THE RELEVANCE OF TECHNOLOGICAL CHANGE IN LONG-TERM WATER RESOURCE PLANNING

by

Roger G. Kraynick and Charles W. Howe

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REPORT ON INVESTIGATIONS CONCERNING THE RELEVANCE OF TECHNOLOGICAL CHANGE IN LONG TERM PLANNING

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by

Roger G. Kraynick

Charles W. Howe

Department of Economics
University of Colorado

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Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado 80523

Norman A. Evans, Director

ABSTRACT

In the planning of long-lived public investment projects in the water resources area, decision-makers have been encouraged to explicitly consider the consequences of technological change. This report investigates the potential significance of such a recommendation through the analysis of historical reconnaissance and construction cost data. It further investigates the sensitivity of optimal water supply system sequencing to rates of technological change. The major part of the investigation derives trends of real unit costs associated with major sub-project tasks of large-scale water projects. Data from U. S. Bureau of Reclamation water supply projects from 1935 to 1970 show that real unit costs of large-scale excavation and other construction operations have declined significantly, but the separation of static scale economy effects from the effects of true technological change poses a difficult problem. A second analysis examines how technological advances may contribute to the reduction of physical and engineering uncertainties in project construction and operation. A specific instance is geologic reconnaissance activities used in water project implementation, an activity which has benefitted from great technological advance in the post-war period. Data from U. S. Bureau of Reclamation projects show that there exists a statistically significant negative relationship between expenditures on reconnaissance investigations and geologically related construction cost overruns and post construction failures. The returns to geologic reconnaissance appear to have improved over time, suggesting significant technological improvement. Lastly, a dynamic investment planning model was utilized to determine the impact which inclusion of technological change as manifested in rates of change of the costs of various technologies would have on an optimal scheduling of projects in water supply system development. The results indicate that while

some of the low historical rates of real cost reduction have been too low to affect the optimum sequencing of projects, rates well under 1% per annum can significantly change the optimum sequence of projects and the present value of system net benefits.

TABLE OF CONTENTS

Preface

This completion report transmits the results of empirical and modeling analyses of the importance and impacts of technological change on water resources planning and management. The authors wish to acknowledge the generous assistance of personnel of the Engineering and Research Center of the Bureau of Reclamation (Denver, Colorado). In particular, thanks are extended to Mr. W. W. Reedy, Chief of Planning Operations and Mr. Ron Hicks, Chief, Estimates and Analysis Branch. The University of Colorado provided support for the project-related dissertation[1] in the form of funds for computer time and related services. In several instances, the investigations contained herein are abridged for space considerations. The reader should consult the project-related dissertation.

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[1] Kraynick, Roger George, "Studies on the Relevance of Technological Change in the Planning of Public Projects in the Civil Works Category," Boulder, Colorado, University of Colorado (unpublished Ph.D. dissertation), 1976, 289 p.

List of Tables

List of Figures

Chapter 1

Introduction

It has been alleged that the planning of long-lived public investment projects in the water resources area where the influence of high technology is not pronounced inappropriately omits consideration of future technological change. The National Academy of Sciences Committee on Technologies and Water (June 1971) included the following in their recommendations:[1]

> Recommendation #1: Technological change and impacts must be brought explicitly into water planning. Past procedures for water planning have always taken a conservative stand toward technology, i.e. they have worked almost completely within existing technologies and have not counted on new technologies being available. ...
>
> Recommendation #3: Water planning must be continually reassessed to consider the benefits of new technology. ... it is essential that reassessments be carried out on a continuing basis. This requires that the water planning process remain closely keyed to new and impending technical developments so that the benefits of these technologies are realized at the earliest possible time.
>
> Recommendation #4: Water planning must have built-in flexibility. ... this implies the need for some form of formalized systems analysis which considers a host of relevant factors, some of which will certainly relate to new technologies, before irreversible decisions are made.

This report investigates the potential significance of these assertions through the analysis of historical data and further investigates the sensitivity of optimal water supply plans to rates of technological change.

The first of three investigations is termed the major study in this report. It deals with the technology of conventional surface water supply systems, characterized as a process combining labor, materials, and capital equipment. However, each type of system component is so vastly different

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[1] National Academy of Sciences, Committee on Technologies and Water, 1971, "Potential Technological Advances and Their Impact on Anticipated Water Requirements" (A Report to the National Water Commission): Washington, D. C., NTIS Accession No. PB 204053, 177 p.

from the rest in its construction and operating processes that it can be exceedingly difficult to examine technological advance. Consequently, the hypothesis that advancing technology in construction sub-processes has resulted in reductions in unit costs is examined only for water supply projects constructed over the period 1935 to 1972.

The two other investigations are referred to below as the minor studies. One of these investigations takes up the issue of the physical uncertainties inherent in the planning of civil works. Certain types of advancing technology can reduce the uncertainties arising from imperfect information regarding the physical setting and related engineering system performance. This is studied in detail with respect to engineering geology reconnaissance of the potential sites for water resource projects. Technological advance has had a decided influence as evidenced by the emergence of sophisticated tools and the increasing effectiveness of such reconnaissance activities in reducing construction costs and post-construction failures.

The second minor study presents an investment planning model for water resources systems and investigates the sensitivity of optimal investment programs to different rates and forms of technological advance. A model of water supply capacity expansion was made to reflect the influence of various technological advances on both the water supply and water demand sides.

A list of the major results would include the following points:

1. In the cases of a few basic construction operations, (constant) dollar unit costs have declined significantly over time.
2. Static economy of scale effects are interwoven with technological advance and are difficult to separate in attempting to discern evidence of technological advance.

3. Technological advance in the reduction of physical uncertainties inherent in civil works projects through geologic reconnaissance is an important activity which yields significant net returns to expenditures.
4. Water resources planning models can be designed effectively to incorporate technological change through changing cost functions and demand functions.
5. Reasonably projected technological changes appear to be capable of significantly affecting the optimal sequencing and timing of water projects in system development.

Chapter 2

Technological Advance and Civil Works

How important over time is technological change which is incorporated into new civil works?

The likelihood that significant technological change will lead to the obsolescence of a project is naturally a function of the lifetime of the project. Highways may have expected physical lifetimes of several centuries. A waste-water treatment plant may have an expected physical life of 30 years, but both may be subject to considerable uncertainty regarding economic obsolescence. The underlying reasons for such uncertainties include technological change in complementary and competing technologies. In the case of highways, a change in transport technology could shorten the useful life by many years. This points up the need to examine long-lived civil works technology with respect to complementary, competitive, and replacement technologies and what these imply for the economic lifetime of projects.

Technological advance is frequently posited as being induced by influences endogenous to the economic system, a phenomena referred to in the literature as the "induced innovations" hypotheses[1]. Specifically, relatively high prices for a factor of production will induce technological change which conserves that factor. Technological changes in the contract construction industries are often termed labor-saving because they are aimed at reducing total labor costs. This has been noted in reference to construction of highways, public housing, and hospitals:

> ... Construction of new federally-aided primary highways -- amounting to almost $5 billion in 1970 -- required nearly 30 percent fewer manhours for each $1000 of highway expenditures in 1970 than in 1958. ...[2]

Technological change in civil works activities may also be induced by regulatory standards relating to materials and procedures. Emission and effluent standards are examples of standards which may induce markedly different technologies. In a global sense, the introduction of a new technology in these cases should be aimed at net reductions in environmental costs.[3] Unit

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[1] Recall the usual distinction between invention and innovation: the former term indicates the original creation of a scientific principle or idea; the latter infers adaptation of that idea into some marketable product. Cf Nordhaus, W. D., 1969, <u>Invention, Growth, and Welfare</u>: Cambridge, Mass., MIT Press, especially Chapter 6.

[2] Ball, Robert, 1973, "Labor and Materials Required for Highway Construction": <u>Monthly Labor Review</u>, vol. 96, no. 6, pp 40-45. Also cf. Finn, J. T., 1972, "Labor Requirements for Public Housing": <u>Monthly Labor Review</u>, vol. 95, no. 4, pp 40-42; Riche, J. F., 1972, "Man-hour Requirements Decline in Hospital Requirements": <u>Monthly Labor Review</u>, vol. 95, no. 5, p. 98.

[3] Cf. Lakhani, Hyder, 1975, "Diffusion of Environment-Saving Technological Change -- A Petroleum Refining Case Study": <u>Technological Forecasting and Social Change</u>, vol. 7, no. 1, pp 33-55.

cost increases of civil works projects associated with environmental or other regulations may, however, complicate attempts to discern cost-saving technological change.

An important factor seriously complicating the identification of technological change is the matter of "economy-of-scale" effects in the construction of civil works. It is important to distinguish such scale effects from technological advance effects in the analysis of cost over time, since the average size of construction projects has constantly been increasing. In the civil works literature, there is a tendency to speak of a combined effect in most cases. The discussion of this issue is continued in the following section in connection with the empirical investigations there.

Given that technological advance can be analyzed in civil works, the question arises as to whether or not the <u>rate</u> and <u>direction</u> of technological advances are socially optimal. Studies of "public technology"[1] have shown that the level of government where an agency is located is an important factor in determining how quickly technological change will be implemented. For example, at the <u>major city</u> government level

> ... (e)xperience has shown conclusively that fractionalized technical information is a source of frustration for those local officials who are actively seeking innovative improvements and a defense for those local officials who are confounded by rapidly changing technologies and who, as a result, are recalcitrant to switch from once reliable, but now outdated techniques...[2]

At the state level, a high degree of interest appears to be emerging in creating

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[1] The phrase "public technology" has a broad meaning, but does encompass technology utilized in civil works projects. Cf. Federal Council for Science and Technology, 1972, "Public Technology: A Tool for Solving National Problems": Washington, D. C., U. S. Government Printing Office, 136 p.

