ECONOMIC CAPACITY EXPANSION PLANNING: AN APPLICATION TO THE TELEPHONE INDUSTRY

By

LORENZO FLORES-HERNANDEZ

Ingeniero en Communicaciones y Electronica
Instituto Politecnico Nacional
Mexico, D. F.
1970

Master of Science
New Mexico State University
Las Cruces, New Mexico
1975

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
July, 1982

ECONOMIC CAPACITY EXPANSION PLANNING: AN

APPLICATION TO THE TELEPHONE INDUSTRY

Thesis Approved:

Philip M. Wolfe
Thesis Adviser

Hamer K. Eldin

Joe H. Mize

Scott Sink

Lyle Broemeling

Norman N Durham
Dean of the Graduate College

ACKNOWLEDGMENTS

There are so many people behind this achievement who have contributed their time, talent, and encouragements that, surely, many will remain unnamed. To these persons - my heartfelt thanks.

First I would like to express my sincere appreciation for the guidance, support, and friendship from my major adviser, Dr. Philip M. Wolfe, during the preparation of this thesis and in my residency at OSU. For Dr. Joe H. Mize, I express my honest gratefulness for his understanding, guidance, and assistance both personally and professionally. I consider myself very fortunate to have met such a great person. Also, I deeply appreciate the support and guidance given freely by Dr. Hamed K. Eldin. Likewise, I am grateful to Dr. D. Scott Sink for his priceless help, invaluable advice and support. Thanks are also extended to Dr. Lyle D. Broemeling for his help and assistance.

To the School of Industrial Engineering and Management I would like to let them know that I will be always grateful for giving me the opportunity to pursue the Doctor of Philosophy degree under their excellent teaching and research atmosphere.

To my beloved father and mother, Mr. Teofilo Flores Vazquez and Maura Hernandez de Flores, I have no words to express my gratefulness for their constant encouragement and support.

Especially, I wish to give my deepest gratitude to my wife, Carmen, who has been pushing me since high school, and to our children: Axayacatl, Xochitl, Citla, Erendira, Tizoc, Tepes, and Yaxkin. They have showm me nothing but encouragement, support, and love in exchange for having a husband/father student, with all the uncomfort and sacrifices this means, for such a long period of time. I pray that in the future I will be a husband and father worthy of such a faithful and wonderful family.

I acknowledge the financial support given by the CONACYT, since their loan provided the economic means to go through with this enterprise. Also, I express my gratefulness to Telefonos de Mexico S.A. for its support and the leave permission given to realize these graduate studies.

Thanks are also extended to Mrs. Grayce S. Wynd for her typing of the earlier draft, and to Mrs. Margaret Estes, for her excellent typing of the final version.

Thanks in advance are given to the readers of this work for blaming only the author for remaining errors.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure | Page

LIST OF SYMBOLS

C_a	First installation cost of the facility installed τ years after t=0
C_i	Cost of the i^{th} substitution after the useful life of the facility - installed at t=i-1
C_o	Cost of installation at time t=o
C_{Mj}	Expected operation and maintenance cost for the j^{th} year
C_{Sk}	Salvage net value of the k^{th} facility, installed at $t = (k-1)u$
C_T	Net present cost at t=o, for the case of constant demand
C_{To}	Net present cost at t=o, for the case of linearly increasing demand
n	Number of times the substitution is considered
i	i^{th} Installation (realized at the end of the useful life of the $(i-1)^{th}$ installation).
r	Cost of capital (expressed in decimal form)
R	Inflation rate for the cost of the facility installed
u	Useful life expressed in years
d_o	Initial demand at t=o
d_a	Annual increment of demand
Dt	Total demand at t years from t=o
K	Unit cost of the elements of the facility that is being augmented
β	Increment rate for the value of the material forming the facility
α	Increment rate on the maintenance and operation cost
μ	Percentage (to express operation and maintenance costs as a part of the installation cost)

ε Percentage (to express salvage value as a part of the installation cost)

β_o, β_1 Regression parameters for primary or secondary cables

p number of pairs in a cable

ρ $(1+R)/(1+r)$

γ $(1+\alpha)/(1+r)$

θ $(1+\beta)/(1+r)$

λ $1 + \frac{\rho^u}{1+\rho^u} + \mu \frac{\gamma^u}{1+\gamma^u} - \varepsilon \frac{\theta^u}{1-\theta^u}$

τ Regular intervals of time at which the capacity is increased

δ $\frac{\beta_o}{\beta_1 d_a}$

CHAPTER I

INTRODUCTION

During my twenty years of industrial experience in the communications field, I have become interested in the way in which a telephone network is expanded and the consequences of the present planning policies. These policies vary from country to country due, among other things, to the set of particular factors involved in the expansion process [5]. These factors are complex and large in number; consequently, it is difficult to determine the "optimum" way to expand a telephone plant.

Analytical methods have not been practical when all aspects of a plant expansion were considered simultaneously. As a result, analytical approaches have relied on simplifying the problem, such as treating it as being deterministic rather than stochastic.

