Management Applications

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Price/Performance Patterns of U.S. Computer Systems

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Econometric models of the U.S. computer market have been developed to study the relationships between system price and hardware performance. Single measures of price/performance such as "Grosch's Law" are shown to be so oversimplified as to be meaningless. Multiple-regression models predicting system cost as a function of several hardware characteristics do, however, reveal a market dichotomy. On one hand there exists a stable, price predictable market for larger, general purpose computer systems. The other market is the developing one for small business computer systems, a market which is relatively unstable with low price predictability.

Key Words and Phrases: price/performance, Grosch's law, U.S. computer market

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Introduction

The relationship between computer price and hardware performance has long been an object of study. Many attempts have been made in the past to define such a relationship, but none has occurred within the last five years. Given the rapid evolution of the industry, particularly in terms of improved hardware technology, a new effort in this area seems well worthwhile.

Many of the past studies focused on a concept known as "Grosch's Law," a rule of thumb in the industry which states that the power of computer systems increases as the square of their costs. In other words, if one pays twice as much for computer B as for computer A, one can expect that computer B will be four times as powerful as A. Dr. Herbert Grosch formulated this principle in the late 1940's. First appearing in print in 1953 [6], "Grosch's Law" has become a generally accepted description of the economies of scale of computer hardware.[1]

This economy of scale concept has been an important factor in the arguments of those who favor highly centralized data processing operations. By centralizing, it is argued, an organization can perform its work on one large machine, rather than on a number of decentralized, smaller machines. Since larger machines are less expensive per unit work performed, the result is an overall cost savings (in terms of hardware).

Several studies in the mid-1960's lent support to Grosch's Law. The most rigorous and widely cited was completed by Kenneth Knight during and after his doctoral studies at the Carnegie Institute of Technology [9]. Knight developed a complex algorithm for measuring computer power which he applied to several hundred computer systems. He then ran regression models, using this power measurement, along with year of introduction (as a proxy for technological advance), as a predictor of system cost. (Actually, Knight's model, like all later ones, used the system *price*, which was an obtainable figure, as a surrogate for system *cost*, which was usually not divulged by the manufacturer.) The results indicated that the cost of computer systems did, in fact, grow as the square root of the power increased. Knight also identified an effect of advancing technology, indicated by the generally improving power/cost ratio over time.

Sharpe compared Knight's work with a number of more limited studies, all of which came to the same general conclusion concerning economies of scale [11, p. 317]. Later literature on the subject (e.g., Golub [5] and Stoneman [11], refer to these studies, the last of which was completed in 1971, as the basis for their discussion on returns to scale.

Recent advances in electronics technology, manifested by the introduction of a large variety of very low-cost minicomputers and microcomputers, have raised some doubts about the continuing validity of Grosch's Law. Booth [4] suggests that the law should be restated to say that the economy of scale only exists within classes of technology. Hayes [8] and Booth also suggest that discontinuity has developed in the relationship, with very large and very small computer systems offering a superior power/cost ratio as compared to "medium" priced and sized systems. Theis suggests the exact opposite, citing the superior price/performance of a number of "midi" computers [12]. Grosch claims that the relationship described in his law is still valid, but neither he nor those supporting the opposite view have made any rigorous examination of the computer systems of this decade [7].

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[1] In its original form, "Grosch's Law" stated that the speed of computer systems increases with the square of their costs. Subsequent tests and publications of the "Law" have usually related system costs to some concept of system power.

One purpose of this study is to explore the power/cost relationship for the computer systems introduced in the 1970's. The following questions will be addressed:

(1) Does Grosch's Law have any meaning or validity?

(2) Is there any definite relationship between computer power and cost, and if so, what is it?

(3) What are the differences in computer power/cost characteristics which are attributable to the vendor? To technological advance?

(4) If computer systems are divided into classes, such as minis, micros, small business machines, etc., can power/cost relationships be identified within classes? Across classes?

A second, more general goal is to determine what, if any, significant relationships exist between hardware characteristics and computer price. If a simple price vs. power relationship cannot be established (which, we will see, is the case), then what parameters do relate meaningfully to computer price? In this case the goal will be to describe the present computer marketplace in terms of these relationships, and to identify any definite trends. Specific questions to be answered include:

(1) What *measurable* computer characteristics are related to computer price in a statistically significant way?

(2) Do these relationships change for different types of computers? For different vendors?

(3) What changes over time can be identified for these relationships?

1. Data

Much of the data was collected from *DataPro70*, a "consumer guide" to computer systems. *DataPro*, in its hardware volume, groups business computer systems into two classes, general purpose computer systems and small business computers. The general purpose computers comprise the large and intermediate systems manufactured by Burroughs, Control Data, Digital Equipment, Honeywell, IBM, National Cash Register, Sperry-Univac, and (before its demise) Xerox. These are the "old standard" computer companies, most of which have been manufacturing computers for over 20 years.

