Faculty Working Papers

FACT IN FICTION? THE RELATIVE COSTS OF STEAM AND
WATER POWER: A SIMULATION APPROACH

Jeremy Atack, Assistant Professor of Economics

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Summary:

    Between 1820 and 1900, the steam engine replaced the water wheel and water
turbine as the prime mover in American industry before itself succumbing to the
fractional horsepower electric motor. The relative costs of alternative power
sources were crucial in the decision to adopt technology A (steam) over
technology B (water) yet there exist no systematic and unbiased estimates of the
relative costs of these two alternate power sources during the nineteenth centruy.
This paper develops and explores an elaborate simulation model to generate cost
probability distributions for the two power sources from limited, scattered and
uncertain historical evidence. The simulation model is a more elaborate and
generalized version of the Hertz model and imposes minimal constraints upon the
nature and form of the input probability distributions.

FACT IN FICTION? THE RELATIVE COSTS
OF STEAM AND WATER POWER:
A SIMULATION APPROACH *

Over the past decade or so, simulation modeling has become common-

place in the analysis of economic problems where it can perform a number

of important roles such as supplementing otherwise inadequate data, avoid-

ing the difficulty of formulating a mathematical model to describe the

behavior of a complex system, predicting behavior or validating the model

by facilitating statistical testing (Naylor, 1966). However, economic

historians, including cliometricians, have largely ignored this development

despite the clear applicability of the method to historical analysis. This

paper introduces a simulation model of wide applicability and demonstrates

the power of simulation methods to illuminate difficult and complex histor-

ical problems, by discussing the diffusion and adoption of the steam engine

in the nineteenth century.

Increased Use of the Steam Engine by American Manufacturers

Although the history of the steam engine in America can be traced

back to the Hornblower engine which was imported in 1753 to relieve flooding

in the Schuyler copper mine at Passaic N.J. (Loree, 1929), little attention

was paid to the invention until after 1800. In part, this reflected the

high fuel consumption and operating costs of the Newcomen-style (i.e.,

atmospheric) engines and the delay in the spread of James Watts' improvements

caused by the Revolutionary Wars, but more fundamentally the neglect probably

reflected lack of familiarity with the invention among American engineers

and would-be users. According to Dickinson (1938), as of 1803, "not more

than six engines could be mustered in the whole of the States; mechanical

construction and skill were at least fifty years behind those in England."[1]
However the pioneering work of Oliver Evans closed the technological gap
between Britain and America and served to popularize steam power and its
use in manufacturing industry in America. The contribution by Evans was
two-fold. First, the prototype high pressure engine successfully power-
ed his plaster-of-Paris mill (a notoriously demanding task) providing
a convincing demonstration of the power of his engine and second, with
the publication of The Abortion of the Young Steam Engineer's Guide
in 1805, Evans placed the power of steam at almost anybody's command by
providing for the first time a detailed outline of construction methods
and operating principles. Not surprisingly other engineers duplicated
Evans' engine designs, infringing his patents. Evans sued but lost
(Pursell, 1969).

While the high pressure engine was also simultaneously invented in
Great Britain by Richard Trevithick, it was never as popular there as it
was in America, so that from this time on British and American steam
technologies began to diverge. In part this reflected the biases of the
leading engine builders in each country--Boulton and Watt in England and
Oliver Evans in America,[2] but it also reflected more fundamental differences.
The high pressure engine was more cheaply constructed, used more fuel per
horsepower and wore out more quickly than the low pressure engine favored
in Britain. Presumably the price of capital relative to fuel was higher
in the United States than in England and American entrepreneurs, histor-
ically, seem to have been less averse to obsolescence and replacement
than their British counterparts. Demand for ship's engines also affected
the choice. The high pressure engine exhausted steam under pressure to

the atmosphere and consequently was a voracious consumer of fresh water necessitating constant supply and mandating against salt water use thereby limiting its usefulness to the British shipping interests.

By 1820, the incomplete manuscripts of the Fourth Census (National Archives, 1964) show 43 engines in use by forty firms.[3] Eighteen years later, the Report on the Steam Engines in the United States (Woodbury Report, 1838) gave detailed statistics on 1173 stationary steam engines in use in manufacturing plants across the country and estimated the total number in such use at 1420. Almost all these were high pressure designs.[4] Like the 1820 Census, the Seventh and Eighth Censuses (1850 and 1860) requested details of the motive power sources used by manufacturers, and while these responses were never compiled and tabulated, they are given in the census manuscripts. On the basis of the Bateman-Weiss samples from these documents,[5] it is estimated that by 1850 the number of steam engines in use had grown to over 8,000 and to over 25,000 by the time the 1860 Census was taken. From 1870 onward, the published censuses record the number of engines in use. These figures are shown in Table 1.

Table 1 shows quite clearly the relative and absolute decline in the importance of water as a motive power source. Whereas in 1819-1820, virtually all plants that required inanimate power sources used the waterwheel, by 1899 the steam engine outnumbered the waterwheel and water turbine by almost four to one. This decline occurred despite the development of the water turbine which was introduced to American industry in 1846[6] (Clark, 1929) and brought about a dramatic improvement in the operating efficiency of waterpower.[7] Further, despite its ability to overcome one of the more

Table 1

Steam Engines and Waterpower Sources in Use
1820-1900
(48 states)

Year	Steam Engines in use	Water Wheels and turbines in use	Percentage of plants using steam to those using steam or water
1820	43	n.a.	1[a]
1838	1,420	n.a.	6[a]
1850	8,598	37,602	18
1860	25,577	46,260	35
1870	40,191	51,018	46
1880	56,123	55,404	58
1890	91,390	39,003	71
1900	155,724	39,155	80

[a]Estimated

Sources: 1820, National Archives (1964)
          1838, Woodbury Report (1938)
          1850 and 1860, Bateman-Weiss sample data
          1870, Ninth Census (1872)
          1880, Tenth Census (1883)
          1890, Eleventh Census (1895)
          1900, Twelfth Census (1902)

significant disadvantages of the wheel, namely the poor performance

under backwater conditions[8] the turbine did not noticeably check

the advance of steam.

The estimates of the percentage of plants using steam or water

power that actually adopted the steam engine in Table 1 were used to

estimate a logistics curve.[9] After 1880, the rapid development of

electrical power led to the gradual replacement of the steam engine

by the fractional horsepower electric motor and the use of steam power

peaked about 1910 when approximately 82 percent of all manufacturing

plants in the nation were using steam power.[10] These data led to the

estimate of the logistics curve defined by:

$$\log_e[P/(82 - P)] = -4.2831 + 0.0932 \cdot t \qquad r^2 = .981 \qquad [1]$$
(t-statistic)   (-17.3204)   (18.9581)

where P is the percentage of plants using steam and t is the time vari-

able. As can be seen from the adjusted R^2, the fit of the data to the

equation is very close and yielded the S-shaped growth curve shown in

Figure 1. This curve suggests that the adoption process did not begin

to accelerate until the 1840s and was essentially complete by 1890.

This is consistent with the flow of literature describing the virtues

of steam power vis a vis alternate power sources and with the evidence

in Table 1.

The Adoption of a New Technology

The decision to adopt a new technology is dependent upon a large

number of factors, dominant among which we would expect to be the profit-

ability of switching from the existing technology to the new. In the

Figure 1

Percentage of all plants adopting steam in the U.S.
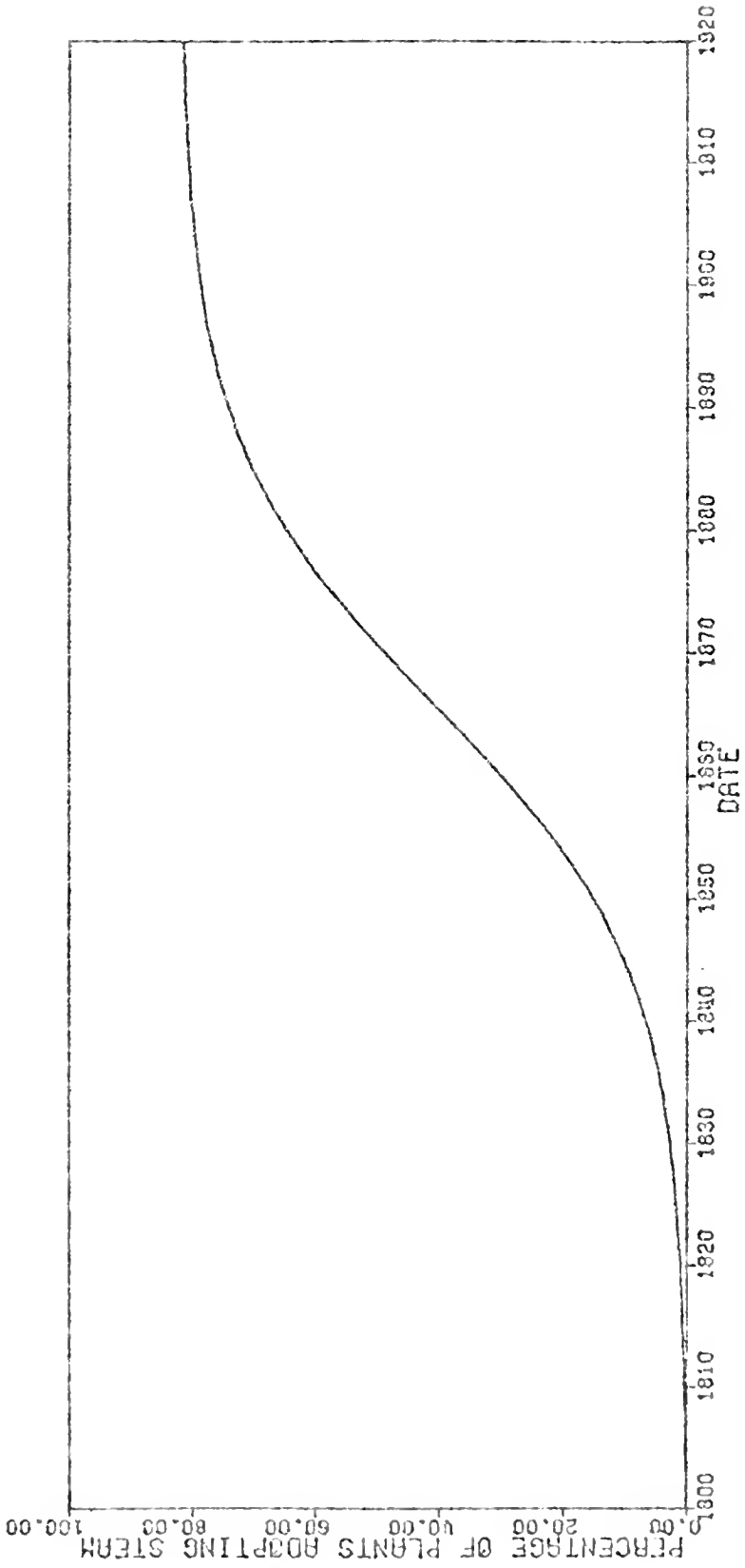
context of the present discussion of steam- versus waterpower, "profit-ability" is defined as the difference in per horsepower costs between steam power and waterpower adjusted for any productivity differences between the two, i.e., the real cost difference between the technologies.