[2] McPherson, M. B., 1974, "Innovation: A Case Study": American Society of Civil Engineers Urban Water Resources Research Program Technical Memorandum No. 21.

technology diffusion channels within and between states.[1] At the federal level, there would appear to be great opportunity for coordination of the incorporation of technological advance, since federal government outlays for civil works activities are in the $50 billion per year range and federal grant funds destined for civil works activities amount to about $6 billion.[2]

Chapter 3

Findings of the Major Study: An Investigation into the Technology and Costs of Conventional Water Supply Projects

The Nature of Construction Activities for Large Civil Works Projects

The construction of large civil works projects is typically thought of as an aggregate capital intensive process involving large machinery items. Indeed, studies have well documented the tendency toward capital intensiveness, as in highway construction where onsite labor requirements have decreased 3 percent over the period 1958 to 1970.[3] This trend is, however, a continuation of a major shift in construction technology which occurred during World War II and the immediate postwar period.[4] Using earthmoving machinery as an example, it is noted that the increasing capacity, speed, power, and durability of equipment permits the movement of greater masses of earth and other materials

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[1] Harris, C. C., 1974, The Regional Economic Effects of Alternative Highway Systems: Cambridge, Mass., Ballinger, p. 297.

[2] Ibid., p. 161.

[3] Ball, Robert, "Labor and Materials Required for Highway Construction," Monthly Labor Review, vol. 96, no. 6 (1973), p. 42.

[4] Dreiblatt, D. E., The Economic of Heavy Earthmoving. New York, Praeger, p. 20.

than was previously possible. Up to the 1970's, the size of machines seemed to have no limit, but recently evidence has emerged suggesting that size and weight levels may have reached restrictive proportions. Future changes in construction equipment may be oriented only toward improved quality of the finished product and the speed of work.

What has happened to labor during this period of growing capital-intensiveness? In highway construction, the proportion of onsite skilled workers has increased by 5 percentage points in the period 1958 - 1970[1]. In water resource project construction, a similar but less pronounced trend appears to have occurred. In any event, there has been a decrease in labor intensiveness across almost all construction.

Derivation of a Data Base for the Analysis of Technological Advances in the Construction of Water Resource Projects.

Data on actually realized unit costs of specific operations are private property and are carefully guarded by contractors. Thus, alternative approaches to costs had to be taken in this study. The approach adopted involved the analysis of bids. It is, therefore, necessary to understand the competitive bidding process and the estimation of costs of projects by prospective construction firms interested in performing the requested work for a public agency.

An agency notifies by announcement or selective invitation that it wishes interested parties to submit bids on a project. Generally, the announcement entails a list of necessary steps or *specification items* which must be performed

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[1] Ball, *op. cit.*, p. 42.

in the course of completing the project. Upon receipt of all bids, an agency such as the U. S. Bureau of Reclamation (USBR) may elect to issue an abstract of bids, a facsimile of which is represented in Figure 3-1. An abstract of this sort may entail as many as several hundred specification items or as few as one.

For each item in Figure 3-1, a short description is given in addition to the applicable units of measurement. The next column contains the quantity of material or number of units specified for completion of the task. The remaining columns are estimates of unit costs bid by each construction firm on the particular item in question.[1] For the analysis of unit cost data which follows, fifteen specific specification items for which the task has remained essentially unchanged over time[2] were selected for analysis. An obvious example is excavation.

The abstracts of bids for some 1200 major or appurtenant features in water supply construction projects were analyzed in the data acquisition process. Table 3-1 is a list of the fifteen different operations for which data were obtained. Note that in some cases there were two units of measurements (or scale variables) which were relevant to an operation. The number of unit cost bids which were submitted for any operation varied from 2 to as many as 21. The average number of bids per contract reflects the number of firms engaged in certain kinds of construction work.[3] Note, for instance, the relatively small

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[1] The column labeled as "engineers estimate" lists the unit cost determined by the in-house engineering staff of the public agency or by a private consultant retained by the agency.

[2] See Table 3-1 below for a list of those items selected for analysis.

[3] The engineers estimate is not included as a unit cost bid.

FIGURE 3-1

FACSIMILE OF AN ABSTRACT OF BIDS

Specification Item		Unit	Quantity	Engineers Estimate $	1	2	3	N
No.	Description				Firm A $	Firm B $	Firm C $	
1	Diversion and Care of River	--	lump sum	20000	21345	22585	22554	
2	Excavation, Common, in Found.	cu yd	540000	.09	.11	.10	.14	
3	Excavation, Rock, in Found.	cu yd	38000	.31	.36	.34	.24	
4								
5								
:								
:								
:								
:								
M								
Totals				$2367000	$2166885	$2220320	$2456000	

TABLE 3-1 CHARACTERISTICS OF THE SAMPLE OF CONSTRUCTION OPERATIONS

Item Number	Operation Name	Unit of Measurement		Number of Contracts	Average Bids Per Contract	Total Number of Bids
		Primary	Secondary			
1.	Excavation,common,in foundation	$10^6 yd^3$	----	205	9.7	1988
2.	Excavation,rock,in foundation	$10^6 yd^3$	----	183	10.3	1830
3.	Excavation,common,plus haulage	$10^6 yd^3$	miles	179	10.0	1844
4.	Excavation,sand,gravel,haulage	$10^6 yd^3$	miles	155	8.7	1349
5.	Excavation,common,for canals	$10^6 yd^3$	----	94	10.5	987
6.	Excavation,common,for pipelines	$10^6 yd^3$	----	87	11.4	992
7.	Tunneling in rock	$10^3 yd^3$	----	53	5.6	296
8.	Tunneling in rock	$10^3 ft$	ft^2 Area	37	4.5	165
9.	Backfill in pipelines	$10^6 yd^3$	----	84	11.4	958
10.	Placement,common materials,dams	$10^6 yd^3$	----	64	8.7	557
11.	Placement,sand and gravel,dams	$10^6 yd^3$	----	57	8.6	490
12.	Placement, mass concrete, dams	$10^6 yd^3$	----	35	6.2	217
13.	Placement,mass concrete,tunnels	$10^6 yd^3$	----	43	8.0	344
14.	Placement,mass concrete,canals	$10^6 yd^3$	----	58	10.5	609
15.	Furnish,place concrete pipe	$10^3 ft$	ft^2 Area	87	12.0	1044

number of firms that submit bids on tunneling work.

The acquisition of these data was only the first step in the derivation of a data base suitable for the analysis of technological advance. To explain adequately the second step, further digression on the competitive bidding process is necessary. Naturally, it would be desirable to have the actual *ex post* unit costs. The construction firm conducting the work records with some precision the magnitudes of these costs but, for proprietary reasons, they remain confidential. We seek a procedure which transforms bid prices into useful estimates of actual *ex post* unit costs. Bureau of Reclamation personnel suggested a *hueristic* method for reducing an array of unit cost bids to a single estimate of the *ex post* unit cost for each operation in the sample. The procedure attempts to work backwards through the steps that a construction firm is hypothesized to follow (Figure 3-2) in preparing a set of unit cost bids for the items in the specifications list.[1] The first step undertaken by a bidding firm is termed an "honest" appraisal of unit cost, the second is the determination of "optimal" markup, and the last is the "unbalancing" strategy.

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[1] Several hypothesized estimating procedures are described in the literature. Hillebrandt suggests a three-stage decision-theoretic approach involving the firm's perception of uncertainty with regard to environmental and business conditions and the firm's risk-taking (or risk-avoiding) behavior. Cf. P. M. Hillebrandt, 1974, *Economic Theory and the Construction Industry:* London, McMillan, 233 p. Optimal bidding models attempt to operationalize some of the decision-theoretic concepts to arrive at techniques usable by firms. A simple model is provided in Benjamin, N. B. J., 1972, "Competitive Bidding: The Probability of Winning": *Journal of the Construction Division, ASCE*, vol. 98, no. CO 3, p. 104-111. More complex is the model described in Emil Attanasi, 1974, "Some Interpretations of Sequential Bid Pricing Strategies": *Management Science*, vol. 20, no. 11, p. 1424-1427.

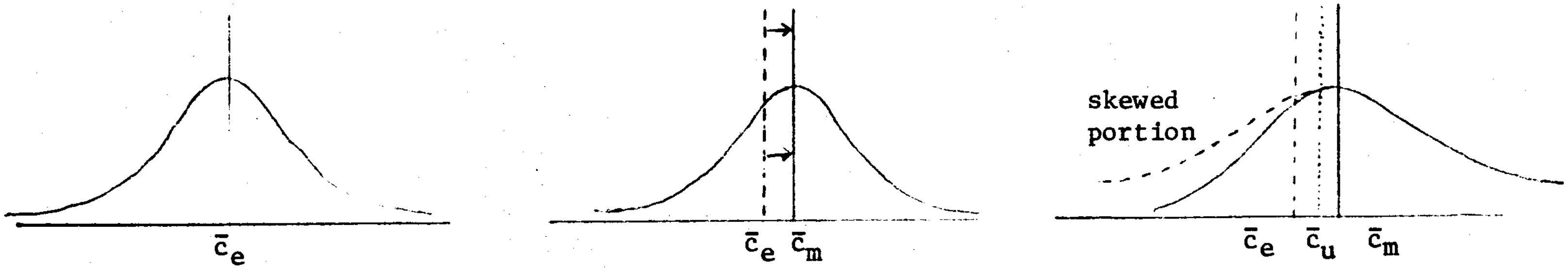
FIGURE 3-2

HYPOTHESIZED PROCEDURE USED BY CONSTRUCTION FIRMS TO GENERATE OPTIMAL UNIT COST BIDS

1. Estimating staffs of firms prepare estimates of unit costs; expected value of estimate assumed to equal actual *ex post* unit cost if firm wins bid

2. Management adds maximum markup consistant with desire to win contract

3. Management unbalances bids and includes other adjustments to maximize cash flow, increase profits



distribution of estimates of all firms assumed to be normal; $\bar{c}_e$ equals mean

$\bar{c}_m$ equals mean of estimates with markup added

$\bar{c}_u$ equals mean of estimates with unbalancing added; resultant distribution may be skewed

The heuristic reverse process proceeds as follows. The mean and standard deviation of the actual bids are calculated. Then bids falling outside of 1.6 standard deviations on either side of the computed mean are deleted. If the specification item is of such a nature that unbalancing of bids is likely to have resulted in a skewed distribution, data falling outside 1.2 standard deviations on the skewed side and 1.6 standard deviations on the other side are deleted. Next, the mean and standard deviations are recomputed. This mean is adjusted downward by one-tenth of a standard deviation to allow for the markup procedure as explained previously. Finally, the remaining bids are examined to insure that they fall within 1.6 standard deviations of the adjusted mean. If not, those bids falling outside are deleted and a final adjusted mean is calculated.