There have been several serious attempts, with different approaches, to handle the capacity expansion problem. The common point which almost all of the papers agree upon is that the problem of expansion is complex. As Kalotay [24] points out:

> . . . the problem of determining the optimal expansion policy given the above constraints is a formidable one that we have not succeeded in solving . . . [p. 57).

Or, as Manne [26] says:

> The problem is complicated by (1) the presence of substantial economies of scale in plant construction; (2) the penalties involved in accumulating backlogs of

> unsatisfied demand, and (3) the use of random-walk pattern rather than a deterministic upward trend in demand [p. 632].

Or, as Freidenfelds and McLaughling [19] say about this problem:

> . . . Even after making many simplifying assumptions (e.g., deterministic demand, no "node-costs"), we end up with a problem that appears to be combinatorial in nature. That is, we cannot get the best solution by local searching but must try out many possibilities . . . [p. 567].

The problem of capacity expansion in the telephone network embraces several items, as is shown in Table I. Each one of these parts, even though highly linked with the others, has its own problems and characteristics, proving that the solution for one part may not be suitable for another.

TABLE I

AVERAGE PERCENTAGE INVESTMENTS IN PUBLIC TELEPHONE EQUIPMENT

Item	Average for 16 Countries
Subscriber's plant	13%
Outside plant for local networks	27%
Exchanges	27%
Long-distance trunks	23%
Buildings and land	10%

Source: International Telegraph and Telephone Consulting Committee [5].

According to my experience in this field, specification of the primary and secondary cables network is the most complex part of determining the "optimal" policy for expansion. Improving the present methods, can result in substantial savings and significantly improve the financial status of the firm. With this in mind and desiring to contribute to the solution of this problem, the research described in the following pages was conducted.

Terminology Used in the Telephone Expansion Process

Brief Description of a Typical Telephone Network

General. Although there are different types of systems for telephone networks around the world, we can for the purpose of this paper say that a telephone network can be defined as a system of interconnected elements with a means of interchanging information among them. In a broad sense, those elements can be classified as either stations or traffic-switching exchanges. Stations on a traffic network intended for voice communications are, of course, telephone instruments. Stations on other types of traffic networks may be other devices such as computer terminals, teletypewriters, or picture-phone sets. Consequently, a traffic network carries a variety of types of traffic (voice, data, picture, etc.) between a number of stations that can be connected on demand.

Types of Switching Systems. The first basic job of a switching system is to interconnect calls economically. This includes connections not only between customers' lines, but also between line and trunk or between trunk and trunk. Relating to traffic networks, there are three types of offices: local, tandem, and toll. The local or end office switches a number of customer lines, connecting them to other lines or to trunks. Tandem and toll offices switch trunks, which are usually much busier than lines.

Hierarchy of Switching Offices. The elementary hierarchical structure for switching offices is formed by an office that provides switching service to customer stations, whereas two offices being served by a third switching office constitutes a hierarchical structure of two offices on the lower level and one on the higher level, as shown in Figure 1.

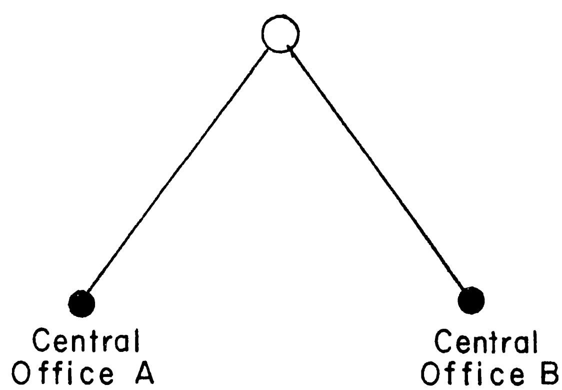


Figure 1. A Two-Level Hierarchy

If several of these two-level hierarchical structures are served by a third one, then there is introduced a third level. By continuing in this fashion, it is possible to construct the public telephone network which has several levels in its hierarchy of switching offices. This is shown in Figure 2.