For these systems, the observations used were the "typical" system configurations given in *DataPro*. These are examples of what are felt to be representative configurations of the various systems, including all necessary peripheral equipment. The memory size, DASD capacity, and purchase price used in the analysis are the ones given for the typical configurations for each machine. The rationale for using this approach was discussed by Knight [9]:

> Although only a few configurations eventually are produced, the modern systems potentially consist of several hundred alternatives. It would be impossible to calculate power for even a few alternatives of each system. We must therefore settle on one configuration for each computer. There appears to be a good method for selecting the configurations, and that is to consider the most typical configurations of the computer.

Exhibit 1 lists the general purpose computer systems included in the study, along with some of their characteristics.

The second class of systems is what *DataPro* [1] refers to as "small business computers." It describes the members of this class as

> ... a business computer scaled down ... Though current small business machines differ widely in their architecture, data formats, peripheral equipment and software, they are generally characterized by purchase prices in the \$5,000 to \$100,000 range, and by a strong orientation, in both equipment and software, toward conventional business data processing applications.

There are several types of vendors in this marketplace, ranging from "Fortune 500" type companies such as IBM and NCR to small independent systems integrators, who fit their software to another vendor's computer and then market the entire package. In general, however, this is a new market, and most of the firms in it are both new and small.

To get typical configurations for the small business computers, vendors of these systems were directly contacted (*DataPro* did not have representative configurations for these). Each vendor listed in the small business computer section of *DataPro* was asked to give characteristics and pricing of what were considered "typical or balanced" configurations of their systems. Exhibit 2 shows the results of this survey. (The response rate was approximately 50 percent.)

Data compiled on each machine included: main storage size; direct access device (DASD) on-line storage capacity; instruction timings; year of introduction; purchase price; peripheral characteristics (printer speed, etc.).

2. Price vs. Power

Ideally, we would like to have some measure, such as horsepower for internal combustion engines, which could be used as a standard of performance. Unfortunately, the concept of computer productivity or performance is confounded by the great flexibility, both in design and in use, of these machines. Computer characteristics or capabilities which are essential measures of performance for one user are often irrelevant or unimportant to another user. Additionally, recent architectural advances which allow software to perform previous hardware functions, and vice versa, further blur the concept of "machine" performance.

Benchmarking several "jobs" on a number of computers can provide a prospective buyer with useful performance information. This has been done in very limited studies such as Solomon's [10, P. 190], in which only a handful of systems were considered. Due to the large effort and expense of programming and acquiring the systems required for benchmarking, this approach is clearly impractical with any large number of systems. Further, the utility of such an approach is limited because

Exhibit 1. General Purpose Computer Systems Used in Analysis.