Since water and steam power are substitutes for one another, the choice between these investment opportunities may be made by appealing to the capital budgeting model (Hirshleifer, 1958; Bailey, 1959). Consider two mutually exclusive projects, W and S, each with a life of $\underline{n}$ years in which costs of C(W) and C(S) are incurred. The capital budgeting decision would then lead to the selection of the project with the lowest present value of future costs. That is, if:

$$PV(S) = \frac{C(S)}{r} \cdot [1 - \frac{1}{(1+r)^n}] < PV(W) = \frac{C(W)}{r} \cdot [1 - \frac{1}{(1+r)^n}] \qquad [2]$$

where $\underline{r}$ is the discount rate and PV(S) and PV(W) are, respectively, the present values of project S and project W costs, then project S would be selected in preference to project W. However a number of factors serve to complicate this seemingly simple proposition.

Let us identify Project S as the decision to install a steam engine, while Project W is the alternative decision to install a water power source (wheel or turbine, depending upon the date at which the decision is made[11]). The available evidence suggests that the former, steam, was much shorter lived than the waterpower sources[12] and that while both became longer lived as the nineteenth century progressed, the relative gap between the life expectancies of these two assets probably remained unchanged. Let $E[n(S_t)]$ be the life-span of a steam engine purchased at time t and $E[n(W_t)]$ be the life expectancy of a waterpower source installed at

time t, where $E[n(S_t)] < E[n(W_t)]$ and $E[n(S_t)]/E[n(W_t)] = $ constant. This change seriously complicates the standard capital budgeting model, but a number of alternative variations are possible.

The simplest alternative model is to assert that the planning horizon of the firm is less than or equal to the life expectancy of the shortest lived asset so that costs incurred beyond this planning horizon are irrelevant to the decision. Analogously, we could base the decision on the present value of costs over a period equal to the life expectancy of the shorter-lived asset, $E[\overline{n}(S_t)]$. Both these models are simple and, perhaps, naive, but more complex models can be devised.

Consider, for example, a model over the period $E[n(W_t)]$ where the entrepreneur who selects waterpower at time t is forced to live with his decision over the entire period, while the entrepreneur who selects steam at time t, will, at the end of $E[n(S_t)]$ years, have the opportunity to reassess the situation and either purchase a new steam plant or switch to waterpower. Regardless of whether water or steam is then chosen, the entrepreneur will be purchasing the technology existing at time $(t + E[n(S_t)])$ and contracting at the interest rates etc. prevailing at that time. If waterpower is selected then the entrepreneur remains committed to water until the end of the period at $(t + E[n(W_t)])$, while if steam is selected the entrepreneur will have a total of N opportunities to recontract and switch to water, where N is the largest number such that:

$$\sum_{i=0}^{N} E[n_i(S_{t+i})] < E[n(W_t)], \quad N \geq 1 \text{ and integer.} \tag{3}$$

For example suppose $E[n(S_t)] = 10$ years and $E[n(W_t)] = 25$ years, and that at time $(t + 10)$, $E[n(S_{t+10})] = 10$ years, then the entrepreneur who selected

steam at time t would have the chance to switch at time $(t + 10)$ and again
at time $(t + 20)$ provided of course that he did not switch at time $(t + 10)$.
On the other hand if at time $(t + 10)$, $E[n(S_{t+10})] \geq 15$ years then there is
only one opportunity to switch and that would be at time $(t + 10)$. The deci-
sion rule of whether or not to switch has not been specified but could be based
on estimates of the probability that steam will be cheaper than waterpower[13]
derived either from past experience (i.e., a adaptive model) or from future
expectations.

Even this more complex model ignores the possibility of abandonment
of an asset before the end of its useful life. This would be an economically
rational decision whenever the present value of future costs including
abandonment is greater than the present value of future costs of the alter-
native over the same period. At the limit over a period of T years, a
total of T switches could be made. This, however, is unlikely.

Because as we shall show below, steam power costs declined over the
period at a faster rate than water power costs, allowing switching actually
means permitting recontracting for steam power and taking advantage of the
technological improvements in the steam engine and secular decline in
market interest rates. Switching then would widen the difference between
the present value of steam power costs and waterpower costs to the advantage
of steam. We have, therefore, opted to present the weaker results based
on the simpler model in which we assume a planning horizon for the firm
of ten years.

The Simulation Model

Thus far we have avoided defining $C(S)$ and $C(W)$, the costs per horse-
power of steampower and waterpower respectively on an annual basis (309

working days[14]). Waterpower costs include not only the capital charges
against the cost of the wheel, gearing, forebays, etc. and the cost of a
wheelman, but also the purchase of water rights and other miscellaneous
expenses such as repairs and insurance. Similarly costs of steampower
include capital charges against the cost of the engine, boilers, founda-
tions, etc., the cost of the fuel and labor charges for an engineer and
fireman together with miscellaneous costs similar to those for water
power. Explicitly,

$$C(W) = WHEEL \cdot [INT + DEPRC(W) + REP(W) + INS(W)] + [WATER/EFF]$$
$$+ [WAGE \cdot DAYS(W)] \qquad [4]$$

and

$$C(S) = ENG \cdot [INT + DEPRC(S) + REP(S) + INS(S)]$$
$$+ [FUELCON \cdot COALP \cdot DAYS(S) \cdot HOURS] + [2.0 \cdot WAGE \cdot DAYS(S)] \quad [5]$$

where:

$C(W)$	= Cost of waterpower per horsepower,
$C(S)$	= Cost of steam power per horsepower,
INT	= Rate of interest;
DEPRC(W), DEPRC(S)	= Straight line depreciation rate on waterwheel or steam engine, ($= 1/E[n(W_t)]$ or $1/E[n(S_t)]$);
REP(W), REP(S)	= Repairs for waterwheel or steam engine as a fraction of original cost;
INS(W), INS(S)	= Insurance rate on waterwheel or steam engine as a fraction of original cost;
DAYS(W), DAYS(S)	= Days of operation per year for waterpowered or steam powered plant;
WAGE	= Average daily wage rate, semi-skilled, per horsepower;

WHEEL   = Original cost of waterwheel, gearing, forebays,
                           etc. per horsepower,

WATER   = Annual cost of water-right capable of producing
                           one theoretical horsepower (= [Flow of water
                           (cubic feet/minute) · Height of Fall (feet)
                           · Weight of One Cubic foot of Water (pounds)]/
                           33000);

EFF   = Design efficiency of waterwheel, (=[Realized/
                           Theoretical] horsepower);

ENG   = Original cost of steam engine, boilers, etc.
                           per horsepower;

FUELCON   = Coal consumption, pounds per hour per horsepower;

COALP   = Bituminous coal price, dollars per pound;

HOURS   = Average daily hours of operation.

These variables, however, are not single-valued.[15] Rather they are

uncertain and subject to both random and systematic fluctuations. They

may also be imperfectly observed and measured and in some cases only the

most rudimentary kind of information about the variables is available.

Indeed, in some cases, none could be unearthed. We are thus dealing with

a capital budgeting problem under uncertainty (Hillier, 1963; Van Horne,

1966). However, whereas most studies of capital budgeting under uncer-

tainty assume normally distributed variables, no such assumption is made

here. Given the limited information at our disposal on the distribution

of each variable (upper bound, lower bound, mode, mean, variance, etc.)

we have attempted to characterize each as approximating some definitive

probability distribution. The simulation model provides for six distinct

probability distributions and an almost infinite number of possible varia-

tions in each, depending upon the relationship between the various parameters

of each distribution. Essentially the same kind of simulation model was

proposed by Hertz (1964) but while the Hertz article is frequently cited as a classic method, few have since used this approach.

The six probability distribution types provided for in the simulation model are:

1. Normal, which takes as parameters estimates of the mean and standard deviation;

2. Exponential, which takes as parameters estimates of the mean and the lower-bound since the standarized exponential distribution is bounded by zero;

3. Gamma, which takes as parameters estimates of the mean, standard deviation and a lower bound estimate as the standardized gamma distribution is bounded by zero;

4. Uniform, which takes as parameters estimates of the lower and upper bounds;

5. Weibull, which takes as parameters estimates of the mode, the upper and lower bounds and estimates of the probability that a value will lie above or below these bounds;

6. Beta, which takes as parameters estimates of the mode, upper and lower bounds and a distributional character, 1-9, describing the skew (left, right or symmetric) and variance (high, medium or low) of the distribution.

These distributions are all described in Naylor (1966) while the Weibull and Beta distributions are further analyzed by Schaefer and Husic (1969). The computer code generating random variates from these distributions is shown in Appendix A. Where the distribution was symmetric and there were sufficient observations to estimate the standard deviation, the Normal distribution was used to describe that variable. Where the distribution was skewed right the Gamma distribution was used. The Weibull distribution was used where information was much more scarce and we normally placed a twenty percent confidence interval about the model estimates. In terms of tracking performance, the Beta distribution program written by Schaefer

and Husic (1969) left something to be desired but fortunately we were able to substitute other distributions for it.

Because of the limited information available, particularly the poverty of observations from which to characterize the frequency, and hence the probability, distributions of the variables, it is not clear that the "true" underlying probability distribution will always be selected. The margin for error is great and is most acute when deciding between relatively symmetric distributions. Theoretically it should be possible to test each selection through the χ^2 test for goodness of fit. In practice the number of observation was too small to give much confidence in such a method. However, as noted below, one advantage of the simulation approach is that it permits us to judge the sensitivity of the estimates to mis-specification of the model, although it does not allow us to say which is the correct specification.

Faced with uncertainty, the usual response of the economic historian has been to present a range of estimates, often together with a "best" estimate. However, it is difficult, if not impossible, to interpret such results. Consider for example the derivation of the lower bound which is derived by aggregating the low values of each component of the model. To the extent that each low value represents an unlikely event and that each component is independent, the probability of the intersection of the unlikely events is going to be very small. For example, it is reasonable to suppose that each of the ten variables we use to estimate steam power costs is independent of one another (or at least not perfectly correlated) and let us suppose that the probability of each occurring is 0.1 or less, then the joint probability, which is the probability that we would observe

a cost estimate equal to or less than the lower bound, would be 10×10^{-10}. Thus although the lower and upper bounds provide us with some information, it is not clear whether it is particularly useful, given the remoteness of the event. This same argument applies equally to best estimates. Even if we assumed that the mean or mode occurred with a 0.75 probability for each component in the model, the resultant "best" estimate would only have slightly better than a five percent probability of occurring in our steam power model.

Use of a range also severely handicaps hypothesis testing, unless the range only embraces values that reject or confirm the hypothesis. Consider for example our interest in the difference between steam and water power costs per horsepower. If the range of this difference contains only positive numbers then we may say conclusively that steam power was more expensive than waterpower at that particular time. Likewise if the range of the difference contains only negative numbers then we can say that steam was cheaper than water. However in every case, the actual range contains both positive and negative numbers and hence using only the range it is impossible to arrive at an unambiguous conclusion.

Schaefer and Weiss (1970) raise one further subtle problem with the range method and that is the difficulty of interpreting sensitivity analysis results when all that is observed is the effect of the change on the upper and lower bounds. Such a change is probably a poor predictor of the impact upon the best estimate and the probability that the best estimate lies in some interval.[16] This problem does not arise with the simulation approach.