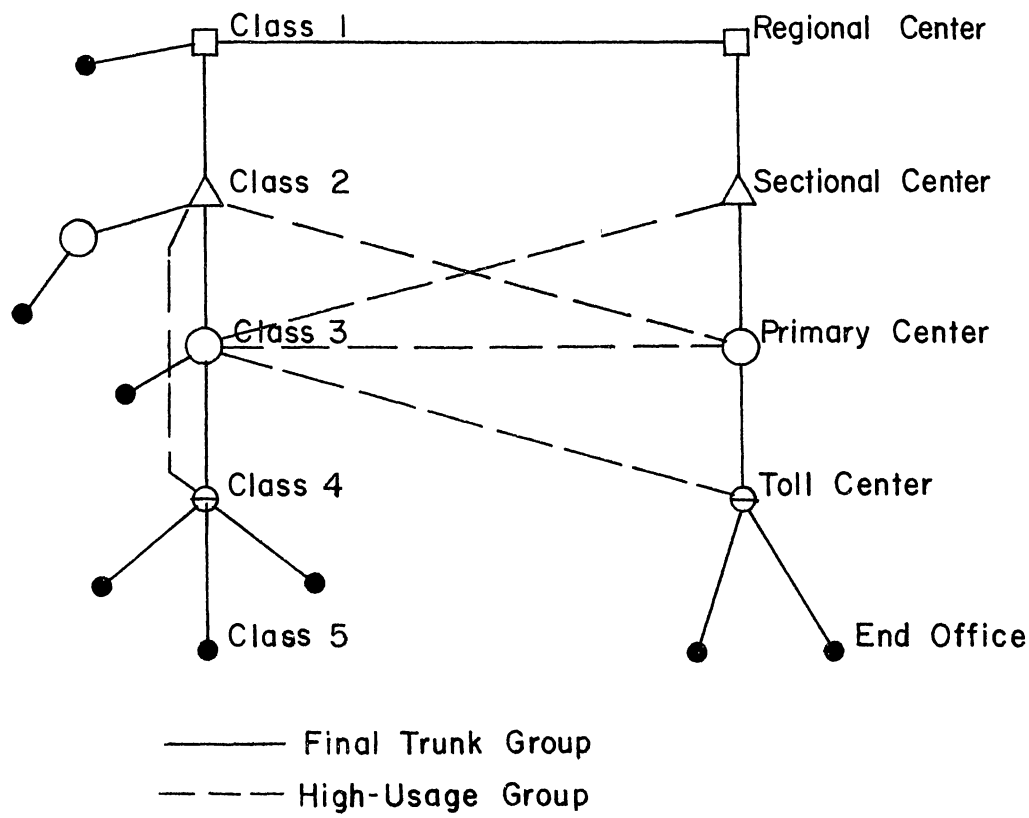


Figure 2. Nominal Toll Network Pattern

Structure of the Facilities Network. Elements of the facilities network--that is, station equipment, transmission facilities, and switching facilities--make possible the traffic network. The structure of the facilities network is quite complex, and can best be discussed in terms of three separate levels:

1) long-haul facilities,

2) exchange-area facilities, and

3) local facilities.

A long-haul facilities network consists of long-haul transmission systems and toll switching systems. The long-haul transmission system includes various coaxial cables and microwave radio systems.

The exchange area level of the facilities network is intermediate between the local facilities network and the long-haul facilities network structure. It can be thought of as a network consisting of local and tendem switching systems and the transmission systems of the types ordinarily used to provide relatively short trunks, that tie them together.

Local facilities are the local switching systems, also known as interior plants, through which customers are connected to the central office. (A pair of copper wires is needed from each telephone to the switching equipment in the central office.)

An exterior plant is partitioned into two categories: distribution or secondary, and feeder or primary, or principal. Distribution is the portion of the network nearest to the customer. Each distribution cable goes from a small cabinet, called a terminal or spreading point, which serves a small well defined geographical area. The collection of a set of those spreading point areas form an area which is known as a district or serving area.

A telephone exchange area is constituted by an amount of about 100 districts, which are identified within the exchange area by a number assigned in a progressive manner. Secondary cables are of small capacity (number of copper wire pairs forming the cable) at the ends of the network, and are spliced into larger cables that lead to a distribution cabinet, called cabinet district or serving area interface, from which depart the principal cables to the central office. Principal cables have a capacity of 100 to 2700 pairs and run from the telephone exchange in a tree-like manner into the district areas associated with the exchange. A local facilities network structure is shown in Figure 3.

Portrait of the Telephone Expansion Process

Some of the most common terms are:

DEMAND: This term covers the following concepts:

- Existent subscribers (also known as satisfied demand): Subscribers with telephone service already installed.
- Subscribers on waiting list (also known as unsatisfied demand): Subscribers who have already made an application for the service, but because of the present unavailability of the telephone plant they are placed on a waiting list.
- Potential subscribers: Subscribers who are expected (in the short or long term) to need and contract the telephone service.

PLAN: This concept specifies the year for which well defined courses of actions are planned in order to achieve a pre-established increment of new subscribers during the specific year. This increment of new subscribers is also named "gain" of the year. It would be helpful, for description purposes, to take an example of another more familiar industry, like the automobile industry, to describe this concept. In this context, a "PLAN" for the telephone industry is analogus to the year's model for a car.