System	Price ($000)	Memory (K-bytes)	DASD (M-bytes)	Year Introduced
CDC 3170	725.6	195.0	236.0	1970
HONEYWELL 115	166.0	12.0	18.4	1970
NCR CENTURY 300	976.7	512.0	400.0	1970
BURROUGHS B6748	1271.5	768.0	543.0	1971
HONEYWELL 1015	639.0	48.8	36.8	1971
HONEYWELL 2015	916.0	196.5	175.0	1971
HONEYWELL 6030	1209.2	441.0	235.0	1971
HONEYWELL 6050	2032.6	882.0	470.0	1971
HONEYWELL 6070	3319.7	1179.0	707.0	1971
IBM 370/145	1969.7	524.0	1600.0	1971
UNIVAC 70/2	610.7	65.0	14.5	1971
UNIVAC 70/3	927.3	262.0	116.8	1971
UNIVAC 70/6	1282.2	262.0	116.8	1971
UNIVAC 70/7	1821.1	524.0	233.4	1971
XEROX SIGMA 8	770.3	256.0	60.9	1971
XEROX SIGMA 9	1598.2	1024.0	220.1	1971
DEC 1060 (A)	475.1	432.0	25.6	1972
DEC 1060 (B)	826.2	864.0	200.0	1972
HONEYWELL 6040	1279.1	441.0	235.0	1972
HONEYWELL 6060	2113.3	882.0	470.0	1972
HONEYWELL 6080	3434.4	1179.0	707.0	1972
IBM 370/135	583.8	98.0	140.0	1972
IBM 370/135 (B)	860.3	524.0	280.0	1972
BURROUGHS B3741	500.0	100.0	182.4	1973
HONEYWELL 6025	1027.0	360.0	235.0	1973
IBM 370/168	4434.2	2096.0	1216.0	1973
NCR CENTURY 251	490.1	192.0	120.0	1973
UNIVAC 9480	571.0	131.0	116.0	1973
UNIVAC 90/60 (A)	677.2	524.0	600.0	1973
UNIVAC 90/60 (B)	878.5	1048.0	1000.0	1973
UNIVAC 90/70	1678.6	1572.0	1200.0	1973
BURROUGHS B4771	928.9	250.0	543.2	1974
CDC CYBER 172	1452.7	1425.0	472.0	1974
CDC CYBER 173	1976.7	1920.0	472.0	1974
CDC CYBER 174	3077.6	4755.0	1890.0	1974
CDC CYBER 175	4618.8	5242.5	1890.0	1974
HONEYWELL 62/60	187.4	81.0	58.4	1974
HONEYWELL 64/20	362.2	128.0	87.0	1974
HONEYWELL 66/20	1113.9	131.0	400.0	1974
HONEYWELL 66/60	2462.2	1179.0	800.0	1974
HONEYWELL 68/80	3525.5	5850.0	9600.0	1974
IBM SYS/3 MOD 15 (A)	121.2	48.0	4.9	1974
IBM S/3 MOD 15 (B)	252.8	128.0	87.0	1974
NCR CENTURY 151 (A)	133.7	32.0	9.8	1974
NCR CENTURY 151 (B)	275.8	128.0	96.0	1974
NCR CENTURY 201 (A)	300.0	64.0	96.0	1974
NCR CENTURY 201 (B)	634.4	256.0	192.0	1974
UNIVAC 90/30 (A)	162.7	32.0	57.8	1974
UNIVAC 90/30 (B)	231.8	98.0	173.7	1974
UNIVAC 90/30 (C)	417.7	196.0	231.6	1974
XEROX 550	328.7	64.0	14.3	1974
XEROX 560	980.0	160.0	405.8	1974
BURROUGHS B4790	1523.4	400.0	892.8	1975
DEC 1080 (A)	739.6	1152.0	200.0	1975
DEC 1080 (B)	969.5	1152.0	300.0	1975
HONEYWELL 62/40	108.0	65.0	11.6	1975
HONEYWELL 64/40	523.7	160.0	400.0	1975
IBM 370/158-3	2518.2	1048.0	678.0	1975
UNIVAC 1100/20	1173.0	589.5	200.0	1975
UNIVAC 1100/20 (B)	1925.4	1179.0	604.7	1975
BURROUGHS B6807	1030.0	786.0	20.0	1976
BURROUGHS B1776	198.0	81.0	174.4	1976
BURROUGHS B1726	186.8	65.0	87.2	1976
BURROUGHS B1728	416.9	163.0	182.5	1976
DEC 2040 (A)	315.0	576.0	100.0	1976
DEC 2040 (A)	531.4	1152.0	400.0	1976
IBM 370/115-2	268.6	65.0	140.0	1976
IBM 370/115-2	354.3	98.0	140.0	1976
IBM 370/125-2 (B)	525.7	131.0	280.0	1976
IBM 370/148	1225.1	1048.0	420.0	1976
NCR CRITERION 8550	259.0	128.0	200.0	1976
CRITERION 8570	458.3	256.0	300.0	1976
UNIVAC 1100/10	763.6	589.5	116.6	1976
UNIVAC 90/80 (A)	2156.7	1048.0	1200.0	1976
UNIVAC 90/80 (B)	3131.1	2096.0	1600.0	1976
BURROUGHS B1830	108.7	48.0	4.6	1977
BURROUGHS B1860	230.0	128.0	130.4	1977
BURROUGHS B1870	550.0	393.0	361.8	1977
DEC 2050	485.0	1152.0	200.0	1977
IBM 370/138	706.0	512.0	540.0	1977
UNIVAC 1100/80	2430.9	2394.0	2450.0	1977
IBM 370/3033	3800.0	4192.0	1216.0	1978

Exhibit 2. Small Business Computers Used in Analysis. * DEC PDP Based Processor. ** DG Nova or Eclipse Processor. *** INTEL 8080 Processor. # Microdata Processor.