Once estimates of the actual ex post unit costs represented by the various bids on a job falling within one of the fifteen construction operations had been completed, adjustments for price changes over time and for systematic differences in unit costs by geographic region could be made.

The adjustment of costs to take account of price changes, both current and expected, is seriously undertaken by clients and construction firms alike. Clients attempt to incorporate expected rates of price changes in order to plan construction budgets several years in advance. Construction firms attempt to incorporate expected cost changes in their unit cost bids when bidding on available contracts which have future starting dates and possibly long construction programs.

When considering an array of unit cost bids over a span of 35 to 40 years as in the present study, some concern must be expressed for the adequacy of the index used to convert all costs to a constant dollar base. The Common

Labor Component of the Engineering News-Record (ENR) Construction Cost Index was viewed as an adequate index with some reservations concerning its usefulness in dealing with a 30- or 40-year time series of current dollar unit cost figures.[1]

Two approaches were taken to spatial adjustment of the cost index series. First, the Engineering News-Record lists geographic adjustment factors for its Construction Cost Index for a group of 11 cities in the 17 western states where all of the projects under consideration were constructed. However, use of these adjustments does not adequately cover the spatial dispersion of the entire sample. The ENR index adjustment factors are derived primarily from data from urban areas, whereas most of the cost data gathered in this study reflect rural or even non-settled locations. A second adjustment procedure was thus devised using BLS average hourly earnings for contract construction in each of the 17 western states and the nation.[2] The principle drawback to this procedure was that the earnings records extend only from 1947 to the present. The geographical adjustment factor for the period 1930 to 1946 was estimated on the ENR adjustment factors, taking care to insure that the two adjustment series were consistant with one another.

This step completed the derivation of the data base.

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[1] Published weekly by Engineering-News Record.

[2] BLS, 1973, Handbook of Labor Statistics. Washington, D. C., GPO, especially Table 105, p. 244, 245. The adjustment factor becomes simply the ratio of the hourly earnings figures for each state to the national figure.

A Model for Distinguishing the Effect of Technological Advance in Construction Activities.

The principle objective in the analysis of the data was to formulate and test hypotheses regarding the impact of technological advance on the levels of unit costs. The analysis was originally envisioned to consist of the delineation of trends of unit costs of construction operations over time. Figure 3-3 depicts the characteristics of the items involved in a single observation. The dependent variable in the trend analysis is the estimate of actual unit cost for a particular operation. Five independent variables are assumed to influence actual unit cost: time, scale of operation, adequacy of transportation, elevation of construction site, and incidence of severe weather. The latter three variables were assigned 0, 1 values. There are 15 different data sets, one for each operation as defined previously in Table 3-1. Evidence is sought concerning changes in "real"(constant dollar) unit costs for these 15 construction operations over time.

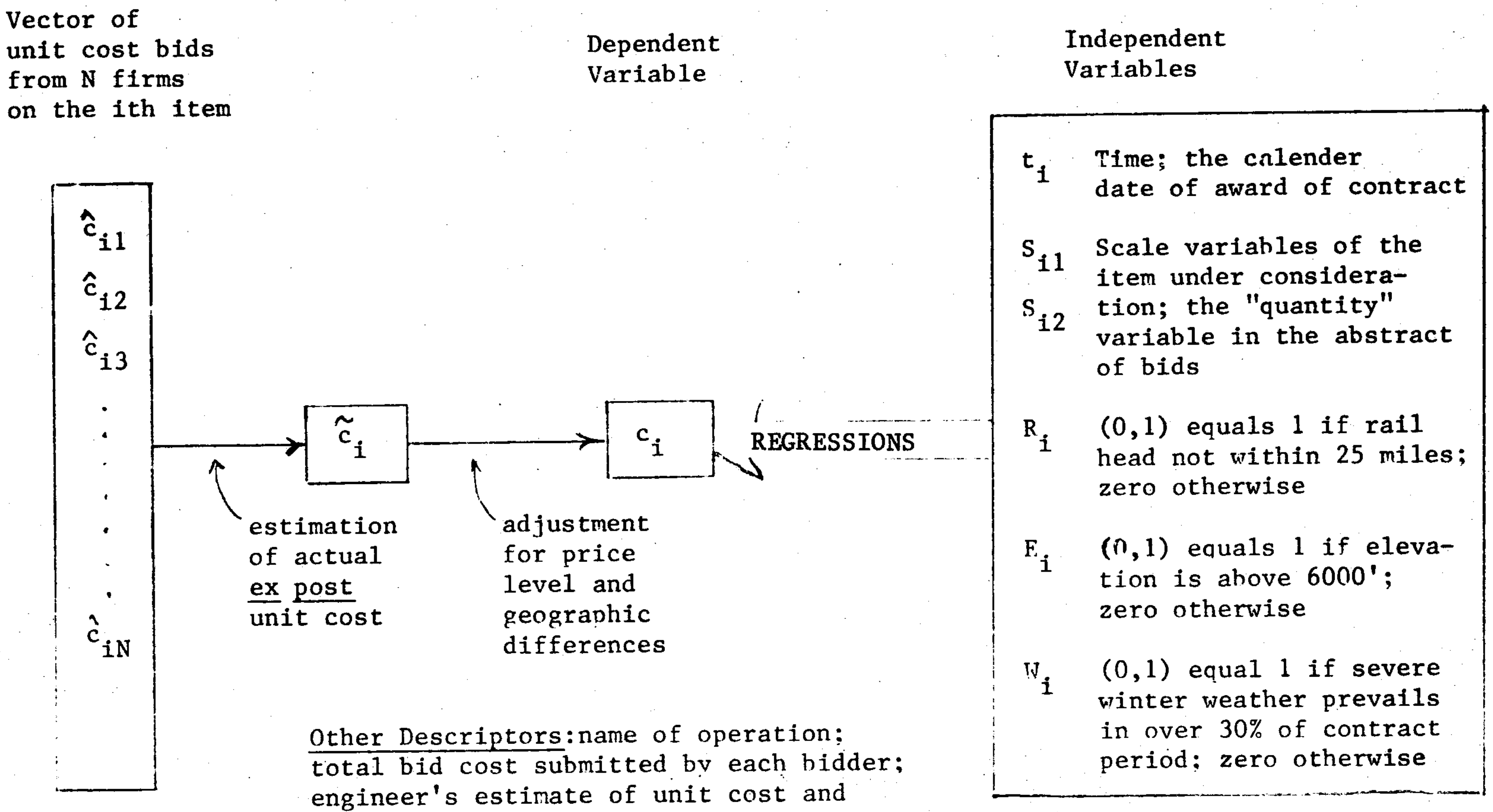
It has been noted above that the effects of technological advance and the effects of economies of scale may be difficult to distinguish over time. To distinguish between these two effects, it was decided to represent each operation as a production process with an underlying Cobb-Douglas (log linear) production function characterized by

$$(3.1) \qquad q = a_o(t)X_1^{\alpha_1} X_2^{\alpha_2} X_3^{\alpha_3} u$$

where q, X_1, X_2, X_3 are respectively output, labor, capital, and materials. The α_i are parameters, the sum of which is indicative of the existence of decreasing, constant, or increasing returns to scale. For the indicated

FIGURE 3-3

SUMMARY OF DATA FOR EACH OBSERVATION



t_i Time; the calender date of award of contract

S_{i1} S_{i2} Scale variables of the item under consideration; the "quantity" variable in the abstract of bids

R_i (0,1) equals 1 if rail head not within 25 miles; zero otherwise

E_i (0,1) equals 1 if elevation is above 6000'; zero otherwise

W_i (0,1) equal 1 if severe winter weather prevails in over 30% of contract period; zero otherwise

Other Descriptors: name of operation; total bid cost submitted by each bidder; engineer's estimate of unit cost and total bid estimate; name of facility: USBR project name operations, increasing returns to scale are anticipated. $a_o(t)$ is a functional which describes the impact of technological advance on output. The technological advance in this specification of the production function serves to augment the productivity of all factor inputs (termed "Hicks-neutral" in the economic literature). Lastly, u is a random perturbation term representing the net effect of all other factors. The total costs of this production process for one operating time period are given by:

(3.2) $$C = p_1X_1 + p_2X_2 + p_3X_3$$

Minimization of (3.2) subject to the constraint imposed by (3.1) yields the long-run total cost function.

(3.3) $$C = a_o(t)^{-\frac{1}{r}} q^{\frac{1}{r}} p_1^{\frac{\alpha_1}{r}} p_2^{\frac{\alpha_2}{r}} p_3^{\frac{\alpha_3}{r}} z$$

where $$z = r\alpha_1^{\alpha_1}\alpha_2^{\alpha_2}\alpha_3^{\alpha_3} u^{-\frac{1}{r}}$$

$$r = \alpha_1 + \alpha_2 + \alpha_3$$

The average cost function which we desier to investigate is

(3.4) $$\frac{C}{q} = a_o(t)^{-\frac{1}{r}} q^{(\frac{1-r}{r})} p_1^{\frac{\alpha_1}{r}} p_2^{\frac{\alpha_2}{r}} p_3^{\frac{\alpha_3}{r}} z$$

This function might be estimated using the indicated factor price data. In the case of the construction operations considered here, information on factor prices was not uniformly obtainable. Therefore the price terms are combined with term z as a residual in the estimation process. The technological advance function is assumed to be of exponential form, i.e. $a_o(t) = e^{\rho t}$. Thus, equation (3.4) can be expressed as

$$(3.4') \qquad \frac{C}{q} = K\, e^{\frac{-\rho t}{r}}\, q^{(\frac{1-r}{r})}\, v$$

where v represents the combined terms mentioned above.

In this form, it is perhaps not clear that the technological advance parameter, ρ, and the scale economy parameter, r, could be identified.[1] However, in log form (3.4') becomes

$$(3.5) \qquad \ln\,(\frac{C}{q}) = \ln K - \frac{\rho}{r}\, t + (\frac{1-r}{r})\, \ln q + \ln v.$$

In this form, the technological advance parameter is related directly to the passage of time and the economy of scale effect is related to the natural log of the observable scale variable, q.