PROGRAM: Refers to the actions and expenditures realized during a span of time to install the new plant for a specific

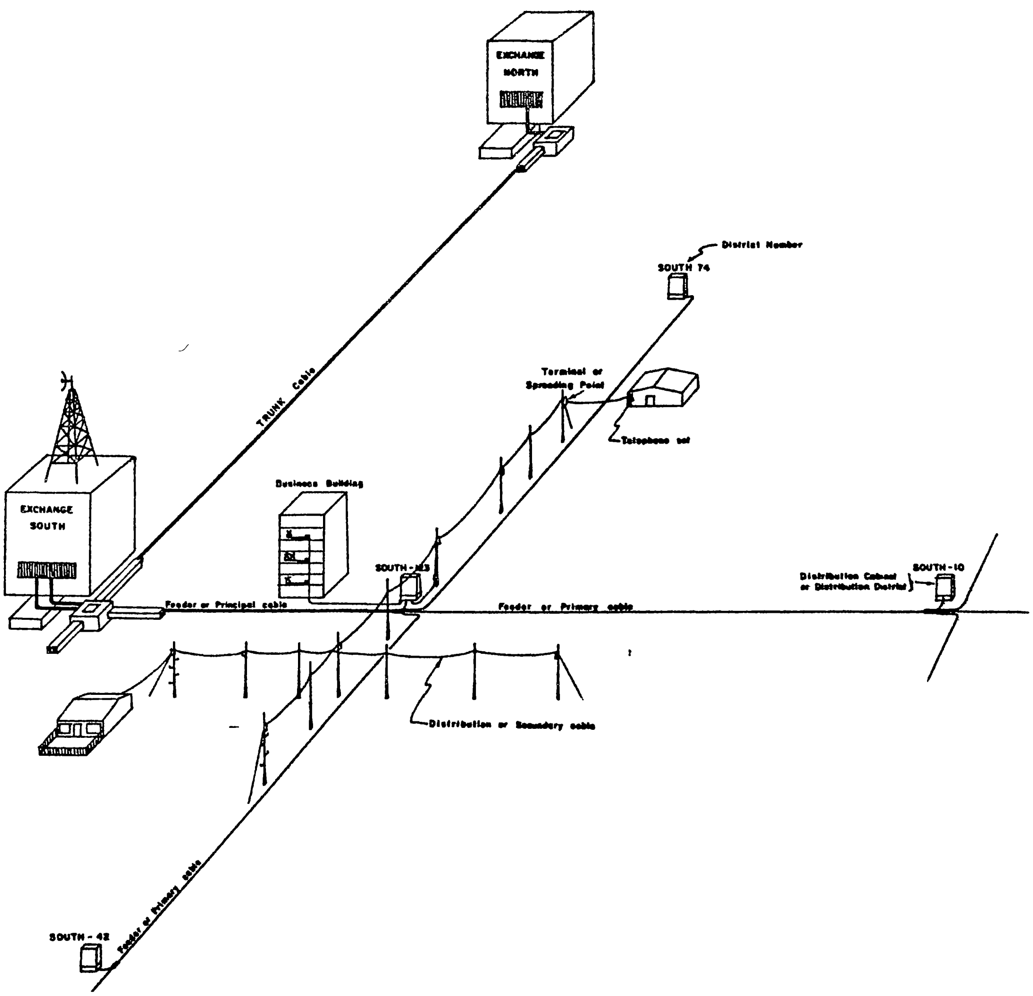


Figure 3. A Local Facilities Network Structure

"plan." For example, the plant augmentation for the plan N+5 is constructed from September, year N+2, to November, year N+4.

PROJECT: Term related to the actions that yield a set of blue prints, diagrams, estimated costs, etc., needed for constructing a new part of the telephone plant.

BUDGET: Word connected with the cashflow during a year--that is, with inflows and outflows from January 1 through December 31. Naturally, this cashflow includes inflows and outflows corresponding to different plans/programs.

Different parts of the plant take different spans of time for installation; that is, from the day they are included in a plan to the day they are available to connect new subscribers. This time varies from country to country, depending on delivery times, weather, etc. For Mexico, the times needed for constructing a new part of the telephone plant are displayed in Figure 4.

The expansion cycle (Figure 4) starts in year N, in which data for the estimation of the demand (short- or long-term) is obtained. In year N+1, this data is analyzed and used to generate preliminary projects. These preliminary projects are evaluated economically by using the techniques provided by engineering economy, and a set of approved preliminary projects is included in the plan of expansion for year N+4. After this selection is made, two sets of activities begin--one for the switching equipment and the other for the exterior part of the plant. The end of these two sets of activities is in the last part of year N+4. The construction of the new plant is planned in such a way that some parts are finished at the end of year N+3, which allows the connection