System	Price ($000)	Memory (K-bytes)	DASD (M-bytes)	Year Introduced
IBM S/3 MOD 10	68.7	12.0	4.9	1970
NCR CENTURY 50	55.8	16.0	8.4	1970
DIG SCI M 4/1130	100.0	64.0	40.0	1970
HONEYWELL 105	77.0	12.0	9.2	1971
BASIC/FOUR M 350	35.0	24.0	20.0	1971
BASIC/FOUR M 400	45.0	32.0	20.0	1971
FOUR PHASE SYS 1V/70	110.0	96.0	2.5	1971
DIG SCI M 4/1800	150.0	96.0	100.0	1971
NCR CENTURY 101	80.5	16.0	9.8	1972
COMP INTER COMPRO II	40.0	16.0	26.0	1972
STC ULTIMACC 2000**	44.0	32.0	10.0	1972
XEROX 530	80.1	16.0	0.0	1973
FOUR PHASE SYS 1V/40	70.0	72.0	2.5	1973
DISPLAY DATA INSIGHT#	64.0	40.0	40.0	1973
HOTEL	250.0	64.0	5.0	1973
ICL 2903	150.0	336.0	120.0	1973
LOCKHEED SIII/A	20.0	32.0	5.0	1973
MICRODATA REALITY#	66.9	40.0	10.0	1973
MICOS 1003 (MINI-COMP SYST)**	49.9	64.0	10.0	1973
MCS-2000A	150.0	48.0	10.0	1973
MICOS 2003**	74.6	64.0	80.0	1973
MICOS 3003**	84.4	64.0	160.0	1973
MICOS 4006**	104.9	128.0	160.0	1973
CHC DIST SYS*	100.0	128.0	88.0	1974
DATASAAB D15	75.0	32.0	20.0	1974
DIMIS TOTAL 100	135.0	64.0	50.0	1974
LITTON 1300 CASSETTE	19.5	16.0	0.0	1974
LMC ADAM	40.0	32.0	10.6	1974
NORTHROP BDS-2000#	62.8	24.0	20.0	1974
WARREX CENTURION III	35.1	32.0	10.4	1974
WARREX CENTURION IV	42.7	32.0	10.4	1974
IBM S/32 (A)	33.6	16.0	3.6	1975
IBM S/32 (B)	45.1	32.0	9.3	1975
IBM S/32 (C)	67.7	32.0	13.9	1975
IBM S/3 MOD8	63.4	16.0	2.5	1975
BINARY DATA UCOM**	60.0	64.0	10.0	1975
DIG SCI M 4/VM-TSO	140.0	96.0	100.0	1975
GRI SYSTEM 99	33.0	32.0	10.6	1975
GEN ROB TSS/11	59.8	120.0	10.0	1975
LITTON 1300 DISK	21.5	16.0	1.5	1975
NIXDORF 8870 (A)	40.0	48.0	10.0	1975
NIXDORF 8870 (B)	94.2	64.0	20.0	1975
NORFIELD NOVA **	110.0	64.0	25.0	1975
NORTHROP BDS-1000#	49.5	16.0	10.0	1975
QANTEL 900	30.0	32.0	6.0	1975
QANTEL 950	40.0	40.0	12.0	1975
QANTEL 1400	65.0	64.0	25.0	1975
RANDAL LINK 100	20.0	32.0	0.6	1975
RAYTHEON PTS/1200	67.6	48.0	5.0	1975
STC ULTIMACC 3000**	94.0	96.0	30.0	1975
WANG 2200	14.7	16.0	0.0	1975
WANG PCS-II	6.2	16.0	0.5	1975
WINTEX 200 NS	15.0	8.0	0.5	1975
IBM S/3 MOD 12	102.9	32.0	100.0	1976
BASIC/FOUR M600	55.0	32.0	20.0	1976
CADO SYS 40 SBS	20.0	5.0	1.2	1976
FOUR PHASE SYS 1V/50	98.0	72.0	2.5	1976
COMPUCORP 450/OPD	18.4	16.0	1.2	1976
SYFA(1) (COMPUTER AUTO)	72.3	64.0	20.0	1976
SYFA(2)	88.0	64.0	20.0	1976
SYFA(3)	117.0	64.0	160.0	1976
COMP COV CPBS-1*	24.0	56.0	0.5	1976
CTL 8030	70.0	96.0	9.6	1976
CTL 8050	147.0	144.0	19.2	1976
ECLIPSE C/330 (DG)**	148.3	256.0	96.0	1976
GIS ABLE/324*	39.0	32.0	7.2	1976
GIS ABLE/322*	24.9	32.0	0.5	1976
GEN ROB GRC 11/03	14.0	24.0	2.4	1976
ICL 2904	260.0	480.0	240.0	1976
IC MIDAS	100.0	96.0	50.0	1976
JACQUARD J100(A)	27.3	64.0	0.0	1976
JACQUARD J100(B)	58.3	128.0	0.0	1976
MICRODATA REALITY 11#	31.5	16.0	10.0	1976
MICRODATA REALITY 11(B)#	45.7	32.0	10.0	1976
MICRODATA EXPRESS III#	70.0	128.0	10.0	1976
MYLEE 3056	40.0	56.0	48.0	1976
MYLEE 3088	80.0	152.0	96.0	1976
Q1 LITE	21.0	16.0	1.0	1976
RANDAL LINK 200	27.0	32.0	10.0	1976
STC ULTIMACC 3370**	200.0	256.0	400.0	1976
APPLIED DC SER 70 FLOPPY***	12.0	32.0	1.0	1977
APPLIED DC SER 70 CART. DI***	27.0	32.0	10.0	1977
CADO SYS 40 TERM***	15.0	5.0	1.2	1977
NORTHROP BDS-700#	38.9	16.0	10.0	1977
WARREX CENTURION I-A	18.0	32.0	1.0	1977

of the constrained relevance of a general set of benchmark jobs to a particular user. Thus the cost is exorbitant and the benefit slight.