Simulation modeling is not, however, an unmitigated blessing. Most serious here is that the simulation model opens a Pandora's box of questions that can in part be resolved by repeated running of the model. For example while I assume independence (i.e., zero correlation) between observation i and observation j and between variable x and variable y it is also plausible that observations ought to be serially correlated with one another and that a high value for one variable should only be accompanied by a high (low) estimate for another. One can thus easily generate so much data that one loses sight of the problem. One begins to stop asking "Is this estimate reasonable? Does it make sense?" and instead treat the simulation estimates as the real world that we seek to explain rather than observable historical facts that we seek to illuminate via the simulation.

The essence of the simulation model is shown in Figure 2. This does not represent an actual run because not all six distributions occurred simultaneously in any one experiment. The procedure is to conduct a series of Monte Carlo experiments that sample from the distribution of each variable and then combine these in the manner described by equation [6] (for water-power) or equation [7] (for steam power). The result provides one observation of the cost of that power source.[17] This experiment was repeated 1000 times to yield an estimate of the output probability distribution such as that shown in Figure 2. Some typical output probability distributions are also shown in Figure 3 below.

As noted earlier, it is believed that this simulation model represents a considerable improvement over most others. Normality in the distributions is not required nor assumed, as it is in models used by
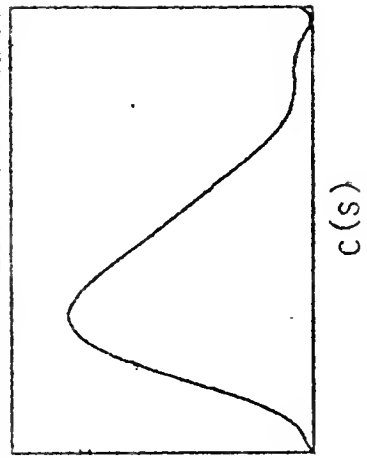
Figure 2

The Simulation Model
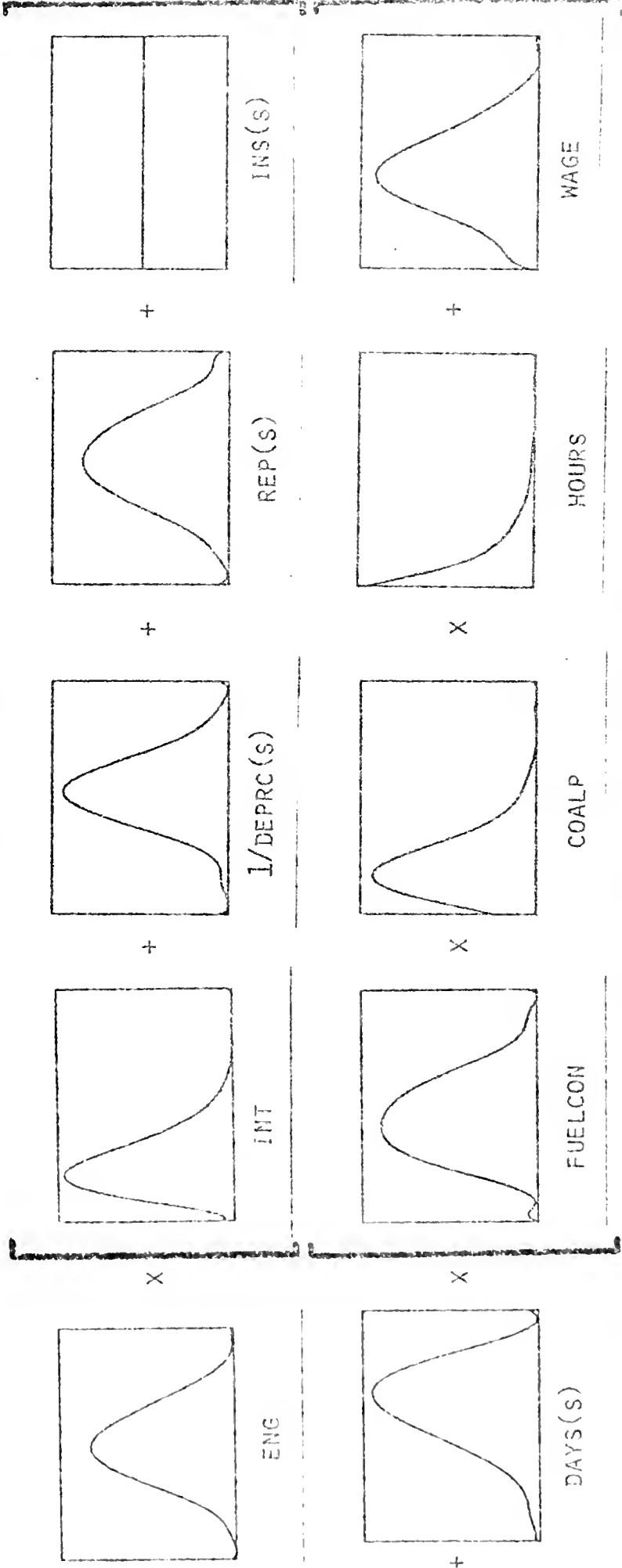
Input Probability Distributions

Output Probability Distribution

others for example that of Williamson (1975). This simulation is
stochastic, and hence uncertain, rather than deterministic. The Schaefer
and Weiss (1971) model is stochastic and does not assume normality, but
was constrained in other ways which the present model is not. That model
was based upon the Weibull distribution, "A Statistical Distribution
Function of Wide Applicability" (Weibull, 1951) because of its ability
to approximate both normal distributions and distributions with a left-
or right-hand skew. However, some quite severe constraints are imposed
upon the distribution and these constraints increase in severity the
more certain one becomes about the form of the distribution. The
principal constraint is upon the ratio of the two tails of the distri-
bution (Schaefer and Weiss, 1971) and this is probability dependent.

The Weibull distribution takes, as parameters, estimates of the
upper and lower bounds of the distribution together with some probability
estimates of a value lying outside this range, and a "best" (modal) esti-
mate. When the probabilities are .20 then

$$\frac{(High-Mode)}{(Mode-Low)} \leq 5.01$$

and if the probabilities of a value outside the range are reduced to
.10 then this value falls to 3.68, declining to 3.10 for 0.05 probability.
For example the range of coal prices quoted in the Coal and Coal Trade
Journal (1889) fall outside these ranges unless we discard some of the
observations (we did not).

While each variable is assumed independent of every other variable
in the equations, when computing the difference between steam and water
power costs not all variables are independent between the two, notably

interest rates and wages should be identical between them. Consequently,

$$\text{Mode}[PV(S) - PV(W)] \neq \text{Mode } PV(S) - \text{Mode } PV(W)$$

although the difference between the two tends to be small.

This simulation model is entirely stochastic rather than determin-istic and it should be noted that the shape of the output probability distribution cannot be predicted a priori on the basis of information about the input probability distributions. Both of these are strong arguments in favor of the simulation modeling.

The Historical Consistency and Validation of the Simulation Results

The simulation model assumes that the planning horizon of the firm is a decade and this period is equal to or less than the life expectancy of either a waterwheel or a steam engine. As argued earlier this model should yield weaker results than any of the more complex models discussed above, because, over the period 1820-1900, steam power costs declined more rapidly than waterpower costs. Under these circumstances, with switching and recontracting allowed there would be a high probability in favor of selecting steam power.

The basic data and the sources are outlined in Appendix B. Table 2 provides best (i.e., modal) estimates of the annual costs of steam and waterpower per horsepower by decade together with estimates of the decadal present value of future costs of steam and waterpower per horsepower, the modal difference between them and an estimate of the probability that over the decade steam power would prove cheaper than waterpower. According to these estimates the costs of both steam and waterpower declined markedly

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The basic data and the sources are outlined in Appendix B. Table 2 provides BEST (i.e., modal) estimates of the annual costs of steam and waterpower per horsepower by decade together with estimates of the decadal present value of future costs of steam and waterpower per horsepower, the modal difference between them and an estimate of the probability that over the decade steam power would prove cheaper than waterpower. According to these estimates the costs of both steam and waterpower declined markedly between 1820 and 1900 with the costs of steam power falling to less than one-fifth their original level while waterpower costs fell by some sixty percent over the same period. With this change in relative cost levels in favor of steam power, the probability that steampower would be cheaper than water rose from 0.22 during the 1820s to over 0.95 by the 1870s. However, the dramatic increase in the profitability of adopting steam in preference to water appears to have taken place before 1850, for after 1850 the cost saving of steam over water remained about constant.

Table 2

Simulation Best Estimates of the Annual Costs per Horsepower
and the Present Value of Future Decadal Costs of Steam and
Water Power, Together with the Probability that Steam Will
Be Cheaper Than Water, 1820-1900[a]

Decade	Mode C(S) ($/hp/yr)	Mode C(W) ($/hp/yr)	Mode PV(S) ($/hp/yr)	Mode PV(W) ($/hp/yr)	Mode [PV(S)-PV(W)]	P[PV(S)<PV(W)]
1820s	$167.89	$137.73	$1122.77	$895.67	$169.01	.22
1830s	125.50	113.25	829.93	759.16	84.14	.34
1840s	80.83	91.68	551.84	618.77	-74.15	.74
1850s	65.67	77.34	434.10	524.54	-93.81	.85
1860s	60.65	68.63	428.60	466.53	-29.68	.71
1870s	39.46	57.60	281.83	415.64	-153.10	.98
1880s	32.56	46.95	248.89	354.29	-104.26	.96
1890s	25.29	39.19	195.13	304.27	-113.01	.97

[a]Assuming 100 hp prime movers. There are economies of scale in steam engines and
water turbines, diseconomies of scale in waterwheels.

between 1820 and 1900 with the costs of steam power falling to less than one-fifth their original level while waterpower costs fell by some sixty percent over the same period. With this change in relative cost levels in favor of steam power, the probability that steampower would be cheaper than water rose from 0.22 during the 1820s to over 0.95 by the 1870s. However, the dramatic increase in the profitability of adopting steam in preference to water appears to have taken place before 1850, for after 1850 the cost saving of steam over water remained about constant.

Figure 3 presents the annual cost estimates of steam and water power and the difference between them for the 1820s and the 1890s. The radical changes that took place in the costs of each power source and in the difference between the cost of steam per horsepower and the cost of water per horsepower is readily apparent. The average per horsepower cost of steam power fell from $170.29 per year in the 1820s to $26.22 by the 1890s, while the average cost of waterpower over the period fell from $145.28 to $46.88. As a result the mean difference between the cost of steam power and the cost of waterpower was $31.23 in the 1820s in-dicating that on average steam was that much more expensive than water, but by the 1890s, steam was, on average, $20.76 cheaper than water.