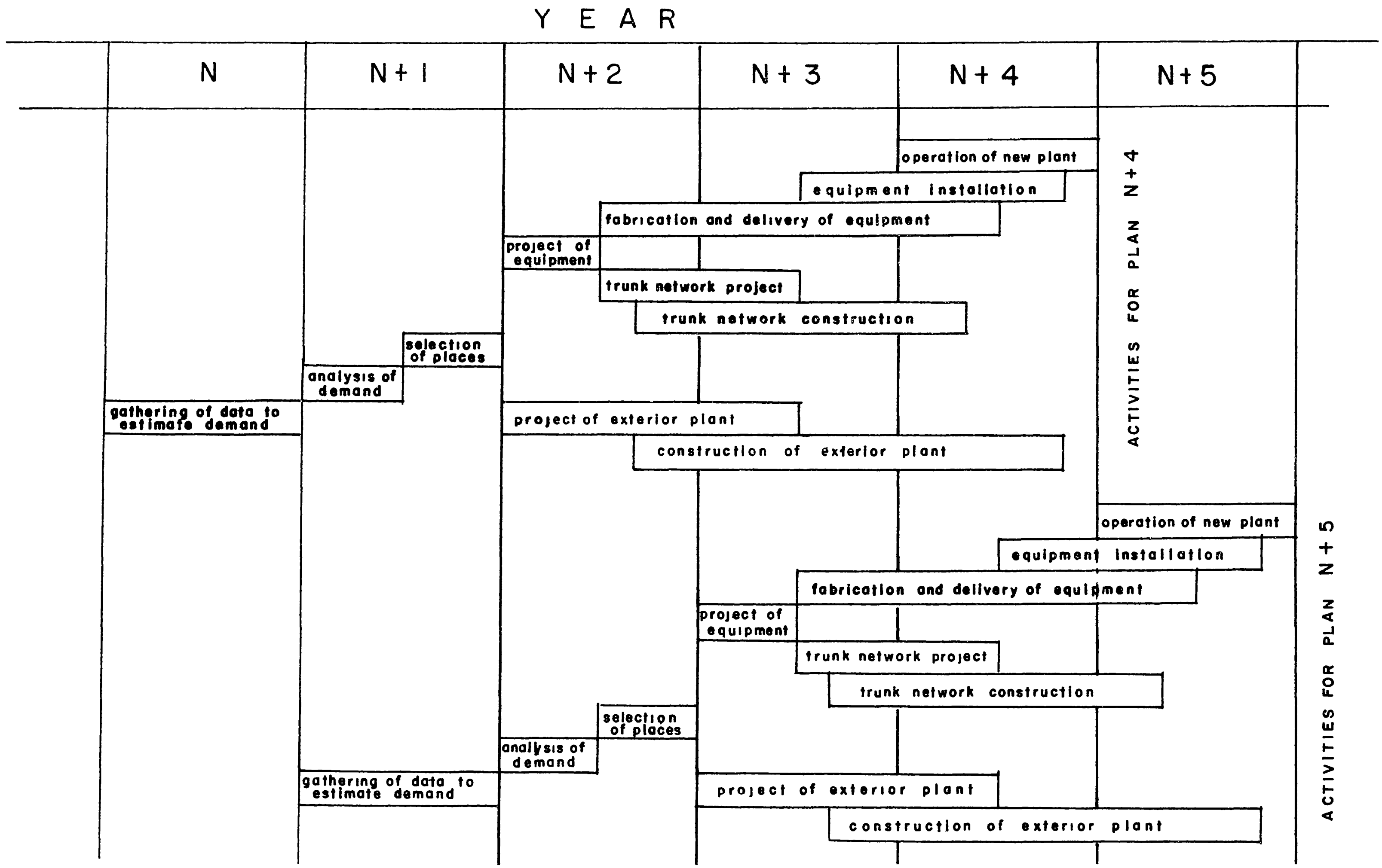


Figure 4. Activities For the Definition, Project, and Construction of a New Part of the Telephone Plant

of new subscribers at the beginning of year N+4 (Figure 4).

Figure 4 is a very concentrated chart and represents all of the villages, towns, cities, etc., included in a plan. This process is started again in N+1 and ended in N+5 (plan N+5), etc.

Problem Definition

Quantification of the Exterior Plant Investment Among the Total Investment

For most countries, the investment in different parts of the telephone plant follow the distribution shown in Table I. These percentages can vary from country to country, depending upon factors such as labor costs, importation or fabrication at home of some or all parts of the equipment/cables, parts assembled in the country, or totally manufactured at home, etc. Tables II and III present figures related to Mexico, from where data was gathered to test and validate the resulting model(s). From Tables II and III it can be observed that the exterior plant investment represents a significant part of the total investment and, consequently, savings made in this area will produce relevant economies in the whole.

Damage to Firm's Economy Due to the Present Way of Expanding the Telephone Plant

As can be seen in Figure 4, the expansion process depends almost entirely on the estimated demand at the beginning of the expansion cycle. This demand is assumed to be deterministic, for simplification purposes. However, the reality is quite different. When the new plant is finally installed at year N+4, the capacity of the installed plant

TABLE II

DISTRIBUTION OF INVESTMENTS OF THE MEXICAN TELEPHONE PLANT

	For Years Ending December 31 - Thousands of Pesos						
	1972	1973	1974	1975	1976	1977	1978
Automatic and Manual Central Offices	1.159,753	1.103,378	1.743,122	1.890,307	2.260,622	2.863,296	3.533,856
Telephones and Private Branch Exchanges	172,567	169,771	237,107	204,974	245,574	372,011	416,404
Outside Installations for Local Service	428,541	481,303	589,972	956,247	1.252,772	1.674,792	1.897,469
Installations of Lines and Equipment for Long Distance Service	340,144	384,517	383,866	461,482	651,708	1.058,399	1.202,154
Buildings and Land	148,308	155,156	122,034	316,178	315,189	253,690	251,437
Other Equipment	24,348	29,128	33,619	48,868	91,682	102,701	156,202
TOTAL	2.273,661	2.323,253	3.109,720	3.878,056	4.817,547	6.324,889	7.457,522

Source: Telefonos de Mexico [43].

