown by the considerable increases in r^2 and logarithmic regression coefficient values as his sample was changed somewhat between his 1963 article with Griliches [2] and his 1966 book [4, p. 145]. The principal changes entailed eliminating the shoemaking industry, with high patenting but poorly measured investment, and adding railroads (which in most years had the highest investment and patenting of sampled industries).

[11]See [8].

patents than the relationship between diversely inflated using industry patents and demand-pull indices. R^2 values should be correspondingly higher, all else equal.

The simple regression of patents on origin industry sales (in millions of dollars) was as follows:[12]

$$(1) \quad P_i = 40.2 + \underset{(.0015)}{0.0135} \; S_{74i}; \quad r^2 = .243, \; N = 241,$$

with the regression coefficient's standard error given in parentheses. When logarithms are taken (requiring the omission of 17 industries originating no patents), the regression is:

$$(2) \quad \log P_i = -1.45 + \underset{(.083)}{0.904} \log S_{74i}; \; r^2 = .351, \; N = 223.$$

In both instances, the r^2 are somewhat to substantially higher than those for the industrial materials use regressions. In untransformed regression (1), r^2 is less than half its capital goods industry-of-use counterpart, but in logarithmic regression (2), it is nearly as high as, and insignificantly different from, the value in equation 1.2. Here, in contrast to the Table 1 regressions, taking logarithms suppresses the noise associated with a few very large but low-patenting industries (notably, automobile assembly). The support for Schmookler is again equivocal. The flow of appropriately matched inventions appears to be

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[12]When the same regression is run with observations weighted by the reciprocal of the industry coverage ratios, making the weights given industry observations correspond more closely to those of Table 1, the slope estimate is 0.0131 and the r^2 is slightly lower at 0.187.

more closely correlated with using industry demand (measured by investment or materials purchases) than with originating industries' sales only for capital goods inventions, and then only for one regression specification, and not for the logarithmic form emphasized in Schmookler's 1966 work.

The capital goods inventions analyzed in Table 1 consist of two rather different subsets: inventions that were internal processes to their originators, and those that were products to the originators but processes to their users. It would not be unreasonable to suppose that demand-pull influences are transmitted differently between these two cases, e.g., intra-firm markets (for process inventions) might work more efficiently than inter-industry markets. To explore this possibility, the invention sample was bifurcated into internal process inventions PCI_j (where using industry j = origin industry i) and externally sold products PCE_j (where $j \neq i$).

An insight provided by this procedure merits a brief digression. Both our data and National Science Foundation surveys reveal that 96 to 98 percent of all industrial inventive activity and corresponding patenting occur in the manufacturing sector. The bifurcation disclosed that manufacturers are their own most active suppliers of specialized capital goods inventions. Fully 75 percent of the 7,935 (inflated) capital goods patents with specific manufacturing industries of use were internal processes. Of 214 manufacturing industries with non-zero capital goods invention use, 78 percent drew a larger fraction of inventions from inside than outside. However, the companies in our sample also supplied 5,699 (inflated) capital goods inventions to nonmanufacturing industries -- e.g., agriculture, mining, telecommunications, and national defense operations. Eighty-eight percent of those inventions crossed industry bounds, being products to the originating industry and processes to the using industry.

Focusing on manufacturing uses alone, equations 1.7 and 1.8 in Table 1 reveal somewhat higher r^2 values for external use inventions than internal processes -- i.e., 0.578 for the former as compared to 0.435 for the latter. Evidently, external markets are at least as responsive in transmitting demand-pull stimuli as internal markets.[13] And they may even function with less slippage.

One further elaboration of the basic results is warranted. A plot of equation 1.1 and its diversely lagged variants showed that three industries -- auto assembly, auto parts, and steel -- were ill-behaved outliers. They had particularly high levels of investment, but drew far fewer capital goods inventions than one would have predicted from the general linear relationship estimated for all industries. When the three were deleted from the sample, the untransformed regression r^2 (equation 1.9) rose

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[13]The correlation coefficient differences are significant in a z-test at the 0.03 level.