As can be seen from the graphs in Figure 3, the simulation approach allows us to establish any arbitrary confidence intervals around our estimates although we have selected the 95 percent confidence interval for the purposes of the tests here. Presentation of the annual cost estimates in Table 2 provides us with the opportunity for comparing the simulation estimates with those made by contemporaries. The most comprehensive annual cost estimates for steam and water power were
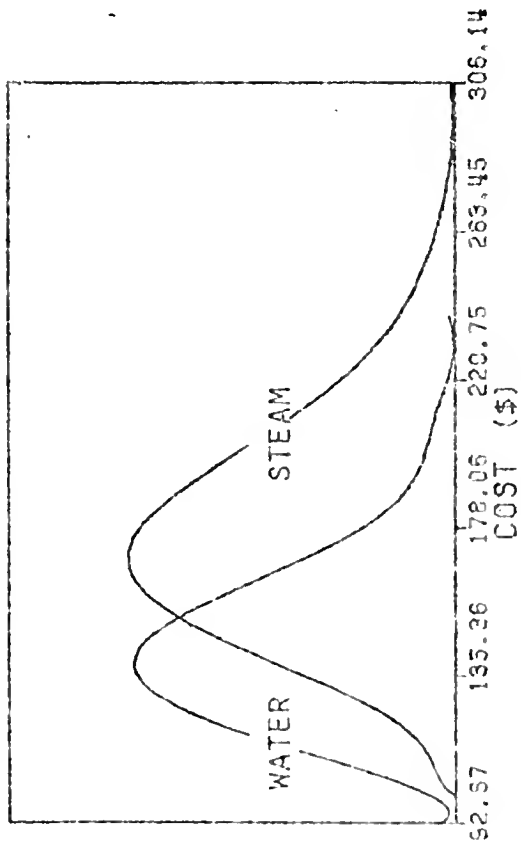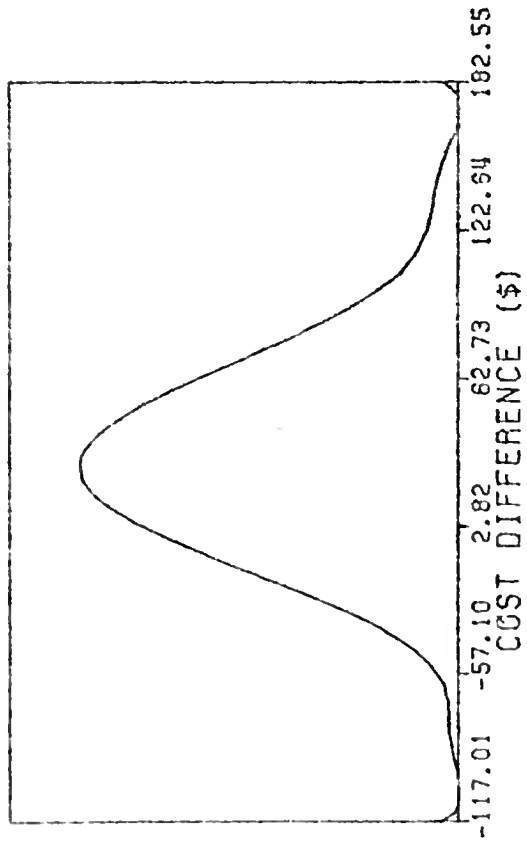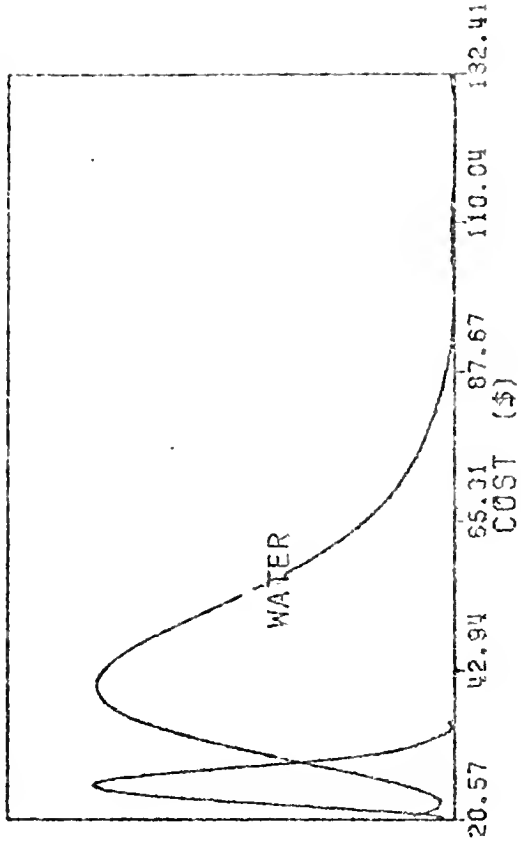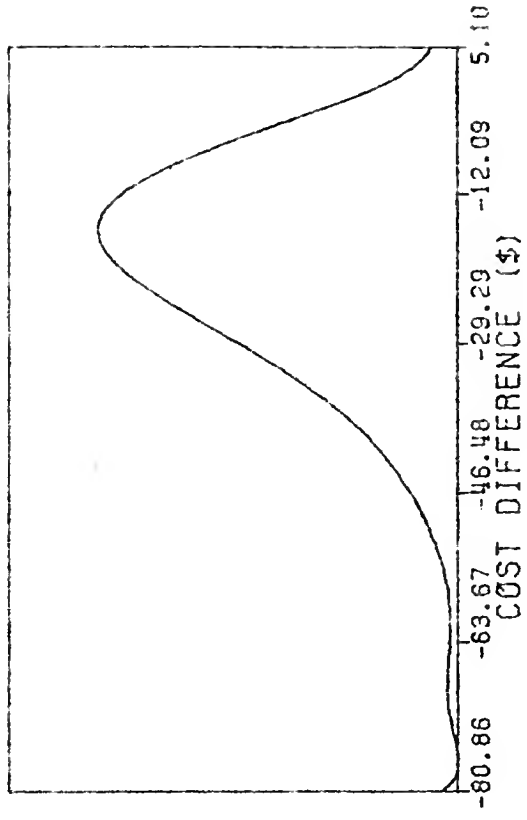
FIGURE 3

SIMULATION OUTPUT PROBABILITY DISTRIBUTIONS

made for the period after 1870 and are drawn from engineering studies.
For example, Emery (1883) presents a series of detailed cost estimates
for a variety of steam engines ranging in size from 5 hp. to 500 hp.
in 1874. These cost estimates range from $176.46 per horsepower per
year for the smallest engine to $25.66 per horsepower per year for
the largest engine, with a figure of $36.02 being reported for a 100
horsepower engine comparable to that on which the simulation estimates
are based. Our mean estimate of $39.32 per horsepower per year as the
annual cost of a 100 hp. engine in the 1870s has a ninetyfive percent
confidence interval of ($33.03, $46.56) and includes Emery's estimate.

Although not presented here, we also made a simulation run to estimate
per horsepower annual costs of water and steam prime movers for average-
sized units of each type. In the 1870s the average steam engine produced
38 hp. and the estimate of the mean cost of operating this size engine was
$53.86 with a ninety-five percent confidence interval of ($39.96, $68.18).
While Emery (1883) does not make an estimate for a 38 hp. engine his
estimates for 25 hp. and 50 hp. engines were $67.28 and $52.16 hp. respec-
tively, falling within our 95 percent confidence interval.

We have attempted to summarize most of the contemporary estimates of
the annual per horsepower costs of operating steam and water prime movers
in Table 3 and have presented with them the ninety-five percent confidence
interval about the mean annual estimates. These results would suggest
that our steam power estimates are more accurate (in terms of duplicating
contemporary estimates) than those for waterpower. Contemporary estimates
of the cost of waterpower do not intersect with the ninety-five percent
confidence intervals about our simulation estimates.

Table 3

Contemporary Annual Cost Estimates of Steam or Water Power Per Horsepower Versus the Simulation Results

Power Source	Date	Contemporary Estimates		Simulation Estimate	
		Range	Mean, or Estimate for 100HP	$P(\hat{o} < \bar{x}) < 0.025$	$P(\hat{o} > \bar{x}) < 0.025$
Steam	1837		$39.97	99.35	171.89
	1840	$105.33-$45.77		63.37	106.31
	1853		72.89	50.10	83.87
	1874	176.46-25.66	36.02	33.03	45.56
	1889		19.24	28.22	38.91
	1890	39.85-16.23		22.17	31.48
	1896		52.17	22.17	31.48
Water	1840	50.00-23.33		67.44	147.40
	1889		22.62	33.14	90.69
	1890	23.18-18.11		28.20	79.18

Sources: 1837; U.S. Congress (1837-38)
1840; Justitia (1941)
1853; DeBow (1853)
1874; Emery (1883)
1889; Manning (1889)
1890; Main (1890)
1896; McElry (1896)

For a variety of reasons I am not prepared to concede the superiority
of the contemporary estimates in general and those for waterpower in par-
ticular. First, the waterpower estimates all are referenced to the cost
of waterpower at Lowell Massachusetts where waterpower was exceptionally
well-developed under the control of the Locks and Canals Company and was
as cheap if not cheaper than almost anywhere else in the country (Tenth
Census, 1883; Swain, 1888). Moreover, Merrimac waterpower was not a sig-
nificant portion of total developed or potential waterpower. Second, most
of these contemporary estimates (but particularly these for waterpower) fall
short of the standards of objectivity that one might desire. For example,
one of the chief proponents of steam power in the mid-nineteenth century,
Hamilton Smith, was one of the owners of the American Cannel Coal Company,
a important shareholder in Cannelton Mills (a major attempt to establish
steampowered cotton mills in the South and mid-West), and commissioned many
of the articles and pamphlets extolling the virtues of steam that appeared
about this time such as that by James (1849) and those appearing in
De Bows' Review (1848, 1849, 1850a, 1850b, 1850c, 1853). But the pro-
water faction was even more shameless. In the mid-nineteenth century,
they were led by the Lawrence family. The Lawrences were founders of the
Lawrence Manufacturing Company and later (1853) established Pacific Mills,
both of which were water-powered. More significantly, however, the
Lawrence family was the major stockholder in the Essex Company which owned
all waterpower rights at Lawrence Massachusetts which amounted to 11,000
gross hp. in 1880 valued at $14.08 per horsepower per year (Tenth Census,
1885). Later in the century this role was fulfilled by James B. Francis
and Colonel James Francis, agents and engineers to the Locks and Canals

Company at Lowell and Samuel Webber, consulting engineer to the Essex
Company at Lawrence. The contemporary cost estimates in Table 3 are
thus specific to a given location rather than representing the range
of costs over the nation as a whole and represent best rather than
average practice techniques for the power source which they favor. The
overall result is a strong bias toward the preferred power source and
this bias is most pronounced for the water-powered proponents.

Although the ninety-five percent confidence intervals given in
Table 3 imply that there was no significant difference between water
and steam power costs (that is that the hypothesis that the two costs
were the same could not be rejected) during the nineteenth century, the
results in Table 2 give lie to this opinion, for by the 1870s steam power
was significantly cheaper than waterpower. This result accords with
the opinions expressed by both Manning (1889) and Main (1890) in their
presentations to the American Society of Mechanical Engineers.

Turning once again to the cost estimates given in Table 2, the
question is, "Do these results make sense?" We would expect that the
greater the expected cost savings from adopting steam over water or the
greater the certainty surrounding that result, the larger would be the
probability that steam would be adopted in preference to water. However,
while the latter expectation was quite convincingly fulfilled, the former
was not. Notwithstanding the limitations imposed by having only eight
observations, a number of regression equations were estimated for a variety
of economically plausible explanations of the percentage of all plants that
adopted steam at any one time. These are shown in Table 4.