TABLE III

INVESTMENT PLANNED BY MEXICO FOR THE EXPANSION OF THE PUBLIC TELEPHONE NETWORK

Period	Total Investment		Interior Plant		Exterior Plant		Toll & Other Eqpmt.	
From - To	For the Period	Average Per Year	For the Period	Average Per Year	For the Period	Average Per Year	For the Period	Average Per Year
1981-1985	64.9	12.98	20.9	4.18	17.8	3.56	26.2	5.24
%	(100.00)		(32.20)		(27.43)		(40.37)	
1986-1990	140.3	28.06	46.2	9.24	38.6	7.72	55.5	11.1
%	(100.00)		(32.93)		(27.51)		(39.56)	
1991-1995	282.1	56.42	88.7	17.74	77.9	15.58	115.5	23.1
%	(100.00)		(31.44)		(27.61)		(40.94)	
1996-2000	572.1	114.42	175.7	35.14	157.2	31.44	239.2	47.84
%	(100.00)		(30.71)		(27.48)		(41.81)	
1981-2000	1.059.5	52.97	331.5	16.57	291.5	58.3	436.5	21.825
%	(100.00)		(31.29)		(27.51)		(41.20)	

Amounts in thousands of millions of Mexican pesos (current values).

Figures inside parentheses are percentages related to the total investment in the period.

will probably not match the true needs for that year, because the true demand at that time may be different from that estimated at the beginning of the cycle year (year N). The result may be a network with insufficient capacity or a network with idle capacity. Also, since the "gain" of new subscribers is one of the firm's most important goals for financial aspects (earnings per share, loan repayments, etc.), actions are taken in places in which there is available netowrk in order to contract the pre-established goal of the total number of new subscribers. Therefore the network is used in a different way than planned. For instance, if a cable of 100 pairs was planned to last five years (at 20 pairs/year) and 50 pair/year are used, the cable lasts for only two and not five years. This causes the situation to deteriorate because in defining a new plan, one of the basic premises considered is that all of the previous plans will be realized and used as planned, and if this is not true, the definition of the new plan is made based upon "weak" premises, with costly consequences.

Each country has its own policies regarding the expansion of primary and secondary cables. These policies generally state a fixed number of years that an extension of primary or secondary cables must last. For Mexico, the plans for extension in primary and secondary cables are for three and five years, respectively. Accordingly, due to several years of experience and from some "post mortem" calculations, it is believed that these policies must be restudied since in some cases the cost actually paid is several times higher than the optimum, in the order of thousands of millions of pesos. Therefore, the impact on the firm's welfare may be in that order. The objectives of this research are based on this concept; that is, to restudy the way of planning the expansion of the primary and secondary networks.

The General Problem of Capacity Expansion

The problem of capacity expansion planning is in no way exclusive property of the telephone industry. On the contrary, it is often encountered when the capacity of some facility must be augmented in an "optimal" way to satisfy a demand. Therefore, in reviewing the literature on this topic, cases besides the telephone industry were considered in order to get a broad picture of the problem and to learn different approaches that have been taken.

Fields in Which Capacity Expansion Planning Have Been Studied

Problems of capacity expansion investment have both a theoretical and practical side, and are of interest to managers, engineers, operations researchers, politicians, economists, etc.; consequently, applications can be found in a wide range of fields. For example, Erlenkotter [17] studied two versions of large-scale problems for planning the expansion of India's nitrogenous fertilizer industry; Manne [26] designed a model to be used to find the best policy for expanding a pipeline or a steel plant or a superhighway; Turvey and Anderson [50] dealt with the capacity expansion of electrical power industries; Butcher, Haimes, and Hall [4] examined capacity expansion for water resources development; Rao and Fong [20] worked with a model for a deterministic capacity expansion and shipment planning problems considering a single commodity that can be produced in two regions; Sinden [40] modeled the expansion of a power plant; Doulliez and Rao [11, 12] dealt with the optimal capacity planning of a network; Coleman and York [9] developed a model to find the optimal chemical plant design; Dale [10] studied optimal additions to generating systems such as nuclear, hydroelectric, steam and gas turbine units; and Erlenkotter [16] modeled capacity expansion with two classes of capacity and demands where one type of capacity can supply both demands while the second can supply only one. A similar problem is treated by the Kalotay [24] model in which two types of equipment are considered: one which is general purpose equipment, and a cheaper one which can provide only one service. Also, there are models considering general applications rather than a specific one, such as those of Giglio [21], Reisman and Buffa [37], Shapiro [38], and Erlenkotter [15]. And, of course, there are articles that treat the case of capacity expansion in the telephone field, which is the main concern of this research. The papers written specifically for the telephone industry will be discussed in more detail later.