Knight's algorithm for power was a surrogate for benchmark measurements. First he determined, through a set of benchmarks, how a certain "typical" jobstream engaged the basic operating components of the computer. From this, he developed a set of weights for these operating components so that their characteristics could be used to derive a measure of relatively how fast a machine could run the jobstream. This measure, expressed in instructions per second, became Knight's power measurement. In summary form, it is

$$\text{Power} = f\left[\frac{\text{Memory}}{\text{Compute time} + \text{I/O time}}\right]$$

where *Memory* is basically the number of bits in main storage, weighted by a constant. This weighting factor was derived from the opinions of a group of experts as to the effect of memory size on computing power. *Compute time* is the time it takes the processor to perform a certain mix of basic instructions. Five instructions are used, namely fixed-point addition, floating-point addition, multiply, divide, and logical compare, and the timing for each is multiplied by a weighting factor. *Input/output time* is the amount of time the processor would spend waiting for I/O during the execution of the instruction named above, if those instructions were being executed as part of a typical business program. It is calculated through the use of an extremely complicated algorithm.

The advantage of Knight's approach is that it provides a single measure of computer power that can be statistically related to system cost. Unfortunately, his formulation is no longer usable. Computer design has changed so drastically since the early 1960's that his model, formulated for the computers of that time, does not adequately measure the computers of today. The effect of memory size on computer performance is quite different from what it was in 1963, because most large systems today employ some form of virtual memory. Likewise, Knight's input/output time measure is not really applicable to today's systems. It is oriented towards magnetic tape as the primary I/O medium (as it was in 1960) rather than direct access storage (as it is today). Also, Knight's method of measuring I/O time would yield a zero value for most large modern computers, which employ satellite subprocessors to control input/output.

We attempted to build several simplified versions of Knight's model, with single measure surrogates for memory, compute time, and I/O time measures. Unfortunately, we could not develop a convincing rationale for any particular method of combining the measures. Statistically, the formulation

$$\text{Power} = \frac{\text{Memory size} + \text{DASD capacity}}{\text{Add-time}}$$

provided a good correlation with system cost for any given year of introduction. However, other models with equally good correlation values could be obtained with different combinations forming the power measure; they showed markedly different relationships between system price and power.

Rather than continue the attempt to quantitatively define the concept of power, an alternative approach was taken. Using the free market price of systems as the most generally accurate measure of system performance, a model was developed that directly related system costs to measures of significant system component characteristics. The model which provided the most consistent results was

$$\text{Cost} = (B_0 + B_3 \cdot D_1 + \ldots + B_n D_n) \cdot (\text{Memory}^{B_1} + \text{DASD}^{B_2})$$

or, in a form so that it could be run through a least squares regression program,

$$\text{Ln Cost} = B_0 + B_1 \cdot \text{Ln Memory} + B_2 \cdot \text{Ln DASD} + B_3 \cdot D_1 + \ldots + B_n \cdot D_n$$

the value of the variables for each system being developed in the following manner from the manufacturer's data.

Cost

The total system cost including all the peripheral equipment necessary for a balanced system. It is expressed in dollars.

Memory

The amount of main memory in *bytes* which is obtained where appropriate by dividing the word length by 8 and multiplying by memory size. Adjusting to bytes provides a common basis for memory size among computers with different word lengths.

Direct Access Storage Devices (DASD)

This parameter is the number of megabytes of on-line direct access storage for the system. The same conversion was made from words to bytes where necessary. For the most part this represents disk storage capacity; however, for some systems it includes drum storage, and for some it is diskette (floppy disk) storage.

Year of System Introduction

This system of binary variables representing the year of introduction is defined as follows:

D_1 is 1 if year of introduction is 1972 or 1973; otherwise 0.

D_2 is 1 if year of introduction is 1974 or 1975; otherwise 0.

D_3 is 1 if year of introduction is 1976 or 1977; otherwise 0.

The dummies were set up for two-year intervals because of the uneven distribution of the data over time. With these groupings the distribution of observations was reasonably balanced over the years. Separate variables were used instead of one time variable so that the differing effects over different years could be noted. (Note: The base case, i.e. $D_1 = D_2 = D_3 = 0$, covers computers introduced in 1970 or 1971.)

Identification as Small Business Systems vs. General Purpose

D_4 discriminates between small business computers and general purpose computers. $D_4 = 1$ for small business computers; otherwise 0. The base case of the model then with all variables = 0 is for general purpose computer systems introduced before 1972.

Note that neither add-time nor any other direct measure of processor speed is in the model. The fact is that in all the various formulations which were tried for the model, the coefficient derived for such a measure was not significantly different from zero (i.e. H_0: $B = 0$ could not be rejected at a 95 percent significance level). Thus the final model was run without this variable.