Table 4

Regression Estimates of the Relationship Between the Percentage of Plants
Adopting Steam Over Time and the Costs and Profitability of Steam and the
Probability That This was the Least Costly Decision

Dependent Variable: Percentage of Plants Using
Steam To Those Using Steam or Water[a]
(t-statistic)

Equation Number	Constant	Independent Variables:[b]			Adjusted R^2
		P[PV(S)<PV(W)]	Mean PV(S)	Mean [PV(S)-PV(W)]	
I	-.258 (-1.397)	.845** (3.537)	—	—	.622
II	.769** (6.579)	—	-.001** (-4.191)	—	.703
III	.273** (3.220)	—	—	-.002* (-2.570)	.445
IV	-1.756** (-3.294)	3.289** (3.821)	—	.007** (2.869)	.830
V	-.476 (-.499)	2.136* (2.00)	-.001 (-1.542)	.006** (2.993)	.867

[a]See Table 1.

[b]See Table 2.

*Significantly different from zero at 10% level.

**Significantly different from zero at 5% level.

In each equation that contained the simulation estimates of the
probability that steam would be cheaper than water, the coefficient of
this variable was significantly different from zero at better than the
ten percent level and was of the "right" sign, that is to say an increase
in the probability that steam will be cheaper than water power is asso-
ciated with an increase in the fraction of plants adopting steam. Equation
I implies that every one percent increase in the probability that steam
is cheaper will raise the percent of plants adopting it by 0.845 of one
percent. Equation II which expresses the percentage of adopting plants
as a function of the costs of steampower implies that, _ceteris paribus_,
each $10 increase in the present value costs of steam power will lower
the percentage of adopting plants by one percent. Equation V shows this
same relationship.

Equation III expresses the percent adopting as a function of the
profitability of switching from water to steam as measured by the dif-
ference in the present value of their costs. Each $10 by which the present
value of waterpower costs exceeds that of steam will raise the percentage
of plants adopting steam by two percent. Neither equation IV or V makes
economic sense when looked at _in toto_ as the sign of the coefficient of
the difference between steam and water power costs switches from negative
to positive, implying that a rise in the profitability of adopting steam
over water (indicated by a more negative value for this variable) would
reduce the percentage of plants that adopted steam. This result is probably
attributable to the strong correlation that exists between the cost saving
resulting from adopting steam over water and the probability that steam

will be cheaper than water. Despite this problem though, these regres-
sion results serve to emphasize the importance of the degree of certainty
surrounding the cost saving of steam power over water in the decision to
switch to steam.

Sensitivity Analysis of the Simulation Results

As noted earlier, one important virtue of the simulation approach
is the relative ease with which sensitivity analysis can be performed.
In this particular instance, the only serious hindrance to performing a
complete sensitivity analysis is the number of possible combinations of
changes. Not only can the mean or modal values be changed, but a complete
analysis should also consider changes in ranges, in standard deviations,
in probabilities (for the Weibull distribution) and even changes in the
type of probability distribution since for example a symmetric distribution
could be approximated by the normal, the gamma, the beta, or the Weibull
distributions. Taking all possible combinations would not only be time
consuming and costly but also of little practical use. Therefore we have
attempted to show in Table 5 the sensitivity of the steam and waterpower
cost estimates for the 1870s to a twenty-five percent increase in the
value of each variable, that is to say a right-ward shift in the probability
distribution by 25 percent and show the percentage effect of each on the
mean and modal cost estimates. Interestingly the impact of the changes
on the mode is not the same as on the mean. Although both are in the same
direction, the percentage change in the mean is sometimes greater than the
percentage change in the mode and sometimes vice versa.

According to Table 5, both steam and water power costs were relatively insensitive to large charges in repair or insurance costs, though steam power costs were more sensitive to these charges than were waterpower costs, because of the more frequent repairs needed for the steam engine and the higher insurance rates which reflected the higher risks of accident and loss. The shorter life of the steam engine also accounts for the relatively higher sensitivity of steam power costs to changes in the depreciation rate.

Both steam and waterpower cost proved somewhat insensitive to changes in interest rates. As might be expected from Temin's (1966) work, steam costs were not as sensitive as waterpower costs, but in the 1870s a twenty-five percent increase in interest rates would have increased costs by less than four percent. However, for this variable, sensitivity is very much a function of time. At earlier dates, both capital expenditures and interest rates were much higher relative to all other variables and so that at earlier dates, sensitivity to interest rates would be correspondingly greater, particularly for waterpower since in the 1820s and 1830s per horsepower costs of a waterwheel were about double those of a steam engine but only about 30 percent higher by the 1870s. However interest rates were never as important to the choice of power source decision as might be implied by Temin (1966).[18]

Steampower costs proved relatively sensitive to changes in the size of the engine and to wages. This is attributable to the greater indivisibility of steam power plants as they required the almost constant attention of both an engineer and of a fireman, which results in a proportionately

Table 5

Sensitivity of Steam and Water Power Cost Estimates to
A Twenty-Five Percent Increase in the Value of Each

Variable
(1870s Data)

Variable[c]	Steam[a]		Water[b]	
	Percentage Change in Mean	Percentage Change in Mode	Percentage Change in Mean	Percentage Change in Mode
INT	3.13	2.63	3.79	3.26
WAGE	5.54	5.82	1.68	1.81
DEPRC	2.11	2.63	1.17	1.71
REP	1.32	1.27	0.81	0.73
INS	1.14	1.09	0.61	0.56
HP	-4.42	-5.14	-1.31	-1.32
ENG	8.14	7.62	---	---
FUELCON	11.37	10.51	---	---
COALP	11.77	11.90	---	---
WHEEL	---	---	6.45	7.49
WATER	---	---	15.12	17.00
EFF	---	---	-11.86	-11.00

[a]Steam: Mean = $39.33; Mode = $39.50

[b]Water: Mean = $66.54; Mode = $61.28

[c]Variables as defined in text above.

Mean and Mode differ slightly from those in Table 3 because sensitivity analysis

much higher wage bill for a steam-driven plant and these ministrations were essentially the same for a 25 hp. engine as for a 250 hp. engine.

In the 1870s however both steam and water power costs were most sensitive to changes in variables that were inseparable from the power source, notably the original cost of the power source, with the price of coal and fuel consumption for steam, or the annual cost of water-rights and the design efficiency of the wheel for water.

The original cost of power sources and their respective efficiencies were essentially determined by technological change on the supply side. Over time improvements in design and manufacture lowered production costs and at the same time raised the operating efficiency of the power source. Engine builders for example not only improved parts standardization, but also made improvements in such things as valve cutoffs, flue design, compounding and boiler efficiency. As a result steam engine prices fell from $100-200 per horsepower in the 1820s to about $40 per horsepower by the 1890s, while fuel consumption declined from about 8 pounds of coal/ horsepower/hour to less than a quarter of that by the 1890s.

Until the development of the water turbine, most waterwheels were custom designed and few builders probably built more than a handful of wheels. Thus, although per horsepower costs of a water wheel/turbine declined from $220-400 in the 1820s to about $45 by the 1890s, most of this price decline dates from the 1850s with the establishment of specialist firms of turbine builders. On the other hand, the efficiency of water power sources rose throughout the period reflecting in part the inherent design differences between breast, overshot and turbine wheels, but also

reflecting improvements in bucket design, bearings, and the transmission
mechanism.

The Effect of Different Coal Prices and Water-Right Costs on the Costs of Power

It would seem to me, however, that the most interesting questions
arising from this simulation are raised by the cost sensitivities to the
price of coal and the cost of buying a water right and this can be further
used to demonstrate the power of the simulation approach. Coal prices
varied both over time and across regions while the cost of purchasing a
water-right varied, for the most part, only from place to place. It is
these variations that can explain the persistence of waterpower, which
was by 1900 still used by some 20 percent of all firms, even in the face
of a 0.97 probability that steam power would be cheaper than waterpower.

As noted above, water-right costs varied from place to place, a
variation that depended upon remoteness and the demand for power relative
to the available supply. Thus, for example, water-rights were reportedly
cheapest along the Lower Fox River in Wisconsin where they sold for $4-5
per theoretical horsepower per year or around Augusta, Georgia ($5.50 per
theoretical horsepower) while in New Jersey prices of upwards of $30 were
asked and received (Tenth Census, 1885). The cost of water-rights in the
New England textiles centers on the other hand were much less varied, ranging
from about $10.60 per theoretical horsepower at Lowell to $14.08 at Lawrence.
At Manchester, New Hampshire, the price was $13.65 (Tenth Census, 1885).
The lower price of the Lowell power probably reflects the early date (1826)[19]
at which this power was developed and the long-term leases that were granted.
All mill-powers (= 85.23 theoretical horsepower or 25 cubic feet of water

per second on a fall of 30 feet) at Lowell were soon granted. The development of waterpower at Lawrence (upstream from Lowell) did not begin until 1845. Payment for these water-rights was somewhat complicated. At Lawrence:

> "a mill-power was originally valued at about $15,000, and all the original grantees, including all the large corporations on the north side, paid about $10,000 down, and continue to pay an annual interest on the remainder of about 6 per cent, or $#300 per annum per mill-power, defined in weight in silver. Of late years, however, the company has leased power for annual payment in currency, without an original cash payment, and all the newer mills, including those on the south side, pay an annual rent of $1,200 per mill-power. This rate is equivalent to $14.08 per gross horsepower per annum" (Tenth Census, 1885).

Figure 4 graphs the change in mean waterpower costs per horsepower with respect to the cost of water-rights together with the variation in this over time. The change in mean waterpower costs per dollar change in water-right costs is approximately constant over time, while at the same time, as we have already seen, total waterpower costs were very sensitive to changes in water-right costs. Thus, for example, the mean waterpower cost per horsepower in the 1820s at Appelton Wisconsin was $93.00 compared with $162.00 at Passaic New Jersey. By the 1890s these costs would have fallen to about $13 at Appelton and $59 at Passaic. For the 1840s an estimate of the cost at Lowell would be about $69.50 per horsepower compared with $48 as estimated by Temin (1966).

The wide variation in the per horsepower costs of a water-right is reduced somewhat if these price quotations are weighted by the available and developed horsepower at each location. Prior to about 1880, the average cost of a water-right was probably about $15 and the mode approximately equal to the cost of power at Lawrence, Massachusetts or Manchester,