The null hypotheses with regard to these parameters are taken to be that $\rho = 0$ (technological advance absent) and that $r = 1$ (constant returns to scale obtain), with the alternative hypothesis being that $\rho > 0$ and $r > 1$. For purposes of estimation, (3.5) is restated with the dummy variables (representing controls for transport difficulty and climate) excluded and included respectively:

$$(3.5') \qquad \ln\,(c) = \hat{\beta}_o + \hat{\beta}_1 \ln S + \beta_2 t + v'$$

$$(3.5'') \qquad \ln\,(c) = \hat{\beta}_o + \hat{\beta}_1 \ln S + \hat{\beta}_2 t + \hat{\beta}_3 D + v'$$

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[1] A simple analogy to this process can be found in the case of a series of machines. Technological advance can be examined by observing the input-output relation of the same size machines of different vintages, while scale economies are examined by observing the input-output relation of machines of the same vintage but of different sizes.

where

c = the estimated actual ex post unit cost observed for a construction operation

S = a vector of scale variables; e.g., a specification item may be the excavation of 1.2 million cu. yd. (one scale variable) or it may be excavation of 1.2 million cu. yds. plus haulage distance of 3 miles (two scale variables)

t - time (calendar date)

D - a vector representing the dummy variables for transport and climate.

v' = random residual term

Functions (3.5') and (3.5") were estimated for each of the 15 selected specification items.

In addition to this primary model, it was also felt that alternative forms of the production function (and thus the unit cost function) might also be appropriate. Alternative model 1 is linear in form and is given by:

$$(\frac{c}{q}) = \hat{\beta}_o + \hat{\beta}_1 S + \hat{\beta}_2 t + v \tag{3.6}$$

Alternative model 2 is semi-log in form:

$$(\frac{c}{q}) = \hat{\beta}_o + \hat{\beta}_1 \log S + \hat{\beta}_2 t + v \tag{3.7}$$

For each of the fifteen construction operations listed previously in Table 3-1, standard least-squares regression techniques were used to estimate the coefficients.

Regression Analysis of Unit Cost Data

Limitations on space preclude an in-depth discussion of results for each of the fifteen analyses of construction operations considered. Below, the regression results for the primary model (functions 3.5' and 3.5") are presented.

Results from the alternative models did not present any improvement over the primary model.

For the primary model (Eq. 3.5'), Table 3-2 summarizes the estimated coefficients of function (3.5'), $\hat{\beta}_1$ and $\hat{\beta}_2$, and the related estimates of ρ and r. The level of significance with respect to the appropriate 1-tail tests of the null hypothesis are indicated by symbols in Table 3-2. Note that for those specification items for which there are two scale variables, only the coefficient of the "primary" scale variable is listed. For each specification item, the parameters r and ρ are shown, as are the number of observations, N, and the coefficient of multiple correlation, R^2.

The regression results of Table 3-2 do not include the dummy variables which were described above. The inclusion of the dummy variables (equation 3.5") pertaining to transportation and severity of conditions do not substantially change the nature of results shown in Table 3-2. None of the dummy variables was significant at the 10 percent level in any of the 15 construction operations. This result was quite unexpected since cost estimators actually include such information in the preparation of bids. These auxiliary parameters could be introduced quantitatively into the model for each observation. Further work along these lines was precluded because the information was originally recorded in (0,1) notation.

For the technological change parameter, the null hypothesis corresponding to $\rho = 0$ is $\hat{\beta}_2 = 0$. Only in the case of common excavation for canals is the estimate $\hat{\beta}_2$ significant at the 10 percent level. The reason for this significant result may be that the sample data represent a largely post-war experience. This period of time represented a major adaptation of new technology in

TABLE 3-2 REGRESSION ANALYSIS SUMMARY - ESTIMATES OF PRINCIPAL COEFFICIENTS, SIGNIFICANCE, AND CALCULATION OF ECONOMY OF SCALE FACTOR (r), TECHNOLOGICAL ADVANCE FACTOR (ρ)

	scale unit	coefficient of		r	ρ	N	R^2
		S_1	t				
1. Excavation,common,in foundation	$10^6 yd^3$	-0.095 #	-0.0043	1.105 #	0.00471	205	.702
2. Excavation,rock,in foundation	$10^6 yd^3$	-0.104	0.0052	1.116	-0.00580	183	.557
3. Excavation,common,plus haulage	$10^6 yd^3$	-0.083	-0.0034	1.091	0.00371	179	.602
4. Excav.,sand and gravel,haulage	$10^6 yd^3$	-0.092 *	0.0022	1.101 *	-0.00242	155	.620
5. Excavation,common,for canals	$10^6 yd^3$	-0.109 *	-0.0011 *	1.122 *	0.00123 *	94	.525
6. Excavation,common,for pipelines	$10^6 yd^3$	-0.091 *	-0.0030	1.100 *	0.00330	87	.672
7. Tunneling in rock (drill/blast)	$10^6 yd^3$	-0.185	0.0227	1.227	-0.02785	53	.421
8. Tunneling in rock (TBM)	$10^3 ft$	-0.127 *	0.0070	1.145 *	-0.00801	37	.516
9. Backfill in pipelines	$10^6 yd^3$	-0.087 *	0.0144	1.095 *	-0.01577	84	.682
10. Placement of common material,dams	$10^6 yd^3$	-0.030 #	-0.0022	1.031 #	0.00226	64	.713
11. Placement,sand and gravel,dams	$10^6 yd^3$	-0.027 #	-0.0073	1.028 #	0.00750	57	.661
12. Placement,mass cocrete,dams	$10^3 yd^3$	-0.121	0.0920	1.137	-0.10466	35	.457
13. Placement, mass concrete, tunnels	$10^3 yd^3$	-0.134	-0.0018	1.154	0.00207	43	.510
14. Placement,mass concrete,canals	$10^3 yd^3$	-0.126 *	-0.0082	1.144 *	0.00938	58	.492
15. Furnish,place concrete pipe	$10^3 ft$	-0.111 #	-0.0153	1.125 #	0.01721	87	.578

Notes: Coefficients were estimated using Eq. 3.5'. Values of t-statistic are not shown, but significance at the 10 percent level is denoted by (*), at the 5 percent level by (#). The independent variables are the primary scale variable (unit given to the left) and time (t) in years since 1930.

construction, especially in excavation machinery. In considering results by groups of operations, it is observed that the positive results were obtained for the simplest operations, namely excavation and placement of materials. In the former group, the four operations (items 1, 4, 5, 6) involving the excavation of common or strippable material presented the most significant estimates of the scale variable coefficient. For the excavation of common material from dam foundations, the coefficient of the scale variable was significant at the 5 percent level.

The excavation of rock was an item (item 2) for which the dispersion of the estimated actual unit costs was very high. This was expected since there is felt to be a great deal of uncertainty in the estimation of bids for this kind of an operation. Correspondingly, the coefficients in the estimation were not significant. The pair of operations which involved haulage of excavated material in addition to the actual excavation yielded mixed results. The excavation plus haulage of sand and gravel operation had a primary scale variable (million cu. yd. of excavation) which was significant at the 10 percent level, but the coefficients of the haulage distance variables did not prove to be significantly different from zero. The rules of thumb for haulage of borrow material given in conversations with USBR personnel was that the cost of the first half-mile of haulage was about 2 cents per cu. yd. and each additional mile cost 1/2 cent per cu. yd. The failure to observe anything like these costs in the estimation process is difficult to explain. Many of the haulage distances were short (the average was 0.47 miles), possibly allowing the lump sum charges for haulage to be unrelated to the small observed variations in haulage distance.

The next group of operations analyzed are the two tunneling categories (items 7 and 8). The data sets overlap in several cases since many tunnel contracts for the USBR are advertised both as drill and blast operations and as tunnel boring machine (TBM) operations (item 8). The former technique entails only one scale variable, the amount of material excavated from the tunnel heading measured in cubic yards. The second technique was more difficult to formulate in terms of the relevant scale variables. Contracts stipulating the use of TBM 's in tunneling are stated in terms of cost per linear foot of the tunnel to be bored. After conversations with USBR personnel, it was decided to include cross-sectional area divided by diameter as a variable, based on a rule of thumb which implies that the unit costs of excavation of circular tunnels vary directly with the square of the radius or linearly with cross-sectional area. The regression results indicate that unit costs of tunneling by drill and blast methods are not significantly related to scale nor to time.

The second tunneling method (TBM) exhibited unit costs significantly dependent upon both scale variables at the 10 percent level, but still not significantly related to time. The latter observation is disturbing in view of the abundance of literature on falling costs for tunneling by TBM's. The most plausible explanation is the fact that savings in TBM operations actually result from savings in the amount of concrete needed to line a tunnel which results in turn from the more uniform bore created by the TBM.

The next operations (items 9, 10, 11) concern the placement of materials as a process after an excavation operation. The quantities of materials here are larger because of the volume expansion which results from excavating soil. The increased quantities and the relative ease of handling affect the general level of unit costs, which are usually the lowest among the 15 operations considered here. It was thought the backfilling of pipelines would present a case in which time trends would be apparent. The operation is uncomplicated and increasing use of modern equipment was thought to contribute to lower unit costs. The regression results indicate, however, that the coefficient of the time variable is not significant.

For placement of materials in earthfill and rockfill dams, the coefficients of the scale variables are significant at the 5 percent level. The time trend coefficients are not significant, but this result is consistent with opinions of USBR personnel who felt that the unit costs of these operations are perhaps the most time-invariant of all.

The next operations (items 12, 13, 14 in Table 3-2) involve the placement of mass concrete. Only in the case of canal linings was the scale variable significant (at the 10 percent level). The time trend coefficients were found not to be significant and, furthermore, for the placement of mass concrete in dams, the apparent time trend unit costs is positive, a tendency consistent with the increasing complexity of these operations. In the case of canal linings it was expected that the increasing use of slip-form concreting machines would affect unit costs over time, but the estimate of $\overline{\beta}_2$, while negative in sign, proved not to be significant.