This is explainable by the complexity of modern processors. Add-time, or multiply-time, or the like, is altogether too simplistic a measure of processor power to be useful. Many other aspects of computer architecture (parallel processing, for example) dominate the effect of simple instruction timing. Control Data, for example, specifically points out that because of the concurrent operations of the 12-word instruction stacks in the Cyber 76, 175, and 176, instruction timings are a poor indicator of overall performance [2]. Burroughs even refuses to divulge instruction timings for the B6807, maintaining that because of its unconventional architecture, straightforward instruction time comparisons would be meaningless [2]. Also, memory size and DASD capacity are themselves correlated with and remain a proxy for computer power, thus masking any measurement effect of instruction timings in the model.

Thus we are left with two hardware characteristics as independent variables in our measure of computer performance. This performance characterization assumes that vendors offer and users acquire *balanced* computer systems. The market deems that the critical aspects of modern computers are memory and direct access capacity which are supported by other components that allow them to do proportionately more work than computers with smaller memories and less DASD capacity. This is much the same assumption as used by Chow [3] in his formulation which makes use of only a few characteristics as independent variables. In his words,

> As far as the omitted characteristics of the hardware are concerned, it is assumed that they are highly correlated with the included ones so that our estimate ... would not be too inaccurate.

The high correlation values obtained from the model using only a few characteristics support this hypothesis.

Table I shows the results of a model run on all observations, using dummy variables for time and system type. This model suggests that there are in fact significant differences in the relationship between system price, memory size, and DASD capacity, between different years and system types. To explore this further, the data file was broken into two files, one of which contained the observations on the general purpose systems, and one of which contained the small business computers. A statistical analysis was then run on each set of computers. Table II summarizes the results of these regression models. This analysis identifies a price advantage in the smaller systems. To illustrate this we can look at the predicted cost of a system which falls within the relevant range of either model, and compare how the different models predict.

Table III shows the predicted cost of a system which (1) has 100,000 bytes of main memory; (2) has 100 million bytes of on-line DASD capacity; and (3) was introduced in 1974 or 1975. Such a system is well within the relevant range of any of the models presented. The

Table I. Results of regression model run on all observations using dummy variables for year and type.

Variable	B*	t-Statistic
Constant term	10.3	54
Ln memory size	.5	13.6
Ln DASD capacity	.12	5.7
Effect for 1972–1973	−.3	−2.7
Effect for 1974–1975	−.5	−4.7
Effect for 1976–1977	−.71	−7.2
Effect for small business system	−1.1	−11.2
$R^2 = .925$ (160 degrees of freedom)		
$t \geq 2.5$ = 99% level of confidence		

*B is the coefficient in the regression equation for each variable. It is the amount the dependent variable changes for each unit change in the independent variable.

Table II. Results of regressions using separate data files for different computer types.

	General Purpose Systems		Small Business Systems	
Variable	B	t-Statistic	B	t-Statistic
Constant term	10.2	51	9.3	35
Ln memory	.42	8.3	.46	6.9
Ln DASD	.24	5.3	.11	4.2
Effect for 1972–1973	−.4	−2.9	−.14	−.7
Effect for 1974–1975	−.54	−4.5	−.43	−2.2
Effect for 1976–1977	−.83	−6.4	−54.	−2.8
R^2	.854		.626	
Degrees of freedom	76		79	
$t \geq 2$ = 95% level of confidence				

Table III. Predicted cost of a system introduced in 1974 or 1975 with 100 K-bytes memory and 100 megabytes DASD; predictions according to various models.

Model Used	General Purpose	Small Business Computer
Global	\$313,400	\$104,300
Subdivided by type	\$327,500	\$ 98,200

Table IV. Regression models run on general purpose computer systems only, subdividing the data set by year of introduction.

Year	Constant		Memory		DASD			Degrees of Freedom
	B	t	B	t	B	t	R^2	
1970–71	11	36	.47	4.3	.04	.4	.848	13
1972–73	10	14	.38	2.4	.24	1.6	.669	12
1974–75	10	37	.38	4.8	.3	4.2	.898	26
1976–77	9	21	.49	5.4	.27	3.4	.854	19

Table V. Regression models run on small business computer systems only, subdividing the data set by year of introduction.

Year	Constant		Memory		DASD			Degrees of Freedom
	B	t	B	t	B	t	R^2	
1970–71	Too Few Observations							
1972–73	9.7	14	.45	2	−.6	−.7	.259	12
1974–75	9.1	19	.38	2.5	.18	3.7	.690	27
1976–77	8.5	30	.51	6.9	.14	4.3	.778	29

difference between the predictive models emphasizes the difference in costs—in the individual models the costs diverge by $20,000 greater than with the global model. By way of comparison an integrated SBC system such as the IBM S/3 model 15 used in the database costs $253,000; while a similarly configured nonintegrated SBS, the Computer Horizons Distribution System, comes in at $100,000—some $150,000 less and consistent with our model. The overall appraisal of both analyses indicates that, given hardware characteristics and year of introduction, a system classified as a small business computer is likely to be less costly than its general purpose systems counterpart. The very significant differences in predicted price which result from changing its classification are really reflecting what set of vendors we think that computer might be coming from. If we call it an intermediate system, we are saying that it is coming from IBM, Honeywell, Burroughs, etc. If we call it a small business system, then we are grouping it with those machines which probably do not come from those "old standard" computer companies but from software firms packaging a system around OEM hardware.