FIGURE 4

VARIATION IN AVERAGE COST OF WATER POWER BY DECADE
WITH COST OF WATER-RIGHT
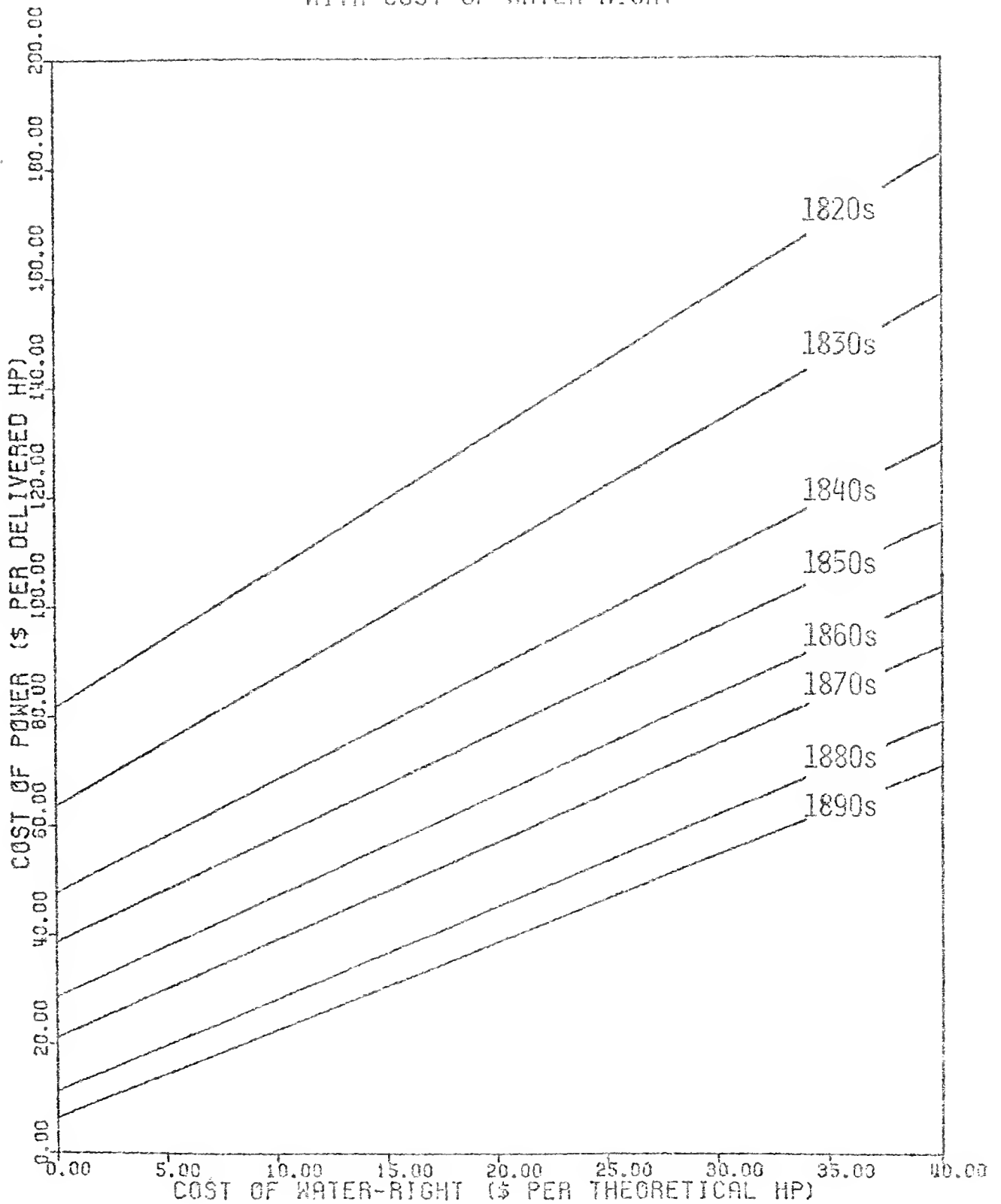
New Hampshire. However, the gradual development of Niagara power in the 1870s dramatically shifted both the mean and the mode to the $10 or so charged by the Niagara Falls Hydraulic Power and Manufacturing Company for each of its estimated 4,000,000 horsepower potential (Tenth Census, 1885).

To the extent that the value of water-rights were demand-determined, our treatment of this cost as exogenous rather than endogenous is incorrect. However, since the purchase of water-rights was generally negotiated on the basis of a long-term contract, the price was fixed once the decision to purchase had been made. The cost for the established firm was therefore not dependent upon year to year variations in the demand for waterpower. At the same time there is little evidence of price fluctuations for water-rights for new firms. For example, at Lawrence, the implicit cost of a water-right to an original grantee was $10.56 per gross horsepower at six percent interest on the initial downpayment while the newer mills from about 1860 onward were charged $14.08 per gross horsepower (Tenth Census, 1885).

Just as power costs in the water-powered plant were most sensitive to the cost of water the costs of steam were most sensitive to the price of coal. This price varied widely over time and between geographic regions. The typical steam engine was fueled with bituminous coal rather than with wood or with anthracite although there is clearly some price at which the operator would be indifferent between wood and bituminous coal or between bituminous coal and anthracite. Unfortunately, as noted in Appendix B there is no series of bituminous coal prices available for the period 1820-1900. Indeed for the most part we have only a few scattered

and hence potentially biased observations. However, since anthracite coal
could be substituted for bituminous coal, and since it was possible to
transport either between regions, we would expect the prices of both to be
quite highly correlated with each other. Figure 5 graphs the variations
in the price of anthracite coal in Middle Atlantic port cities over the
period.[20] Average prices fell over the period, especially between 1820
and 1845 and thereafter fluctuated about the price of \$3.50-\$4.50 per ton.[21]
Figure 6 shows the variation in the cost of steam power with different
coal prices over the period 1820-1900, ceteris paribus.

Figures 4 and 6 together permit us to make some statements the
conditions under which steam might be cheaper than water in various parts
of the country. Consider for example Lowell, Massachusetts where water-
power to original grantees cost \$10.60, then in the 1820s waterpower at
Lowell cost about \$108/hp, declining to about \$59 in the 1850s and to
about \$24 by the 1890s, then if coal had been available at Lowell for
less than \$3.70/ton on the average steam power would have been cheaper
than water in the 1820s. In the 1850s, if coal were priced less than
\$3.10/ton in Lowell this should have been true, or if the price were less
than \$3.00/ton by the 1890s. Over time the probability that coal prices
at Lowell were less than these most likely rose but it is unlikely that
coal prices there were ever significantly lower than \$3.00/ton at any
time during this period. This therefore provides a very convenient
explanation for why so few mills at Lowell were steam-powered even by
the 1890s. Consider now instead the case of a plant locating in Hamilton,
Ohio where water-rights were available for an average of \$30 per horse-
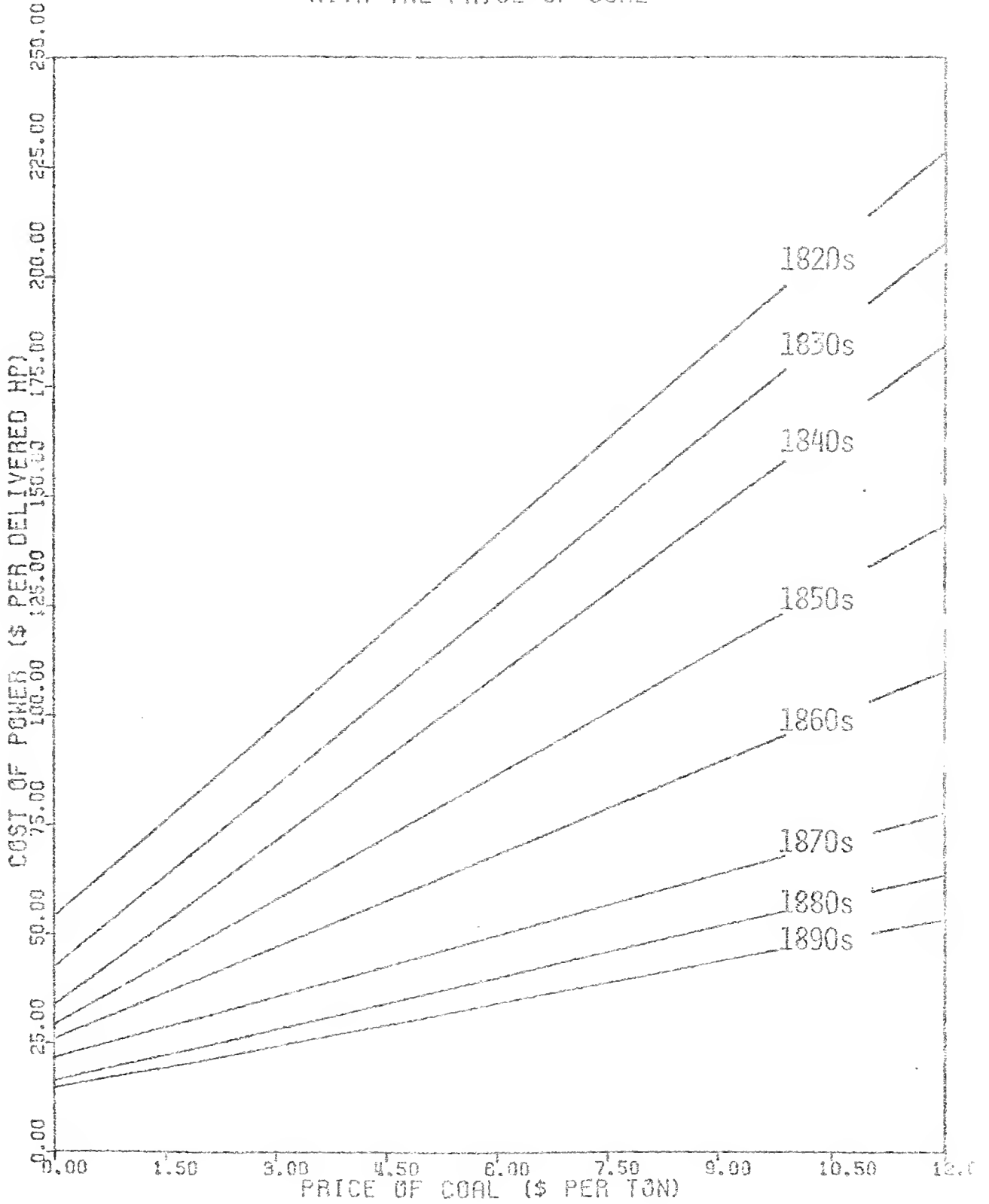power (Tenth Census, 1885). In the 1830s, coal would have had to cost

Figure 5

WHOLESALE PRICE OF ANTHRACITE COAL ($/TON), 1820-1900
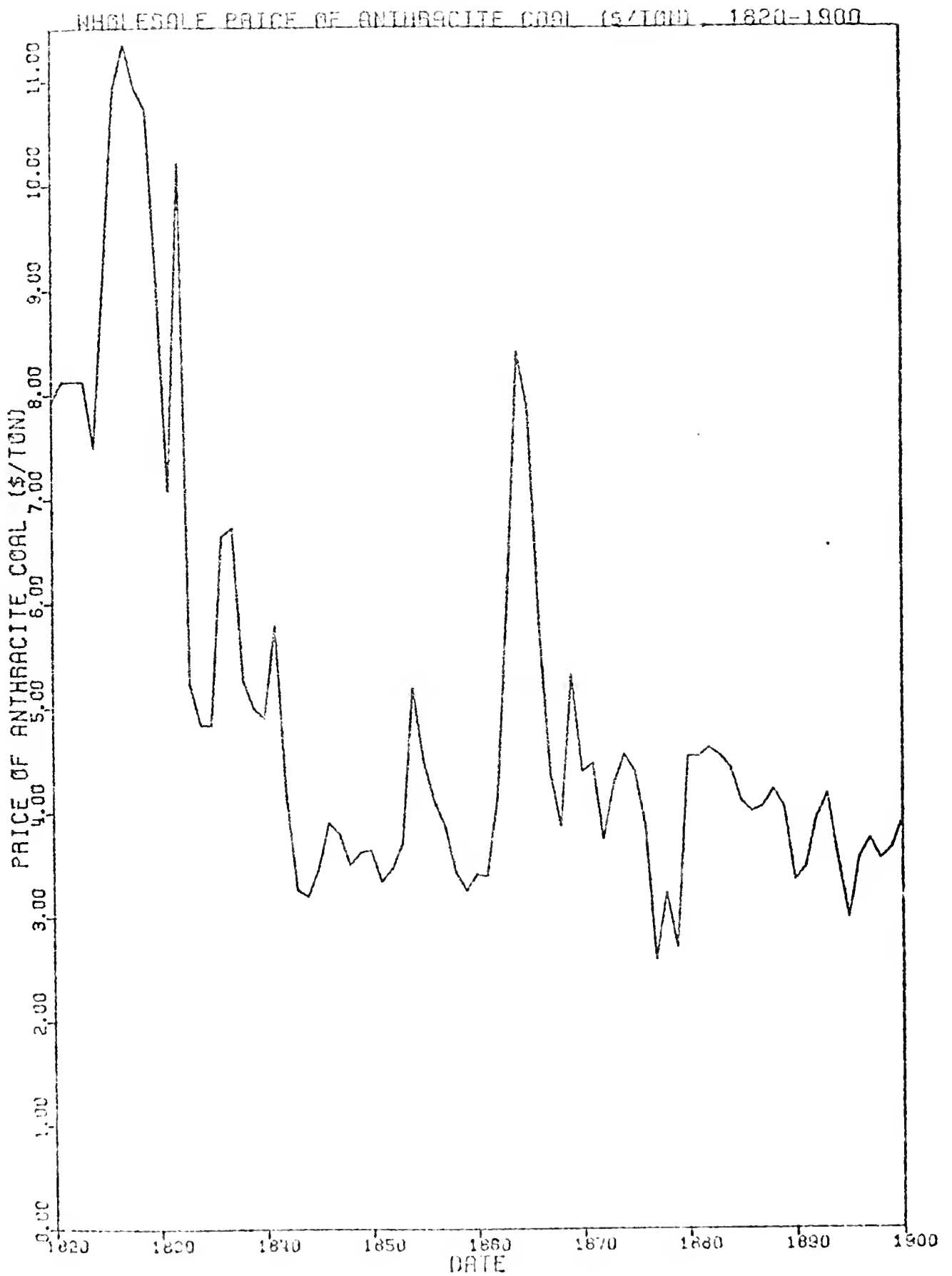
FIGURE 2