The last item of the 15 considered is the finishing and laying of concrete pipe. Care was taken to record data for a specific kind of pipe in a specific range of diameters. Two scale variables were selected for this regression model: the lineal distance along which the pipe was laid and the cross-sectional area of the pipe. The former was significant at the 5 percent level and the latter significant at the 10 percent level. However, the time trend was not significant even though the estimated coefficient was negative as might be expected from the emergence of specialized pipeline-laying companies in the last 20 years.

Summing up the results of the above analysis, it is seen that in 10 out of 15 construction operations, the scale of the operation was a significant determinant of unit cost and scale economies were present. Significant estimates of $\bar{\beta}_2$, the time trend coefficient, were realized only once out of the 15 analyses, in the case of excavation for canals. Table 3-2 also lists the calculation of the two relevant parameters of equation (3.5'), namely r and ρ, for each of the 15 construction operations. It is seen that r is in the range 1.09 to 1.14 (based on 10 significant estimates). The lone significant estimate of ρ is .00123, indicating a reduction in unit cost per year slightly in excess of 0.1% for canal excavation.

One reason for the lack of significant time effects might be multicollinearity between the primary scale variable and the time variable, resulting from larger projects predominating in the latter period of the sample. Examination of the relevant correlation coefficients indicated no correlations over 0.5.

In an attempt to investigate further the influence of the time variable, the data sets were partitioned on the basis of sub-periods of time and sub-ranges of the scale variable. The expectation was that over specific sub-periods of time, in particular, the post-World War II years, downward trends of unit costs might be significant. Table 3-3 presents the partitioned set of regression results for the data set on excavation of common material from foundations[1]. The data set was partitioned into three scale ranges and four time ranges as shown and was analyzed using the <u>linear model</u> (equation 3.6).

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[1] This procedure was repeated for the remaining 14 operations under analysis. Space limitation precludes the inclusion of those results.

TABLE 3-3

REGRESSION RESULTS FOR PARTITIONS OF THE DATA SET - FOR OPERATION: EXCAVATION,COMMON,FROM FOUNDATIONS

SCALE RANGES →	Less Than 20,000 yd^3				20,000 to 60,000 yd^3				More Than 60,000 yd^3				All Scales			
TIME PERIODS ↓	Coefficient of S_1	Coefficient of t	N	R^2	Coefficient of S_1	Coefficient of t	N	R^2	Coefficient of S_1	Coefficient of t	N	R^2	Coefficient of S_1	Coefficient of t	N	R^2
1930 to 1940	-0.340 (1.28)	0.00008 (1.01)	17	.391	-0.260 (1.47)	-0.00015 (1.37)	22	.423	-0.167 (1.33)	0.00009 (1.08)	17	.470	-0.315 (1.52)	-0.00010 (1.41)	55	.504
1941 to 1946	-0.367 (1.79)	-0.00021 (1.37)	8	.406	-0.250 (1.53)	0.00023 (1.28)	14	.472	-0.198 (1.61)	-0.00017 (1.27)	12	.503	-0.331 (1.62)	-0.00031 (1.40)	34	.472
1947 to 1956	-0.351 (1.71)	-0.00031 (1.63)	11	.658	-0.221 (1.88)*	-0.00047 (1.83)*	14	.591	-0.174 (1.83)*	-0.00029 (1.70)	20	.640	-0.308 (1.95)*	-0.00052 (1.78)*	45	.692
1957 to 1970	-0.348 (1.70)*	-0.00015 (1.41)	30	.535	-0.232 (1.60)	-0.00022 (1.26)	23	.584	-0.161 (1.85)*	-0.00017 (1.48)	18	.505	-0.349 (1.78)*	-0.00011 (1.56)	71	.523
All Years	-0.337 (1.64)	-0.00014 (1.29)	65	.491	-0.251 (1.54)	-0.00032 (1.32)	73	.572	-0.122 (1.67)*	0.00087 (1.41)	67	.601	-0.327 (1.71)*	-0.00032 (1.31)	205	.625

Notes: Coefficients were estimated using Equation 3.6. Values of t-statistics are enclosed in parentheses and significance at the 10 percent level is indicated by (*). The dependent variable is unit cost in dollars; S_1 is the primary scale variable ($10^6 yd^3$) and t is time in years since 1930.

These results indicate that, at least for the post-war period of 1947 to 1956, there was some time related downward trend in unit cost. The coefficient for the time variable is -.00052 which would indicate about a one-half cent decline in the unit cost of excavation of a cubic yard of common material from foundations over the eight year post-war period. Furthermore, it is observed that within this time period, the observations which fall in the 20,000 to 60,000 yd^3 interval yield a significant estimate of a downward trend in unit cost. This trend is slightly less than a decrease of one-half cent per cubic yard in the indicated scale range. In seven of the data set partitions, the scale variable is significant at the 10 percent level. In the post-war period 1947 to 1956, the scale variables were significant in the higher scale ranges; that is, above quantities of 20,000 yd^3. In fact, the scale variable is significant most often when the quantities of materials involved in the operations are high. This partitioning experiment suggests that (1) there was a more significant declining cost trend in the 1947-1956 period than in any other period and (2) scale economies are more pronounced for larger project sizes.

Reflecting on the nature of results outlined above, the principal question involves the indeterminancy of the cost-reducing effect of technological advance. One possible factor in the statistical results relates to the definitions of the various construction operation. Clearly, not all specification items can be considered clearly distinct: what is excavation of common material to some may be excavation of rock to others with corresponding difference in unit cost bids. In addition, some differences in terminology between time periods were noted which may have indicated a change in operations. For example, the operation described as "excavation of earth" was assumed to be the same as the more contemporary "excavation of common material."

Secondly, the heuristic method used to infer the ex post unit cost of an operation on a particular project from the bid data may have masked differences over time in some way not now understood. A third area of concern involves the index series used to convert the current dollar unit cost figures to a constant dollar basis. It is felt that the ENR index may possibly introduce factors directly related to time such as changing skill and productivity levels, and occupational differentials which may deflate away much of the evidence of technological advance. Recall that only the Common Labor Component of the ENR index was employed in converting all nominal unit cost estimates to a constant dollar basis. Another alternative was using a composite index such as the ENR Cost of Construction Index, which is designed to accomplish a deflation of nominal costs with the prices of labor and materials. This alternative was rejected on the grounds that most of the operations analyzed in this chapter did not involve purchased materials.

The use of a labor cost index for the deflation of the estimated nominal unit costs, however, still presents some problems in correct interpretation of the results in this chapter. The manifestation of technological advance reflected in the trends of real unit costs of construction operations centers largely (but not exclusively) in the machinery component of cost. The more complex, more versatile machines, however, must be complimented with a more highly skilled labor force. Skilled workers coupled with efficient machines will, in general, draw increasingly higher wages than their unskilled counterparts. The Common Labor Component of the ENR series, when used to deflate the estimates of nominal unit costs, would then result in a series of "real" unit costs which declines at a lower rate than a series deflated with a skilled labor index. The import of this discussion is to suggest that because most of the operations employ a mix of skilled and unskilled labor, deflation with the "common labor" is probably directionally correct, even if it did contribute to the relatively poor results described above. Along these lines, one must also consider the national economic trend of increasing productivity and concomitant wage rate increases to note whether construction wages were above or below that trend. It did not appear that this was the case, however.

Another reason for failing to find evidence of significant technological advance is that its impact may have taken non-quantifiable forms. An example would be the improvement of quality of the finished product. In terms of the excavation operations, this could mean a minimum overhaul. More importantly, the results could have been a shortening of the construction period.

Chapter 4

Findings of the Minor Studies: Other Approaches to Technological Advance in the Planning of Public Projects.

The Case of Geologic Reconnaissance

This section concerns the effectiveness of data collection and analysis activities which are utilized to reduce inherent uncertainties likely to occur in the planning and design of civil works projects. In the water resources field, for example, important areas in which uncertainties arise are hydrology, meteorology, and geology, as well as engineering design and social and economic impacts. We address the effectiveness of geologic reconnaissance activities in reducing cost overruns in project construction and avoiding future rehabilitation costs.[1] The analysis utilizes data from U. S. Bureau of Reclamation (USBR) projects which pertain to geologic reconnaissance and the cost overruns experienced in project construction. Roughly speaking, the objective is to estimate the cost-benefit relationship in geologic data collection and analysis, an area of technology which has benefited greatly from technological advance.

Data collection is recognized to be an important part of water resources planning.[2] But what constitutes an optimum quantity of data? This point is identified by the equality of marginal cost and marginal benefit.

Geologic reconnaissance programs are data collection activities in which sustained periods of observation are usually not necessary. Work is conducted over a relatively short period of time in an effort to determine if the geologic condition of a site will create perils for the facility, the environment, or human populace. Increased costs of construction plus the increased liklihood of repair and rehabilitation costs later on are the usual consequences of an inadequate geologic reconnaissance program.

For large dam/reservoir projects, four general groups of investigative techniques are usually applied.[3] Table 4-1 is an outline of these groups giving

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[1] In their study of the extent, nature, and causes of error in estimating costs of water resource projects, Hufschmidt and Gerin suggest undertaking a systematic review of the costs of geologic information and the relationship of this information to cost overruns which were due to geologic factors. Cf. M. M. Hufschmidt, and J. Gerin, 1970, "Systematic Errors in Cost Estimates for Public Investment Projects," in Margolis, Julius, The Analysis of Public Output: New York, National Bureau of Standards, pp 268-315.

[2] Maass, Arthur, and others, Design of a Water Resource System. Cambridge, Mass., Harvard University Press, 1962, p. 10.

[3] Reference sources in engineering geology seldom classify programs in this manner. However, cf. Wahlstrom, E. E., 1974, Dams, Dam Foundations, and Reservoir Sites: Amsterdam, Elsevier Scientific, 278 p.