A referee commented that regression 1.7 might be viewed as the stronger of the two because its regression coefficient is substantially higher. On this, two observations are required. First, the regression 1.7 coefficient is higher simply because there are roughly three times as many internal as external inventions. Second, the Schmookler hypotheses are concerned primarily with the tightness of the relationships between demand indices and invention, as reflected in a measure such as r^2, and not with the level of particular regression coefficient values.

by 0.107 to 0.651. No similar increase occurred for logarithmic analogue equation 1.10, apparently because the logarithmic regressions were better able to accommodate the nonlinearities associated with these outliers,[14] and perhaps also because there were other industries which, although much smaller, deviated proportionately from all-sample patterns at least as much as autos and steel. When capital goods inventions were broken down into internal and external processes, deletion of the three industries led to 0.07 and 0.08 increases in r^2 relative to full-sample untransformed regressions 1.7 and 1.8. It would appear that both external and internal demand-pull transmission mechanisms were unexpectedly weak. One cannot help wondering whether this failure to elicit process inventions might be related to the auto and steel industries' well-known import competition problems.[15]

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[14] Note the increase in the logarithmic regression coefficient toward unity when the three outliers were deleted.

[15] Compare Abernathy [1], who argues that the auto industry has been deficient in product but not in process innovation. For autos, at least two extenuating explanations might exist. First, the technology of auto production may be such that productivity is most readily enhanced by general-purpose machine tools, computers, and the like, whose uses are less apt to be associated with specific industries and which therefore would not be included in our subsample. Second, although the number of capital goods inventions with specific auto industry uses is small, the average 1974 research and development outlay leading to an auto industry patent, $3.55 million, was much higher than the average of $588,000 for all sample companies. But this low "propensity to patent" is almost surely the result of an R&D orientation that stresses styling amd model testing rather than the creation of new mechanical features. It is noteworthy that the auto parts industry, with equally low patent pull relative to investment, spent only $230,000 on R&D per patent received. For steel, the dearth of process inventions probably reflects a lack of imaginative internal research and development plus the

IV. Further Analysis

We depart now from the direct Schmookler tradition to explore several further hypotheses. It is conceivable that demand-pull influences manifest themselves in ways other than, or in addition to, the level of using industry investment, purchases, or value added. One plausible hypothesis is that profit possibilities are signalled in part by changes in using industry output. Also, labor-saving capital goods invention may be stimulated by unusually rapid increases in using industry wages. To test the first hypothesis, a variable ΔQ_j measuring percentage changes in real using industry output between the Census years 1967 and 1972 was computed.[16] To test the second, the percentage change ΔW_j in using industry production worker wage payments per manhour between 1968 and 1973 was estimated from Census data. The multiple regression incorporating these two variables along with 1974 investment to explain using industry capital goods inventions was as follows:

$$(3)\quad PC_{wj} = 22.9 + \underset{(.014)}{0.229}\, I_{74j} + \underset{(.090)}{0.271}\, \Delta Q_j - \underset{(.468)}{0.828}\, \Delta W_j;\ R^2 = .567,\quad N = 245.$$

Relative to otherwise comparable equation 1.1 in Table 1, the

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atrophying of specialized steel industry process equipment suppliers' R&D when investment for U.S. steel-making capacity expansion remained stagnant between 1955 and 1964.

[16] The source is [9].

increase in R^2 is 0.023, which is statistically significant in an incremental F-ratio test, with F = 6.26. The output change variable is positive as predicted and statistically significant. The wage change variable has a paradoxical negative sign and a t-ratio of 1.77, i.e., not quite significant. Similar results emerged when logarithms were taken of all but the output change variable (which had some negative values) and when the automobile, auto parts, and steel industry observations were deleted. For industrial material inventions, the most closely corresponding regression is:

$$(4)\ PM_{wj} = 2.9 + \underset{(.00043)}{0.00272}\, M_{74j} + \underset{(.054)}{0.168}\, \Delta Q_j + \underset{(.276)}{0.024}\, \Delta W_j;\ R^2 = .182,\ N = 245$$

The change in R^2 compared to bivariate equation 1.3 is 0.033, with F = 4.86. The output change variable is again positive and significant, but the level of demand variable continues to have much greater explanatory power. The wage change variable falls far short of statistical significance. Evidently, past increases in using industry output provide modest additional stimulus to invention above and beyond current <u>levels</u> of demand. No such stimulating role is detected for rapid rates of wage increase in using industries.