Diverse Assumptions Considered in the Literature

Premises considered in studies of capacity expansion are of a large variety, and depend mainly on the interest the author wants to place on the factors that he considers relevant for his problem. Another reason why premises vary from article to article is the kind of detail (specialization) a researcher wishes to consider when formulating a model, this being in most cases for practical relevance. The modeler establishes a tradeoff between the complexity of the model and the useful results he wants to achieve. In other words, the challenge consists of finding "optimal" solutions in special cases, and in devising satisfactory approximations for more general situations where a rigorously optimal solution could be complicated or computationally infeasible. In this respect, Bellman and Dreyfus [2] point out:

> The problem of distinguishing an absolute maximum from relative maxima is one that plagues the optimization field. It cannot be expected that it will ever be oversome at one blow. What we can hope to accomplish is to add class after class of problems to our zoo of tame specimens [p. 83].

With this in mind, it is easy to understand why Doulliez and Rao [11], Erlenkotter [14, 15, 17], Freidenfelds and McLaughlin [19], Fong and Rao [20], Hinomoto [23], Kalotay [24], McDowell [30], Morgan [31], and Sinden [40] consider the demand of deterministic while Giglio [21], Manne [26], and Shapiro [38] take the demand as probabilistic. Also, with respect to demand, Brienkotter [17], Morgan [31], and Rapp [34, 35] assume that the demand grows linearly, while Coleman [9], Dale [10], Erlenkotter [15], and Kalotay [24] prefer to see the demand growing exponentially. Dale [10], Erlenkotter [16, 17], Freidenfeld and McLaughlin [19], Manne [26], Morgan [31], and Smith [41] consider the planning horizon to be infinite; Coleman [9], Doulliez and Rao [12] consider the horizon as being finite.

Intervals between augmentations are considered as non-periodic by Dale [10], Erlenkotter [14, 15, 16, 17], Fong and Rao [20], Reisman and Buffa [37], Shapiro [38], Turvey and Anderson [50], and White [41], and as periodic by Morgan [31] and Rapp [34, 35].

Investment costs are represented by a linear function by Dale [10], Fong and Rao [20], Rapp [34, 35], and Sinden [40]. Erlenkotter [15] considers that operation and maintenance cost are the same for all projects.

Useful life of the facility is taken as finite by Coleman [9], Erlenkotter [14], Rapp [34, 35], and Turvey [50]. Manne [26] estimates useful life as infinite.

Replacement costs are relevant for Coleman [9], Erlenkotter [14], Rapp [34, 35], and Turvey [50]. Giglio [21] includes in his model penalty cost, and Erlenkotter [14] incorporates maintenance and overhead cost.

Fong and Rao [20] include in their model the assumption that no inventory stock is allowed. A salvage value is considered by Morgan [31], Rapp [34], and Reisman [37].

Computational Tools Used in the Literature

Erlenkotter [14, 15, 16, 17], Freidenfelds [19], Giglio [21, 22], Hinomoto [23], Kalotay [24], Manne [26], McDowell [30], Reisman and Buffa [37], Sinden [40], and White [51] use the continuous discount factor, while Dale [10], Doulliez and Rao [12], Morgan [31], Rapp [34, 35, 36], and Turvey [50] use the discrete discount factor. Other tools used are the Taylor expansion, Manne [26]; Laplace Transform, Manne [26]; Markov Chain, Shapiro [38].

Different Methods/Techniques Used to Approach a Solution for the Capacity Expansion Problem in the Telephone Industry

Most authors use in one way or another the net present value approach to evaluate the different alternative solutions. Classical optimization (calculus) is used by Coleman [9], Giglio [22], Hinomoto [23], Kalotay [24], Manne [26], McDowell [30], and Morgan [31].

Fong and Rao [20], Sinden [40], and Turvey [50] use linear programming. Turvey [50] applies non-linear programming, while Freidenfeld and McLaughlin [19] utilize a heuristic branch and bound algorithm. The Dijkstra algorithm is used by Doulliez and Rao [1]. Doulliez and Rao approach the problem by using what they call a dual network shorter path algorithm.

Erlenkotter [14] performs sensitivity analyses on demand and discount rate, and Coleman and York [9] perform sensitivity analyses for a pessimistic, expected, and optimistic demand.

Dynamic programming seems to be a popular technique used to solve the capacity expansion problem, as can be seen in the papers of Dale [10], Erlenkotter [14, 15, 16, 17], Fong and Rao [20], Rapp [36], Shapiro [38], Smith [41], Turvey and Anderson [50], and White [51].

Specific Approaches to the Case of Capacity Expansion Planning in the Telephone Industry

Paul G. Clark [8] presents a sound bases for realistically analyzing the capacity expansion problem in the telephonic field. Clark analyzes the expansion planning activities of the American Telephone and Telegraph Company (Bell System). He compares his study of the simple theory of private investment, also known as the capital requirement theory, to the investment practice in the telephone industry. He says that the essential assumption of the principle in its pure form is that the firm must maintain for technological reasons a fixed ratio between its output and its stock of capital equipment. In other words, the firm must undertake net investment in accordance with changes in its output, or, algebraically:

$$K_t = kO_t$$

$$\Delta K_t = k\Delta O_t$$

where

O_t = the firm's output in time period t

K_t = the firm's stock of capital equipment at the end of the period

ΔO_t = the difference between the firm's output in t and its output in t-1

ΔK_t = the difference between the firm's stock or capital equipment at the end of t and its stock at the end of t-1

k = the fixed technological ratio which the firm is assumed to maintain between its output and its stock of capital equipment.