The impact of time of introduction on cost vs. capacity was analyzed to better understand the computer system market of the 1970's. Tables IV and V summarize the results of these models. The analysis shows evidence of two quite different markets. The large and intermediate computer systems are sold in a market which has been established for some time. This market has an acknowledged market leader (IBM), and the number of firms competing in it is both small and stable. In fact, competition between vendors in this market is rather limited—customers are usually deterred by the massive conversion costs of switching large installed computer systems from one vendor's equipment to another's. This market has grown because of the continuous development of software unique to the vendor. In short, it is a mature, rationalized market.

For the general purpose data in Exhibit 2, this market indicates that memory size alone is a fairly good predictor of system cost for all systems introduced during the 1970's, and its coefficient is relatively stable over time. The consistently high correlation values over all years suggest that not only is memory a proxy for all the other components of computer performance, but also that there exists a stable price/performance relationship in the industry as well. In this breakdown of observations, DASD is significant only after 1974; however, the small size of the samples may have something to do with this. In general, it can be inferred that the basic pricing policies in this segment of the computer industry are set.

The data on small business computers tell quite a different story. For the period before 1974, no satisfactory model can be built. In fact, this segment of the industry was in th early stages of development in the years before 1974. The distribution of observations across time points to this. Only in the last few years does a definite price/hardware power relationship begin to appear. If we look at the coefficients of the model for small business systems, 1976–77, and compare them with the corresponding coefficients for the general purpose systems of the same time, we will again see the small systems model predicting lower prices for the same hardware. For example, going back to our system with 100K memory and 100 megabytes DASD, we find the small systems model predicting a cost of $98,000, and the general purpose systems model predicting $220,000.

Intuitively, such a price differential is understandable. General purpose computers are usually provided to customers with a wide variety of software, documentation, and other services which are not reflected by hardware characteristics. Small business computers are often of single or limited purpose, and are usually delivered with fewer customer services. Additionally, the lesser complexity of the small business computers reduces the time of design and development cycle, allowing certain technical and cost effective improvements more rapid market availability.

In all formulations of the models, the effect of advancing technology is unmistakable. A system of given hardware characteristics would cost less if introduced later in time. Again using our 100K memory-100 megabyte DASD system, we see that the general purpose system model predicts that it would have cost over $550,000 in 1970, $380,000 in 1972, $330,000 in 1974, and $250,000 in 1976. The other formulations of the model would demonstrate a similar decline in cost. Again, intuitively, this is quite acceptable. One has only to look at the dramatic drop in prices of electronic calculators (which are made with much the same technology) to verify that such a strong technological effect can exist.

In probing for differences in the price/hardware characteristic relationships between various vendors, we

Table VI. Average natural residual by vendor, using as a predictor the model based only on general purpose systems, year dummy variables included.

Vendor	Average Natural Residual
Burroughs Corporation	.03
Control Data Corporation	−.02
Digital Equipment Corporation	−.45
Honeywell Information Systems	.10
IBM	.06
National Cash Register	−.15
Sperry–Univac	.03
Xerox Data Systems	.25
Standard Deviation of Natural Residual	.38

can look at the natural residual values (i.e. actual cost minus predicted cost) sorted by vendor. Table VI summarizes these residual values. It will be noted that only one vendor—Digital Equipment Corporation (DEC)—appears as an "outlier," with an average residual value more than one standard deviation away from zero. Intuitively, this is quite acceptable. The systems offered by DEC are in fact somewhat different from the general purpose computer systems offered by other vendors. DEC's systems are time-sharing oriented machines, many being installed in universities. Those that are used in business organizations typically complement systems manufactured by one of the other large systems vendors, with the DEC system performing some special purpose task, such as driving a time-sharing network for program development. It is quite understandable then that the model might not describe DEC systems as well as other general purpose business systems.

No similar analysis was performed for the small business systems because of the large number of vendors, and the small number of observations (usually 2–4) per vendor. The effect of doing such an analysis would be little different from looking at individual systems' residuals.