VARIATION IN AVERAGE COST OF STEAM POWER BY DECADE
WITH THE PRICE OF COAL

as much as $6.70/ton for the average water-power costs to have equalled
the average steam power costs. Since coal was selling for only $1.00/ton
in Pittsburgh in 1836 (Eavenson, 1942) it is doubtful whether coal delivered
to Hamilton via the Ohio and Great Miami Rivers was this expensive, though
there doubtless remained some small probability that water would have been
cheaper. As a result, firms in the Cincinnati area seem to have had a
quite strong revealed preference for steam indicated by the large number
of steam engines in use in the area at this early data (American Railroad
Journal, 1834). By the 1890s, coal would have had to have been priced at
more than $12.00/ton for the average water-power costs there to be less
than the average steam power costs. As a result the probability that water
would be cheaper than steam was close to zero (if not zero) and we would
not expect water-powered plants to have survived there.

Conclusion

The conclusion that the profitability of adopting a new technology
can "explain" the adoption of that technology is not especially surprising,
but this conclusion could only be validated by appeal to the complex
simulation model that we have developed. At the same time by looking at
the response of steam and water power costs to variations in the price
of coal or water-rights it is possible to extend the very general simula-
tion results made for the U.S. as a whole to any particular location or
instance and generate a highly plausible explanation and rationale for the
observed changes that took place.

During the first half of the nineteenth century much of the impetus
to adopt steam came from declining fuel costs. The stabilization of coal

prices after 1850 slowed this trend and the introduction of the water turbine which made more efficient use of the available flow and head of water may temporarily have halted the trend to steam. After 1860 the continued advance of steam came to rest more and more on improved fuel consumption for the steam engine.

Footnotes

*This paper has benefited from discussions with Fred Bateman, Jan Brueckner, Stanley Engerman, Larry Neal, Tom Ulen, Paul Uselding and Thomas Weiss.

[1] This count differs from that made by the Franklin Institute (1876) which noted only five. Both may well be in error as by cross referencing sources we would count two engines in the Philadelphia waaterworks, two in New York city where one powered the waterworks and the other operated a sawmill owned by Nicholas Roosevelt, one in Boston, the reconstructed Hornblower engine in Roosevelt's newly named Soho Works, and the 1802 prototype high pressure engine built by Oliver Evans (Evans, 1805).

[2] Evans' business was taken over after his death in 1819 by his son-in-law and his former partner under the name of Rush & Muhlenberg. The Pittsburg and Philadelphia works of Oliver Evans, however, produced a generation of American steam engineers and engine builders such as Mahlon Rogers and Mark Stackhouse.

[3] Temin's (1966) estimate of "about a dozen steam-powered plants" appears to be based upon the number of engines reported in the census summary rather than on the basis of those reported in the manuscripts themselves.

[4] By my count, the Woodbury Report (1838) notes 65 low pressure steam engines. Temin (1966) reports 63.

[5] Data collected from the manuscript censuses of manufactures for 1850, 1860 and 1870 by Fred Bateman of Indiana University and Thomas Weiss of the University of Kansas under National Science Foundation support. James D. Forest was involved with the early stages of data collection. The samples are described at length in Atack (1976) and Bateman and Weiss (1976).

[6] European experiments with the water-turbine were described in the Journal of the Franklin Institute (1842), while the results of the Lowell experiments were described by Francis (1855).

[7] Contemporary sources placed turbine efficiency at 80-85% compared with 60-70% for overshot wheels, 45-50% for breast wheels and only 27-30% for undershot wheels. However some turbines were somewhat less efficient (for example the range the "New American" type turbine in 1894 was 61-83% (McElroy, 1895-96)) while a well-designed waterwheel such as the Burden Wheel (Sweeny, 1915) was 66-85% efficient.

[8] That is, while partially or totally submerged. This point is also made in Franklin Institute (1842).

[9] The data could also be approximated by the cumulative normal distribution, but the cumulative normal distribution is considerably more difficult to work with than the logistic curve. Use of the cumulative normal would of course lead to a PROBIT analysis rather than the LOGIT analysis performed here. The logistics curve is defined by:

$$P = K/[1 + e^{-(a+bt)}]$$

where $\underline{P}$ is the percentage of plants using steam, $\underline{K}$ is the ceiling rate or maximum percentage of plants that ever adopt the steam engine, $\underline{t}$ is the time variable where it is measured from 1820, $\underline{b}$ is the rate of growth co-efficient and $\underline{a}$ is the constant of integration that positions the logistics curve on the time scale (Griliches, 1957). This equation was estimated in log-linear form:

$$\log_e [P/(K - P)] = a + bt$$

[10] This value also happens to maximize the R^2.

[11] Whenever we refer to waterpower or waterwheel, the actual power source may be a wheel or a turbine depending upon the data. According to contemporary sources, breast wheels were most common in the 1820s. By the 1830s overshot wheel began to assume an increasingly important role and by the late 1840s turbines were being introduced. However breast designs were probably not phased out until the 1840s and overshot wheels not until the 1870s. See also Appendix B.

[12] See Appendix B. Shorter life span was certainly true of high pressure engine designs but less true of low pressure engines. For example a Boulton and Watt engine imported in 1815 to power the Savannah rice mill of McAlpine and McInnis was still operating in 1894 supplying power for the Brush Electric Light and Power Company of Savannah (Engineering News, 1893; Hutton, 1894).

[13] Estimates of this probability are produced by the simulation model.

[14] Three hundred and nine days is the number of days in 52, 6 day weeks, less Christmas Day, New Years Day and the Fourth of July.

[15] The simulation model can, however, accept single-valued variables.

[16] Some attempt to examine this problem is made later in the paper in the sensitivity analysis, but the problems faced in this model are more complex than those treated by Schaefer and Weiss (1971).

[17] See the outline flow diagram in Appendix A.

[18] For example, after the 1840s no possible variation in interest rates would cause the mean or modal water power cost to be less than the mean or modal steam power cost.

[19] The first hydraulic works on the Merrimack were begun in 1792 with the creation of the "Proprietors of the Locks and Canals on Merrimack River" to improve navigation. Although the charter forbade the building of dams, it seems that at least a partial dam was in existence by 1801. (Tenth Census, 1885)

[20] Prices 1820-1824 are for Philadelphia "Virginia" coal. For 1825-32 prices are for New York "anthracite coal (Schuylkill)" and from 1833-1889 prices are for "Schuylkill white ash lump" coal by the cargo at Philadelphia. From 1890 prices are for "Pennsylvania anthracite, chestnut". See Historical Statistics (1975).

[21] Based on the heating value, the anthracite coals of eastern Pennsylvania were worth about 93-97% of the value of the bituminous coals extending from south-central Pennsylvania through Virginia and West Virginia into Tennessee. See for example, Mechanical Engineers Pocket Book (1916).

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APPENDIX A

The Simulation Model

On entering the simulation model, calls are made to SUBROUTINE PLOTS and SUBROUTINE PLOT, both FORTRAN-callable routines in the CALCOMP plotting library, after which SUBROUTINE BSETUP is called. BSETUP sets up the parameters of nine beta equations corresponding to left-, symmetric, and right-skewed distributions with high, medium or low variance as suggested by Schaefer, Husic and Gutowski (1969). BSETUP calls SUBROUTINE EVALUAT which generates observations for the cumulative density functions for each of the nine basic beta equations by evaluating FUNCTION BETAP which is external to BSETUP. The results are then stored, $F(X) = r$ in XTABLE and X in CUM (where XTABLE is dimensioned at 128 and CUM is 9 x 128), pending the possible approximation of an input distribution to the beta distribution. The code for SUBROUTINE BSETUP and EVALUAT and for FUNCTION BETAP is shown below.