TABLE 4-1

GEOLOGIC RECONNAISSANCE TECHNIQUES BY MAJOR GROUP AND SUMMARY CHARACTERISTICS

	Importance of technique at the various stages of a dam project (1=low:4=high)				Qualitative Cost Range			Likely impact of technological advances involving this technique		
	Preliminary	Feasibility	Final design	Post award	Low	Med	High	More data	New data	Better analysis
A. Onsite Evaluation	4	2	2	2			X			X
B. Direct Inspection/Subsurface										
1. exploratory drilling	2	4	2	2		X	X	X		
2. coring of samples	1	4	2	2		X	X	X		
3. downhole inspection	1	4	3	3	X	X			X	X
4. power auger surveys	3	3	1	1	X			X		
5. trenches/test pits	1	3	1	1	X	X				
6. exploratory tunneling	1	2	1	1			X			
C. Geophysical Techniques										
1. permeablity tests	3	3	1	1	X					X
2. other hydrogeology tests	2	3	2	2	X	X			X	X
3. geophysical logging	1	3	2	1			X		X	X
4. seismic refraction	1	3	1	1	X					X
5 electrical methods	1	2	1	1	X					X
6. gravity methods	1	2	1	1		X				X
D. Materials Science										
1. laboratory rock mechanics	1	4	3	3		X				X
2. on site rock mechanics	1	2	2	2			X	X	X	
3. soil mechanics	1	3	2	4	X					X

some characteristics of important techniques including importance by rank, qualitative cost range, and the status of technological advances as regards each technique.[1] Technological advance is hypothesized to make the geologic reconnaissance program more accurate, but not necessarily lower cost. Some advances enable more data to be collected, but this is not an adequate measure of the "output" of the program.

In this investigation it was assumed that the result of a geological reconnaissance program was measured in terms of cost overrun reduction, i.e. cost overruns due to geologically-related cuases. The costs of geologic reconnaissance programs for U. S. Bureau of Reclamation (USBR) dam projects were then related to cost overruns.

Nearly 2350 dams of varying design and size were constructed by the USBR through 1973. Of these, 150 dam/reservoir projects were selected for analysis. Minimum data requirements imposed on each project resulted in a sample size of 72 programs as shown in Table 4-2. The primary data documents were "final" reports prepared for a dam project such as the final geology report or final completion report; secondary documents included "technical appendices" to final reports and "preliminary" reports. In general, about 5 or 6 documents of this kind were consulted for each project.[2]

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[1] The "stages" of a dam project referred to in Table 4-1 pertain to U. S. Bureau of Reclamation nomenclature. It is important to note that at the "post-award" stage, geologic reconnaissance activities may be prescribed to evaluate conditions and possibly alter design as large scale excavation proceeds. Post-award reconnaissance may also be dictated due to the discovery of unforeseen conditions.

[2] The documents were accessioned from USBR archives maintained at the Federal Archives Center at the United States Federal Center, Denver, Colorado.

TABLE 4-2

SAMPLE OF DAM/RESERVOIR PROJECTS USED

IN GEOLOGIC RECONNAISSANCE ANALYSIS

	a/	b/						
1. Pineview	UT	3-35	25. Carter Lake	CO	6-50	49. Emigrant	OR	8-58
2. Ryepatch	NV	11-35	26. Big Sandy	UT	6-50	50. Paonia	CO	1-59
3. Seminoe	WY	1-36	27. Keyhole	WY	7-50	51. Steinaker	UT	5-59
4. Caballo	NW	6-36	28. Trenton	NB	8-50	52. Prosser Creek	CA	4-60
5. Bartlett	AZ	8-36	29. Cachuma	CA	8-50	53. Twin Buttes	TX	4-60
6. Boca	CA	10-36	30. Willow Creek	CO	5-51	54. Whiskeytown	CA	8-60
7. Deer Creek	VT	2-38	31. Glen Anne	CA	8-51	55. Crawford	CO	10-60
8. Shasta	CA	8-38	32. Rattlesnake	CO	8-51	56. Lewiston	CA	1-61
9. Green Mountain	CO	10-38	33. Jamestown	ND	3-52	57. Merritt	NB	2-61
10. Friant	CA	7-39	34. Palisades	ID	5-52	58. Yellowtail	MT	5-61
11. Davis	AZ	1-43	35. Pactola	SD	11-52	59. Fontenelle	WY	6-61
12. Kortes	WY	5-46	36. Kirwin	KA	1-53	60. Spring Creek	CA	7-61
13. Horsetooth	CO	5-46	37. Sly Park	CA	5-53	61. Lemon	CO	7-61
14. Dry Falls	WA	7-46	38. Monticello	CA	8-53	62. Clark Canyon	MT	10-61
15. Granby	CO	8-46	39. Wanship	UT	7-54	63. Agate	OR	2-62
16. Angostura	SD	9-46	40. Glendo	WY	12-54	64. Sanford	TX	3-62
17. Olympus	CO	10-46	41. Haystack	OR	5-56	65. Blue Mesa	CO	4-62
18. O'Sullivan	WA	2-47	42. Casitas	CA	8-56	66. Bullycreek	OR	4-62
19. Anderson Ranch	ID	1-48	43. Trinity	CA	3-57	67. Causey	UT	7-62
20. Hungry Horse	MT	6-48	44. Anchor	WY	4-57	68. San Luis	CA	12-62
21. Cedar Bluff	KA	4-49	45. Glen Canyon	AZ	6-57	69. Morrow Point	CO	6-63
22. North Coulee	WA	4-49	46. Keene Creek	OR	11-57	70. Joe's Valley	UT	6-63
23. Platoro	CO	5-49	47. Flaming Gorge	WY	7-58	71. Lost Creek	UT	7-63
24. Canyon Ferry	MT	5-49	48. Navaho	NM	7-58	72. Senator Wash	CA	2-64

a/ State abbreviation b/ start of construction date

Table 4-3 lists the elements of the overall data set on reconnaissance activities and estimated costs. Estimation of total reconnaissance cost was troublesome. In some cases, the estimate was included in a project document; at worst, the estimate was derived by attributing costs to the individual reconnaissance activities.

Table 4-4 is a listing of the overrun cost categories on which data were collected when there was a reasonable certainty that the overrun was associated with an underlying geologic cause. The items are basically of two types: cost overruns arising from extra quantities excavated or hauled within the allowance of the original contract <u>and</u> cost overruns which necessitated an amendment to the original contract.

The general form of the models hypothesized to be application to information acquisition problems is

$$\mathrm{OVR} = f[\mathrm{RCN},\ T,\ \mathrm{SZE}]$$

where OVR is overrun cost attributable to unforeseen geologic conditions, RCN is geologic reconnaissance expenditures, T is time where 1930 = 0, and SZE is the winning bid for the total cost of the prime contract for the dam. For the purposes of this model OVR and RCN were defined as percentages of the winning bid cost of the prime contract. The estimate of this model was

$$\mathrm{OVR} = 0.0987 - \underset{(2.36)}{0.734\mathrm{RCN}} - \underset{(4.24)}{0.000238T} - \underset{(0.71)}{(1.85 \times 10^{-10})\mathrm{SZE}} \tag{4.1}$$

$$R^2 = .411 \qquad \mathrm{S.E.} = .0449$$

The values in parentheses are t-statistics. In this case, the estimates of the coefficients of RCN and T are significant at the 5 percent level.

A better form for this relation proved to be a log-linear relation. OVR was again expressed as a percentage of the winning bid cost of the prime

TABLE 4-3

The Data Set on Reconnaissance Activities

1. U. S. Bureau of Reclamation Prime Contract Number
2. Name of Dam
3. USBR Project Name
4. Type of Dam
5. Height (m)
6. Crest Length (m)
7. Volume Content of Structure (m^3)
8. Capacity of Reservoir (m^3)
9. Area of Reservoir (m^2)
10. Type of Spillway
11. Capacity of Spillway (m^3/s)
12. River
13. State
14. County
15. Prime Contract Bid Opening Date
16. Start of Construction Date
17. Completion of Construction Date
18. Winning Bid
19. Actual Cost for Completion of Prime Contract
20. Number of Man-hours Required for Completion
21. Pre-Award and Post-Award Exploratory Drilling Programs
    (a) Number of Drillholes
    (b) Total Depth of Drilling (ft)
    (c) Deepest Drillhole (ft)
    (d) Diameter of Drillholes (code)
    (e) Total Amount of Coring (ft)
    (f) Cost of Drilling Alone
    (g) Cost of Coring Alone
    (h) Cost of Field Evaluation of Drilling
    (i) Total Cost of Drilling Program

TABLE 4-3 (continued)

22. Pre-Award and Post-Award Test Pit, Trenching, and Auger Hole Programs
    (a) Number of test pits and trenching
    (b) Approximate total of excavation (yd^3)
    (c) Cost of test pits and trenching
    (d) Number of auger hole sites
    (e) Cost of auger hole drilling
    (f) Total cost of test pit, trenching, and auger hole programs including field evaluation
23. Pre-Award and Post-Award Tunneling Program
    (a) Combined number of distinct shafts and tunnels
    (b) Approximate total of excavation (yd^3)
    (c) Cost of program including field evaluation
24. Geologic Field Evaluation Cost Estimate
25. Types and Costs of All Other Field Methods
    (a) Type of Method (code)
    (b) Quantitative Description (number, ft, etc.)
    (c) Cost Estimate for Method
    (d) Estimate of Total Cost
26. Types and Costs of Laboratory Testing Methods
    (a) Type of Method (code)
    (b) Cost Estimate for Method
    (c) Estimate of Total Cost
27. Total of All Exploration Categories
28. Reported Costs of All Preliminary Surveys by Category

TABLE 4-4

The Data Set on Cost Overruns

1. Cost of Overruns on Specific Specification Items Attributable to Geologic Causes
    (a) Type of Specification Item (code)
    (b) Overrun
2. Cost of Extra-Work Orders Attributable to Geologic Causes
3. Cost of Orders for Changes Attributable to Geologic Causes
4. Difference between Estimated Duration of Construction and Actual Duration

contract while RCN was expressed as the actual value of reconnaissance expenditures. This model was estimated with the results

$$\text{OVR} = 0.664 - \underset{(3.99)}{0.0782 \log_{10}\text{RCN}} - \underset{(2.48)}{0.00148\text{T}} - \underset{(2.23)}{0.0209 \log_{10}\text{SZE}} \tag{4.2}$$

$$R^2 = .604 \qquad \text{S.E.} = 0.0444$$

In this case all three independent variables were significant at the 5 percent level. This regression provides some insights into the effectiveness of geologic reconnaissance activities in dam project construction. The relation can be better understood by examining the use of the estimated equations to predict the payoff from spending funds on reconnaissance.