Finally, we consider an alternative way of assessing the role of technological opportunity in the industries that originate inventions. Extending the concepts employed in two earlier articles [6] [7], industries were classified into seven groups according to the perceived richness of their knowledge bases: organic chemicals, other chemicals, electronic systems and devices, other electrical equipment, the metallurgical trades, industries with "traditional" technologies (such as sugar refining, textile weaving, and cement making), and a base case consisting mostly of industries with mechanical technologies. These judgments were made ex ante, that is, before any analyses were run and indeed before sales and other linked financial data were assembled. The technology class dummy variables were introduced into analogues of origin industry patenting regressions (1) and (2). In the additive (i.e., nonlogarithmic) version, the appropriate specification is for the dummy variables to modify the base case (general and mechanical) regression slopes, and so the standard errors reported here test the hypothesis that the modified slopes differ from the base case slope:

$$(5)\quad P_i = 30.1 + \underset{(.0014)}{0.0116}\, S_{base} - \underset{(.0039)}{0.0154}\, S_{traditional} + \underset{(.0044)}{0.0721}\, S_{organic}$$

$$- \underset{(.0017)}{0.0018}\, S_{other\ chemicals} + \underset{(.0046)}{0.0837}\, S_{electronics} + \underset{(.0164)}{0.0452}\, S_{electrica}$$

$$- \underset{(.0026)}{0.0071}\, S_{metallurgical};\ R^2\ .809,\ N = 241.$$

The most important insight is that this simple method of taking into account differences in technological opportunity has raised the proportion of patenting variance explained from 0.243 in equation (1), with origin industry sales alone as the explanatory (i.e., homogeneous demand-pull) variable, to 0.809.[17] Clearly,

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[16] The source is [9].

[17] Very similar results are achieved when industry research and development spending rather than patenting is taken as the dependent variable.

differences in opportunity play a large and easily systematized role. Not surprisingly, the slope dummy coefficients for organic chemicals and electronics are positive and highly significant, with t-ratios of 16.47 and 18.27, while those for the traditional and metallurgical technology industries are negative (t = 3.92 and 2.74), indicating less patenting per million dollars of sales than base case industries. When the analogue of logarithmic equation (2) is estimated, with the technology class variables introduced as intercept dummies,[18] the result is as follows:

(6) $\log P_i = [7 \text{ constant terms}] + 0.882 \log S_{74i}$; $R^2 = .653$, $N = 223$.

Although not as dramatic as the change between equations (1) and (5), the proportion of variance explained has more than doubled relative to equation (2) as a consequence of taking into account opportunity differences. These augmented industry of origin regressions show a good deal more explanatory power than the Schmooklerian regressions analyzing only the linkage between using industry demand and the flow of inventions from any industrial source favored by opportunity. The latter relationship is apparently attenuated by considerable noise.

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[18] That is, where $P = \alpha S^{\beta}$, they modify the slope term α, which is analogous to the slopes in equation (5), but when logarithms are taken, is estimated as an intercept constant. If $\beta = 1$, regression (6) would, except in its error properties, be identical to a regression (5) with the intercept term constrained to zero.

V. Conclusion

The analysis here does some damage to Professor Schmookler's findings on the role of demand-pull. His detailed results replicate imperfectly when all manufacturing industry, rather than a small subset, is investigated and when industrial materials inventions are the focus. Nevertheless, at least for capital goods inventions, the main thrust of his theory survives. Although weaker than those obtained by Schmookler, the correlations between capital goods patenting and using industry investment are impressive. They persist not only for internal process inventions, but also for capital goods product inventions sold across industry lines. Markets work, both internally and externally, in transmitting demand-pull stimuli. Both the pull of demand and differences in technological opportunity, which determine the specific industries in which inventive activity is concentrated, must be taken into account for an adequate conception of how technological change occurs.

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