Data are then read from cards (or tape) in sets where the first card of each set informs the simulation of the type of model to be estimated, MODEL, the number of input data sets to be read for that model, NSETS, and the number of output cost distribution estimates to be generated, NRAND. A loop ISET = 1, NSETS then reads the parameters of the various input distributions. These data are stored in LOCATE (mean or mode estimates), SCALE (range or standard deviation) and SHAPE (lower bounds or descriptors of distribution shape) according to the value of NDISTR which is set by the Hollerith value of IDISTR which gives the type of distribution: WEIBULL, UNIFORM, NORMAL, EXPONENT'L, GAMMA, BETA or CONSTANT. This value of NDISTR is then stored in the array IDISTRB to be later used as a switch.
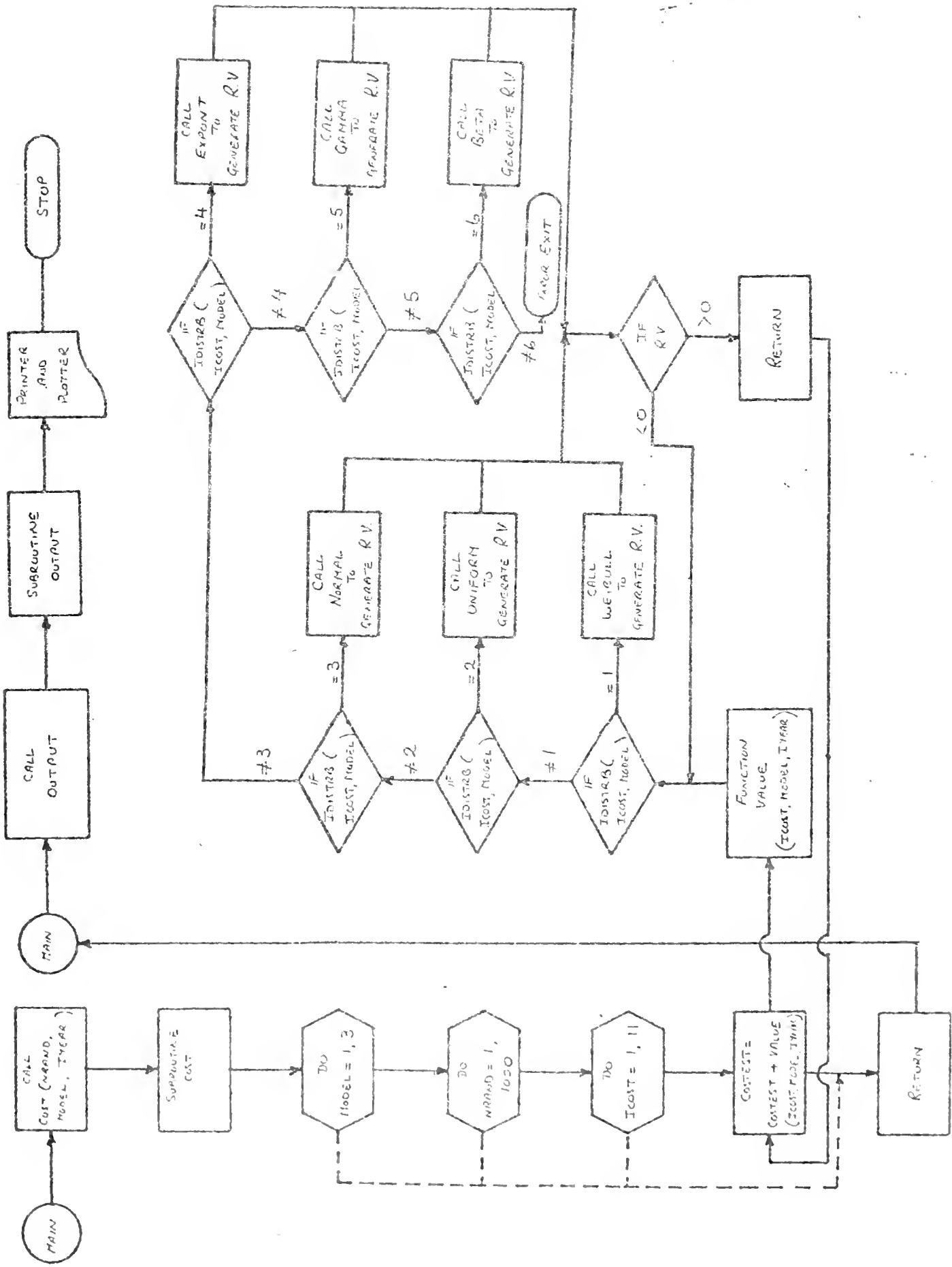
Processing of input data is straightforward except for the WEIBULL distribution in which case SUBROUTINE DISTRIB is called to generate the requisite locational, shape and scale parameters that correspond both to the input of the upper and lower bound estimates and the associated probability estimates that the actual value will lie above or below these and to the input mode. The code for IDISTRIB is shown below and follows that of Schaefer, Husic and Gutowski (1969) except for an explicit check at the beginning that the input parameters do not violate Weibull restrictions that are probability dependent. Failure to do this may result in an abnormal error termination.

The heart of the program is sketched by the flow diagram where SUBROUTINE COST loops over the different models, in this case STEAM, WATER and (STEAM-WATER) estimating NRAND cost observation for NSET items which are combined to yield the output cost probability distribution. These observations are written on tape and subsequently processed by SUBROUTINE OUTPUT. SUBROUTINE COST evaluates FUNCTION VALUE, the value of which is dependent upon the value of VARX, returned by SUBROUTINEs WEIBULL, UNIFORM, NORMAL, EXPONT, GAMMA, BETA or CONSTANT. Selection of the appropriate subroutine depends upon the value of the computed GOTO in VALUE determined by the value stored in IDISTRB for this MODEL and this ICOST item. Code for these routines is shown below.

SUBROUTINE OUTPUT sorts the cost estimates into ascending sequence using an internal SORT-MERGE package, calculates the mean, median, upper and lower bounds, inter-quartile range, standard deviation, standard error, skewness and kurtosis of the distribution, generates a printer plot of the

data and a listing of the percentile points. The data are also processed through SUBROUTINE SMOOTH derived from the SHARE Library which uses a polynomial fit (up to 25th degree) to smooth the data. Smoothed data can then be passed to SUBROUTINE GRAPH for plotting via a CALCOMP plotter.

All work was performed on a CYBER 175 using the CDC random number generator RANF at the University of Illinois Digital Computation Laboratories and the programs were written in CDC Extended FORTRAN.

Flowchart (rotated). Transcribed text content follows:

MAIN → CALL OUTPUT → SUBROUTINE OUTPUT → PRINTER AND PLOTTER → STOP

MAIN

IF IDISTRB (ICOST, MODEL) ≠4 / =4 → CALL EXPONT TO GENERATE R.V.

IF IDISTRB (ICOST, MODEL) ≠5 / =5 → CALL GAMMA TO GENERATE R.V.

IF IDISTRB (ICOST, MODEL) ≠6 / =6 → CALL BETA TO GENERATE R.V.

ERROR EXIT

IF RV >0 / <0 → RETURN

IF IDISTRB (ICOST, MODEL) ≠3 / =3 → CALL NORMAL TO GENERATE R.V.

IF IDISTRB (ICOST, MODEL) ≠2 / =2 → CALL UNIFORM TO GENERATE R.V.

IF IDISTRB (ICOST, MODEL) ≠1 / =1 → CALL WEIBULL TO GENERATE R.V.

FUNCTION VALUE (ICOST, MODEL, IYEAR)

MAIN

CALL CUST (NRAND, MODEL, IYEAR) → SUBROUTINE CUST → DO MODEL = 1,3 → DO NRAND = 1, 1050 → DO ICOST = 1, 11 → COSTEST = COSTEST + VALUE (ICOST, MODEL, IYEAR) → RETURN

APPENDIX B

Bibliographical Note on Data Sources

For the most part, data for the simulation model was difficult to find, limited when found and rarely in the ideal form. This of course was one of the rationales behind the simulation approach.

Interest Rates

Information of interest rates was derived from Macaulay (1938) and from Homer (1977), with supplementary evidence drawn from the various contemporary accounts of the costs of steam and water power and from Kuehnle (1958). Prior to 1857 the data are based on Tables 24 and 25 in Macaulay (1938) which are of monthly commercial paper rates in Boston and from Homer (1977), Table 44 where, in addition to repeating the quotes given by Macaulay, some different quotes are given. After 1857 the data are based on Macaulay (1938), Table 10 and Homer (1977), Table 44.

Wages

Daily wage data are from Lebergott (1964), Table A-25: Common Laborers, Average Daily Earnings 1832-1940 and Table 6-2 (1860-1880). Estimates for the 1840s were interpolated from the 1832 and 1850 data. These were also supplemented by the series given in Historical Statistics (1975) especially series D716 for the 1820s which are Laborers wages in the Philadelphia area, series D718 from 1823-1881 (common laborers on the Erie Canal), series D734 (daily wages of laborers in Manufacturing Establishments), 1860-1880 (also Lebergott, Table 6-2) and from series D847 and 848 from 1890 (Average daily hours and Average hourly earnings).

Fuel Consumption

Estimates of fuel consumption were derived from a wide variety of sources. For the 1820s estimates given in U. S. Congress (1825) and Justitia (1841), for the 1830s, U. S. Congress (1838) and Justitia (1841). In addition to U. S. Congress (1843) and Justitia (1841), estimates for the 1840s were also derived from De Bow (1848). De Bow (1850a, 1850b, 1850c and 1853) also provided the basis for the 1850s estimates. 1860s data were interpolated from the 1850s data and from the 1870s data which came from Emery (1883). Estimates for the 1880s were then interpolated from these and from Unwin (1893-4).

Price of Coal

The basic data on coal prices came from Historical Statistics (1975) serie E129 but these were verified against the price quotations given in the fuel consumption references together with quotes in Manning (1889) and Main (1890) and in Eavenson (1942) and from the Coal and Coal Trade Journal published from 1889.

Cost of Steam Engines and Waterworks

Estimates of steam engine and waterwheel costs usually occurred together. The various reports of the Committee to select a site for a national Armory on the Western Waters, U. S. Congress (1825), (1838) and (1843) for example, all give estimates for a National Armory powered by either steam or water. Justitia (1841) and Montgomery (1840) in the course of their debate over the costs of steam and water power offer a number of estimates that are later updated in James (1849) and De Bow

(1848, 1849, 1850a, 1850b, 1850c, 1853). There is a gap in waterwheel cost estimates then between these and Manning (1889), but comprehensive steam engine cost estimates are given for the intervening period in Emery (1883). Other cost estimates for both steam and water may be found in Main (1890), Webber (1893) and McElroy (1895-96).

Water-Rights

Comprehensive data on water powers and the costs of water-rights are given in the Tenth Census' special report on waterpower of the United States (1885). Much of this information is condensed and summarized in Swain (1888).

Water-Wheel Efficiency

Estimates of water-wheel efficiency came from an account of the water-wheel found in Cyclopaedia of Arts and Sciences (1861) quoting from experimental results, especially those of a Mr. G. Rennie. These results are supported by calculations based on the data given in U. S. Congress (1825, 1838 and 1843) regarding the performance of wheels at the Springfield Armory, by experiments reported in Franklin Institute (1842) and also by trials on the Burden waterwheel reported by Sweeny (1915). Estimates of turbine performance are from Francis (1884), Manning (1889), Main (1890), Webber (1895-96), McElroy (1895-96).

Hours Per Day

Daily hours of operation were required in order to help convert the fuel consumption estimates of steam engines from pounds of fuel per hour per horsepower to tons of fuel per horsepower per year. Estimates were

derived on the basis of a time series regression of series D-847 of

Historical Statistics (1975) between 1890 and 1914 of the form Hours/

day = f(Date), the R^2 of the resultant equation:

Hours/Day = 53.178 - .023 · Date

was 0.837 and this equation yields estimates that are consistent with

contemporary accounts of about 11 hours/day in the mid-nineteenth century.

Other Variables

Other variables not mentioned above, namely days per year, life

expectancy, and repair and insurance rates were much less perfectly

observed. Scattered observations were culled from the works discussed

above but most of the data input for these variables was interpolated

from those scattered observations.

For example most late nineteenth century studies (Emery (1883),

Manning (1889) and Main (1890)) suggest that steam powered plants could

be operated 309 days a year. Historical Statistics (1975) in series

D-846 gives a range for all manufacturing industry of 271-297 days per

year. I assumed that for steam plants the mode was 295 days. A mode

of 265 days for water powered plants would be consistent with the esti-

mates in Historical Statistics and with Manning (1889) and Main (1890)

who suggest that water powered mills lost about 30 production days a

year due to ice, drought and flooding.

Repair rates and life expectancies can also be inferred from the

estimates in U. S. Congress (1825, 1838 and 1843), Emery (1883) and from

Manning (1889) and Main (1890). Insurance rate data were not found prior

to Manning (1889) and for earlier dates we have simply added 0.5 per

cent for each decade back from then for steam and 0.25 percent for water.

M/D/93

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