The optimal tradeoff between <u>information purchases</u> and <u>cost overrun</u> can be explored with the estimated equation (4.2) as given above. Using the hypothetical example of a \$10 million prime contract for a dam in 1975, the resultant relationship (substituting into (4.2)) is

$$\text{OVR} = .4437 - 0.0782 \log_{10} \text{RCN}. \tag{4.2a}$$

The optimum expenditure on geological reconnaissance can be determined from (4.2a) which these increasing returns no longer obtain. Mathematically, this point in this example is found by formulating the total cost function:

$$\begin{aligned} \text{TC} &= \text{RCN} + (\$10{,}000{,}000)(\text{OVR}) \\ &= \text{RCN} + (\$10{,}000{,}000)[(.04807) - 0.0782 \text{ Log}_{10}\text{RCN}] \\ &= 480700 + \text{RCN} - 782000 \log_{10}\text{RCN} \end{aligned} \tag{4.2b}$$

and minimizing with respect to RCN

$$\frac{d\text{TC}}{d\text{RCN}} = 1 - (782000)\left(\frac{1}{\text{RCN}}\right)(\log_{10}e) = 0$$

$$\text{RCN} = \$339{,}610$$

At this level of reconnaissance, the overrun cost which can be expected is \$111,773 (or in terms of the 95 percent confidence interval, the expected overrun falls in the range from \$0 to \$551,773). At this point, an additional dollar spent on reconnaissance would only result in a one dollar (or less) reduction in expected overrun.

Measuring the Importance of Technological Advance in Water Resource Systems Through Capacity Expansion Modeling.

This chapter takes a more explicit approach to the way in which technological advance should affect the decisions of planners. It entails modeling on a digital computer the optimal capacity expansion of a water resources system with specified rates of technological advance applicable to various components involved in the system. In this procedure, technological advance is manifested in rates of cost reduction among water system components. The discussion begins with a short description of the model and its optimizing algorithm, followed by an example of a hypothetical capacity expansion/technological advance problem. A concluding paragraph points out the likely difficulties involved in treating problems of a real world nature.

An entire genre of literature in the water resources management field has evolved around what has become to be known as the "basic scheduling problem." Water needs (or "requirements") of a region are generally assumed to be monotonically increasing functions of time based on expected growth in numbers of water-users and implementation of water-using technologies. The hypothetical construction program of an array of water supply projects (usually undertaken so that the requirements are at least satisfied at all times) is termed the one-dimensional scheduling problem.[1]

The problem is to determine the least cost schedule of N candidate projects (usually storage reservoirs) whose capacity is sufficient to meet requirements at any time up to and including the last year of some finite horizon, T. In other words, solve for those construction times (t_1, t_2, ..., t_N) so as to

$$\text{minimize} \sum_{i=1}^{N} C_i(1+r)^{-t_i} \qquad t_1 < t_2 < \ldots < t_N \tag{4.3}$$

$$\text{subject to} \sum_{i=1}^{N} Q_i(t) \geq D(t) \qquad \begin{aligned} Q_i(t) &= 0 \text{ if } t < t_i \\ Q_i(t) &= Q_i \text{ otherwise} \end{aligned}$$

where r = annual discount rate

c_i = cost of construction of the i th project

Q_i = water storage capacity of the i th project

$D(t)$ = water "requirement" at time t

In this version of the problem, no shortages of water supply are permitted. Subsequent contributions have formalized the more realistic problem in which emergency supplies or the acceptance of shortages make it possible to forestall large investments in supply facilities.[2]

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[1] The description "one-dimensional" refers to the fact that only one objective, the satisfaction of a minimum water capacity requirement, is implied in the problem. The principle article in the literature is W. S. Butcher, and others, 1969, "Dynamic Programming for the Optimal Sequencing of Water Supply Projects": <u>Water Resources Research</u>, Vol. 5, no. 6, pp. 1196-1202. Although this contribution is not a landmark in scheduling problems or capacity expansion problems, it established a reference problem in water resources management utilized by subsequent authors.

[2] D. T. Lauria, 1972, "Water Supply Planning by Mixed Integer Programming" (A paper presented at 53rd Annual Meeting of the American Geophysical Union): Chapel Hill, North Carolina, mimeo, 19 pp.; also D. T. Lauria, 1973, "Water Supply Planning in Developing Countries": <u>Journal of the American Water Works Association</u>, Vol. 65, no. 9, pp. 583-587.

The capacity expansion model utilized in this study is a more elaborate version of that sketched above. A slight increase in the degree of sophistication entails consideration of different sizes of projects at each candidate site.[1] Secondly, a level of hydrologic detail was introduced by modeling the hydrology of a river basin as a network.[2] Thirdly, and most important in terms of the objectives of this investigation, a means of interjecting rates of (cost-saving) technological advance into capital and operating costs for alternative projects was devised.[3] Lastly, it was thought to be desirable to consider explicitly the length of the construction period of projects in the determination of an optimal schedule. One impact of technological advance was felt to be a shortening of the construction period which could expedite the onset of benefits.

Before outlining the series of experiments conducted, a note is made concerning the solution algorithms which were used. The optimal capacity expansion sub-model is formulated along the lives of an integer programming problem. The alternative dynamic programming approach was felt to present

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[1] For an elaborate treatment of this problem, cf. L. Becker and W. W. G. Yeh, 1974, "Optimal Timing, Sequencing, and Sizing of Multiple Reservoir Surface Water Supply Systems: Water Resources Research, vol. 10, no. 1, pp 57-63.

[2] The sub-model which contains the network flow algorithm draws heavily upon O'Laoghaire, D. T., and Himmelblau, D. M., 1974, Optimal Expansion of a Water Resources System: New York, Academic, 273 p., especially pages 83-104 and 106-117.

[3] Another approach to this problem in the context of a capacity expansion model involves a more sophisticated "learning-by-doing" sub-model. Cf. G. C. Rausser, and C. E. Willis, 1975, "Regional Application of a Multi-Source Learning Model for Water Resource Planning": Davis, California, University of California at Davis, mimeo, 51 p.

significant core storage requirement problems when the number of candidate projects became large. The hydrologic submodel is based on a technique to determine optimal flows through a continuous network. The technique is best classified as an iterative linear programming algorithm using a simplex method.

The experiments begin by assuming that a river basin can be represented ay a network of nodes and arcs as is shown in Figure 4-1. The network's headwaters are located toward the upper left and the outflow is at the lower right. Because the network model requires conservation of mass (or mass balance) for solutions to obtain, it is assumed that at any instant the total outflow is equal to the total inflow. In fact, the model links outflow and inflow with an explicitly defined arc, although it is not shown in Figure 4-1. Note that various structural features can be represented by numbered nodes.

To represent a capacity expansion program, the candidate projects must be added to the existing network with the provision that until construction is completed, there are no flows of water through the facility. This is depicted in Figure 4-2 where candidate water-use projects and candidate water supply projects are the "dotted-in" features in the simplified network.

An experiment is formulated as follows: assume the requirements for firm hydroelectric energy to be monotonically increasing. This may induce a new hydro-electric generating facility to be built at one of the potential sites as shown in Figure 4-2. An alternative, however, entails expansion of an existing facility with concomitant augmentation of in-stream flow by either importing surplus water from another region or by precipitation augmentation programs. Feasibility of either of these two alternatives could hinge on