3. Conclusions

A. Grosch's Law

It is highly questionable whether a single, simplistic measure of computer power has any meaning. The "power" of a computer is really its ability to perform a given amount of work; therefore any power measurement must be work-specific. There is no independent, generally accepted definition of a unit of work in the computer sciences as there is, for instance, thermodynamics. In other words, it is meaningful to talk about how well different computers execute *a certain jobstream*; it is not meaningful to talk about the computer's power in a general sense. When we say that computer A is more powerful than computer B, we are really saying that we think, for any relevant jobstream that we are interested in, computer A would be a better processor.

Thus, to examine Grosch's Law one would have to restate it slightly: The power of a computer *to process a given jobstream* increases as the square of the computer's price increases. Knight was implicitly addressing this restatement of the law. His power measurement attempted to estimate how well various systems could perform that jobstream with which he developed his algorithm. To perform a study similar to Knight's one would have to develop an algorithm similar to his, (or actually benchmark all the systems) tailored to modern systems. To do so one would have to develop a jobstream which one considered "typical" of business data processing, and then develop a method of measuring how well the various systems executed the jobstream. This measure of "how well" the systems perform could be used as a power measure. And even this approach would be open to question—how exactly does one measure "how well" a system performs a jobstream? Do you judge the system in terms of speed? User convenience? If not these, then what criteria do you apply?

B. Price vs. Hardware Characteristics

The best single measure of computing power is computer price. There no longer exists a single relation between price and power due to the development of a new nonintegrated market in recent times. The market for large and intermediate systems is served by the "old standard" computer manufacturers, and it consists mostly of the established customers of these vendors.

The new market for small business computers, on the other hand, is in a development stage. Most of the vendors in this market are nonintegrated and relatively small with little software dependence. Many of these companies either do not offer support services to their customers, or at least are perceived by customers to not offer such service. Many of these companies' machines are sold for a special purpose, i.e. tailored to a specific application. This fact, along with the relative newness of the small business computer market, hinders the formation of a clear pricing policy.

In both markets technological advance is clearly causing a decrease in the price of any given hardware component. In fact, it is the technological advance itself which has spawned the development of the small computer market. Ten years ago a system such as the Mylee 3088 might have cost nearly one-half million dollars! Just as advancing technology has made calculators available to anyone who can afford one, so too is it offering computers to any business (and many individuals) that can afford them.

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References
1. All about small business computers. In *Datapro 70*, Datapro Res. Corp., Delran, New Jersey, 1977, pp. 70C-010-30a to 70C-010-30j.
2. Burroughs B6800 and B7800. In *Datapro 70*, Datapro Res. Corp., Delran, New Jersey, 1977, pp. 70C-112-12a to 70C-112-12x.
3. Chow, Gregory C. Technological change and the demand for computers. *Amer. Economic Rev. LVIII*, 5 (Dec. 1967), 114-132.
4. Distributed data processing: It's a question of experience. *Datamation 22*, 9 (Sept. 1976), 160-162.
5. Golub, Harvey. Organizing information system resources: Centralization vs. decentralization. In *The Information Systems Handbook*, F. Warren McFarlan and Richard L. Nolan, Eds., Dow-Jones Irwin, Homewood, 1975, pp. 65-91.
6. Grosch, Herbert A. High speed arithmetic: The digital computer as a research tool. *J. Opt. Soc. Amer. 43*, 4 (April 1953).
7. Grosch, Herbert A. Grosch's law revisited. *Computerworld 8*, 16 (April 16 1975), p. 24.
8. Hayes, Robert H. Europe's computer industry: Closer to the brink. *Columbia J. of World Business IX*, 2 (Summer 1974), 115-120.
9. Knight, Kenneth E. Changes in computer performance. *Datamation 12*, 9 (Sept. 1966), 40-54.
10. Sharpe, William F. *The Economics of Computing*. Columbia U. Press, New York, 1969.
11. Stoneman, Paul. *Technological Diffusion and the Computer Revolution: The U.K. Experience*. Cambridge U. Press, London, 1976, p. 75.
12. Theis, Douglas J. The midi-computer. *Datamation 23*, 2 (Feb. 1977), 79-81.

Management Applications

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A Methodology for the Design of Distributed Information Systems

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A macro model of a distributed information system in presented. The model describes the major costs of using an information system from the perspective of the end-user. The model is intended to provide guidance to the system designer by making evident the effect of various design and operating parameters on overall cost per transaction. The technique is illustrated by application to the design of an interactive transaction processing system.

Key Words and Phrases: distributed processing, system design, cost minimization, distributed database, interactive computing, economic modeling, transaction processing

CR Categories: 4.32, 4.33, 6.2, 8.1

1. Introduction

The ultimate objective of a computer system designer is to provide a system configuration which meets the user requirements at the least overall cost. However, as systems and usage become more complex, it becomes increasingly difficult for the designer to relate the effects of his choices and decisions to this ultimate objective.

In this paper we describe a macro model of a computer system "in use," which is intended to provide the designer with a broader perspective in a constructive way. By constructive, we mean that the model provides practical guidance to the designer in making some of his

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