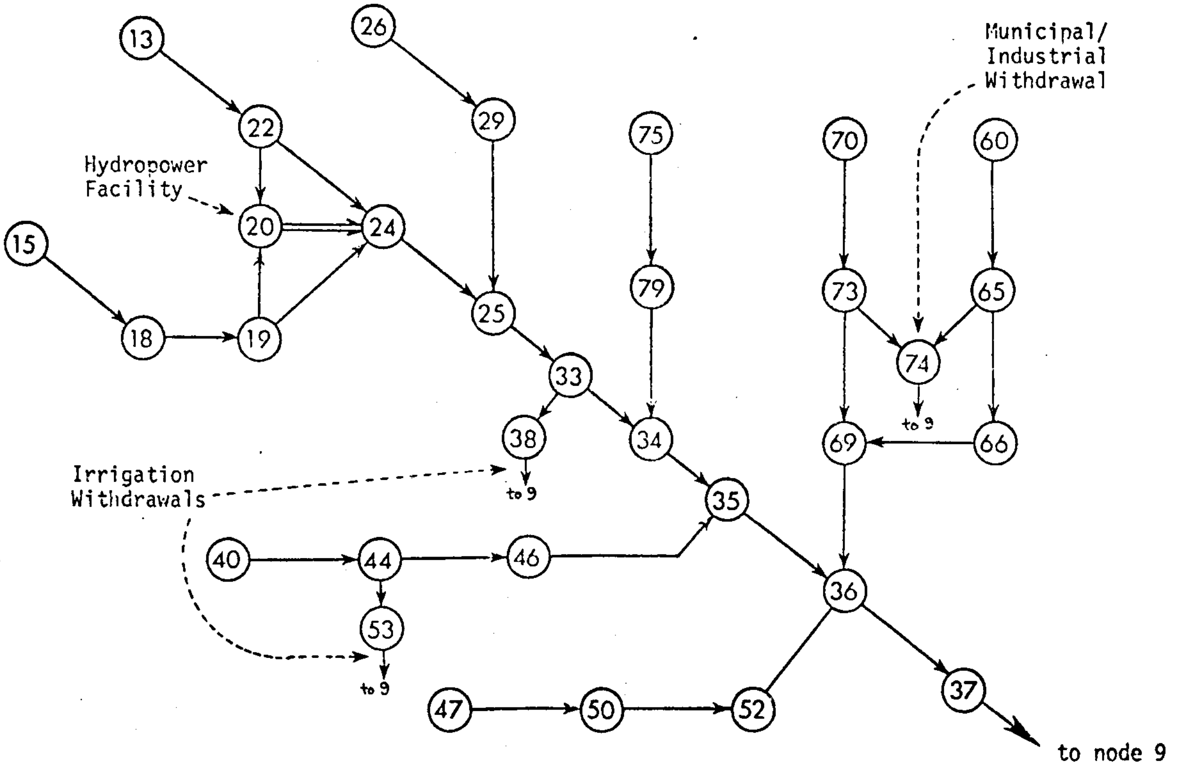

FIGURE 4-1

NETWORK REPRESENTATION OF THE HYPOTHETICAL RIVER BASIN WITH LABELED NODES AND ARCS

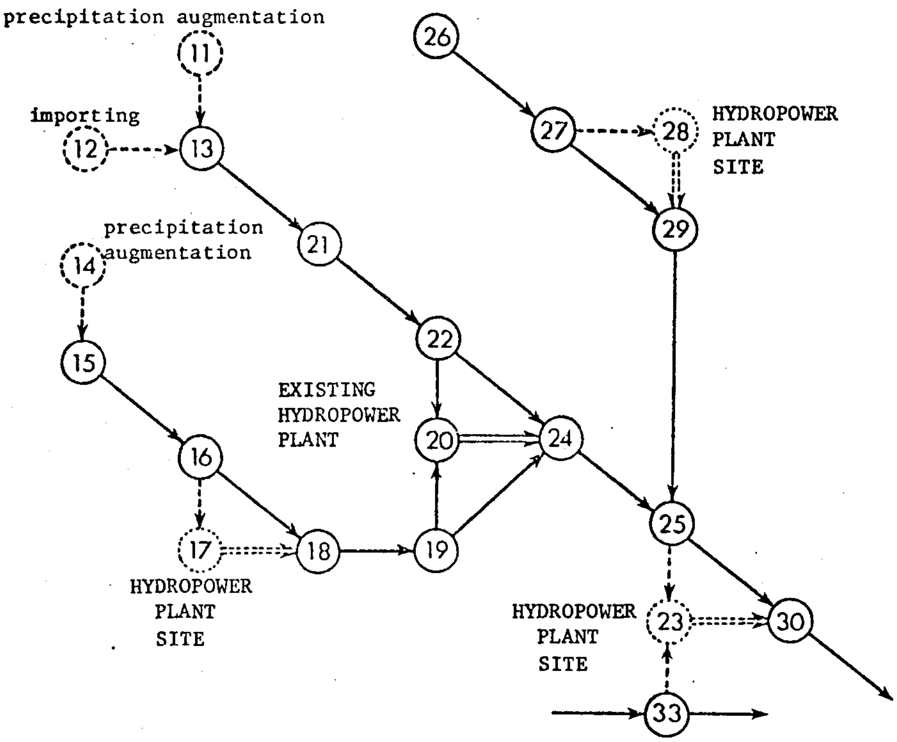

FIGURE 4-2

NETWORK DIAGRAM FOR A SCHEDULING EXPERIMENT - GROWTH IN HYDROELECTRIC ENERGY GENERATION future cost-saving technological advances. In the case of importing, the development of a significantly lower-cost tunneling technology in the future could mean that this alternative would become progressively more attractive. In the case of precipitation augmentation, advances made to reduce the uncertainty of supply and incidence of adverse effects may enhance this alternative.

Alternative capacity expansion plans were evaluated with the model which seeks the least cost expansion schedule and ensures that the solution is hydrologically feasible.

An example set of results from this type of optimization experiment are shown in Table 4-5. In Part II of the table, the alternative projects are assigned various rates of technological advance, stated in terms of fractional cost reduction assumed to hold over the planning horizon. Usually this rate was considered to be constant, but the inclusion of a time-varying rate is permitted. It is observed that as the rate of technological advance is increased, the net returns to the operation of the entire system increase slightly. At higher levels, the optimal schedule of projects becomes altered in significant ways.

The modeling effort and the primary thrust of the analyses concerned the use of the optimization model to analyze the effect of technological advance on cost minimizing capacity expansion-plans of a hypothetical river basin. The three optimization experiments involved the growth of "requirements" for hydroelectric energy, irrigation withdrawals, and municipal/industrial use. It has been demonstrated that relatively low rates of technological advance when explicitly considered can change the optimum sequence of projects quite dramatically. We also feel that the model is usable for actual river basin capacity

TABLE 4-5

RESULTS OF OPTIMIZATION EXPERIMENTS - HYDROELECTRIC GENERATING CAPACITY EXPANSION

I. Schedule of projects when the selection set consists of only reservoir projects:

1st Project	2nd Project	3rd Project	P.V. of Net Returns
(D_1,17,3,5)*	(D_5,23,7,10)	(D_8,28,11,13)	$225,774,811

*means construction of project D_1 at site 17 began in year 3, on line in year 5

II. Schedule of projects when only one technological alternative is considered

A. Inclusion of the Precipitation Augmentation Alternative

Technological Advance Rate *	1st Project	2nd Project	3rd Project	P.V. of Net Returns
0.0060	(D_1,17,3,5)	(D_9,23,7,10)	(PA_1,11&14,12,12)	$227,482,916
0.0070	(D_1,17,3,5)	(D_4,23,7,10)	(PA_1,11&14,12,12)	$228,115,070
0.0080	(D_1,17,3,5)	(D4,23,7,10)	(PA_1,11&14,12,12)	$228,337,849
0.0090	(D_1,17,3,5)	(PA_2,11&14,8,8)	(D_7,28,10,12)	$228,464,124
0.0100	(D_1,17,3,5)	(PA_2,11&14,8,8)	(D_7,28,10,12)	$228,561,705

* fractional cost reduction per year

B. Inclusion of the Large Scale Importing Alternative

Technological Advance Rate	1st Project	2nd Project	3rd Project	P.V. of Net Returns
0.0030	(D_1,17,3,5)	(I_1,12,6,9)	(D_8,28,12,14)	$226,422,608
0.0040	(D_1,17,3,5)	(I_1,12,6,9)	(D_8,28,12,14)	$226,663,704
0.0050	(D_1,17,3,5)	(I_1,12,6,9)	(D_8,28,12,14)	$227,524,821
0.0060	(I_1,12,2,5)	(D_2,17,7,9)	(D_8,28,11,13)	$228,142,720
0.0070	(I_1,12,2,5)	(D_2,17,7,9)	(D_8,28,11,12)	$228,363,294
0.0080	(D_2,17,2,4)	(I_3,12,9,11)	(D_8,28,14,16)	$228,427,691

III. Schedule of projects when the selection set includes both alternatives each having a pre-designated technology advance rate

Technology Advance Rates:

(a) precipitation augmentation	0.01
(b) large scale importing	0.01

Schedule:

1st project	(D_1,17,3,5)
2nd project	(PA_1,11&14,8,8)
3rd project	(D_7,28,11,13)

P.V. of Net Returns $228,725,632

expansion plans in which technologically advancing water supply technologies are considered as alternatives to dam/reservoir projects.

Chapter 5

A Summing Up and Suggestions for Future Research

The first study on the impact of technological advances was an *ex post* examination of the trends in real unit costs of operations involved in the construction of public water resource projects. It was hypothesized that technical advances in machinery and technique would result in lowered real unit costs for standardized operations. The observation of historical unit cost data was complicated by the fact that actual onsite costs are proprietory information to individual construction firms. As a result, a method was adopted for estimating actual constant dollar unit costs from which cost bid data which were tabulated when a construction job was up for bidding. These data, pertaining to excavation, earthmoving, and concrete operations in water supply projects from 1935 to 1970, were obtained from records of the U. S. Bureau of Reclamation. In this way, only public project construction data was included in the analysis. The analysis consisted of a series of regressions designed to estimate the influence on unit costs of scale economies, trends in technology, ruggedness of construction site, accessibility to rail transportation, and weather conditions. Geographic differences in costs due primarily to differences in regional wage rates were already compensated for in the application of cost indexes to the data. Two forms of the regression model, one linear and the other log linear, were tested on three data sets for each of the 15 construction operations.

The results, while exhibiting statistically significant scale economies, failed in almost all cases to indicate any significant time trend in real unit costs. There did exist a sub-period from 1947 to 1956 during which three construction operations exhibited significant downward cost trends in addition to significant economy of scale effects. The three site condition variables were not significant in the analysis.

The implications of the analysis for planning in civil works remain unclear. It appears unlikely that larger-sized projects and larger sized equipment will be used in the future, thus limiting additional scale economies. The findings appear to indicate a narrowing of future possibilities for real construction cost reductions through technological innovation.

The second study concerns the effectiveness of geologic reconnaissance for civil engineering structures. The benefits of such work include providing a safe location and reducing cost overruns in construction due to unforeseen geologic conditions. Technological advances in these reconnaissance techniques have been quite dramatic in a physical sense. Data on geologic reconnaissance activities and geologically-related cost overruns were obtained for 72 U. S. Bureau of Reclamation dam construction projects for the period 1935 to 1964. Interpretation of these data resulted in estimates of reconnaissance expenditures and geologically related cost overruns in constant dollars for each project in the sample. A regression of overrun costs on reconnaissance expenditures, year of project construction as a surrogate for technological change, and project size indicates that overrun costs were significantly and negatively related to all three independent variables in the models. The results were used to demonstrate that for the projects in the sample there are significant estimated returns to increases above present levels in the resources invested in geologic reconnaissance.

The third study dealt with the sensitivity of an optimal water supply capacity expansion plan to various rates of technological advance in different water supply technologies. The model used is flexible enough that different hydrologic configurations can be analyzed; it allows incorporation of technological advances in the form of cost reductions in the candidate projects; and it explicitly considers the construction period involved before a project may begin to yield benefits. The optimization model was used to conduct three experiments on the impact of cost-saving technological advance on optimal project sequencing when dealing with hydroelectric energy generation, irrigation, and municipal/industrial withdrawals. The candidate water supply projects which could be scheduled included precipitation augmentation (cloud seeding), large-scale importing, deep-level groundwater, desalination, and wastewater recycling as well as conventional dam/reservoir projects. The primary conclusion was that, while some of the very low historical rates of real cost change were too small to affect the optimum sequence of projects, in nearly all cases rates well under 1% per annum suffice to change the optimum sequence and to improve the present value of system net benefits.

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