Clark mentions that the pure acceleration principle is subject to four important qualifications as a realistic theory of private investment:

(1) The pure acceleration principle implies that the firm is able to adjust its stock of capital equipment instantaneously to increase in demand for its output, but in practice a construction period of some length (often several years) must intervene between the decision to purchase additional capital equipment and its actual installation.

(2) The pure acceleration principle implies that the firm adjust the capacity of its stock of capital equipment precisely to its output, but in practice a margin of spare capacity is commonly provided. Spare capacity must exist in order to handle temporary increases in demand without delay, and to support fluctuations expected in the demand.

(3) The pure acceleration principle is perfectly symmetrical with respect to increases and decreases in output, but actually in

the firm frequently is unable to react in the same way to decreases in demand for its output as to increase. If demands fall, the firm frequently cannot make its net investment as negative as the pure acceleration principle asserts, but instead, accumulates excess capacity.

(4) The assumed ratio between the firm's output and its stock of capital equipment is changed from time to time by technological developments. This qualification does not destroy the usefulness of the principle, provided that the technological changes are discontinuous, and that the ratio remains stable from one technological change to the next.

Clark's critique of these four qualifications is essential and should be considered in the model formulation and policy definition of the telephone capacity plant expansion. Clark [8] also describes the way in which the Bell System undertakes the expansion process, which in general is very similar to that followed by Mexico.

A pioneer work (1939) on capacity expansion for a telephonic plant is that of Rapp from the Telefonoktiebolaget L. M. Ericsson [34], in which he developed a model that considers initial investment, replacement costs, maintenance cost, and uses the annual cost comparisons and the net preset value to determine the best policy (or, as he called it, the economic stage of extension for a telephone network). First, he considers the case of plants for constant demand, then he extended the model for the case of plants for growing demands. From the set of final equations, he suggests evaluating them for different values of t_x (time between additions) until the minimum cost is derived. He did not provide a closed expression for the optimal solution.

In 1950, Rapp [35] again treats the same program with a model essentially the same as he presented in [34]. This time he presents an explicit expression for the minimum cost. In 1976, Morgan [31] utilized the same approach used by Rapp [34, 35], with basically the same expressions and results.

In 1969, Rapp [36] uses dynamic programming to determine the optimal extensions of conducts and principal cable networks. In this paper he did consider a planning horizon of 25-45 years, and the intervals of calculations (stage of decisions) of one year. His recursive expression for evaluating decisions at each stage is, as in almost all of the works using dynamic programming, to solve the capacity expansion problem of the type:

$$N(0_t) = \min_{0 \le x < t} . \left[\min . N(0_x) + N(x_t)\right] \qquad (t = 1,2,\ldots,T)$$

where

$N(0_t)$ = present value for extensions during the period 0 - t

$N(0_x)$ = present value for extensions during the period 0 - x

$N(xt)$ = present value for extensions during the period x - t.

In 1979, John Freidenfelds and C. D. McLaughlin [19], of the Bell Laboratories, presented an adaptation of a branch and bound solution approach for the problem of expanding the capacity of a telephone feeder cable network to meet growing demand. They generated heuristic bounds, based on analytic solutions of simpler capacity expansion problems. Their approach, as they describe it, is somewhat like that of Doullies and Rao [12] modified by some heuristics to speed it up. In their algorithm they consider the following premises/options:

(1) Demand in a specified area is served by the finest gauge possible (without violating the transmission standards).

(2) Arbitrary demand.

(3) Remove small cables to make room for larger ones.

(4) Utilize the existing "excess capacity."

(5) Demand is deterministic.

(6) Infinite time horizon.

Their model breaks the problem into smaller parts, and analyzes each one recursively (in this way they use the analytical approach of dynamic programming) to form the optimal chain of decisions. They said that obtaining a solution by only dynamic programming would be very difficult because of the large dimensionality of the stated space. So they use a recursive equation very much like those used by Shapiro [38], Rapp [41], Erlenkotter [15], Turvey and Anderson [50], and others, in defining the "best" decision in each node of a decision tree like that shown in Figure 5.

This approach is where their algorithm takes on the name "Branch and Bound." In this tree, each node corresponds to the first "shortage" and in that point a decision must be taken. So, in searching the sequence of cable placements, they systematically search the decision tree for a path with the minimum present worth cost. Their basic solution strategy considers first an horizon of 45 years (as Rapp in [36]), and uses only the first few levels of the tree. The solution has three stages:

(1) An explicit enumeration of all alternatives at the first two levels;

(2) A completion of each two-level subsequence to 45-year sequence

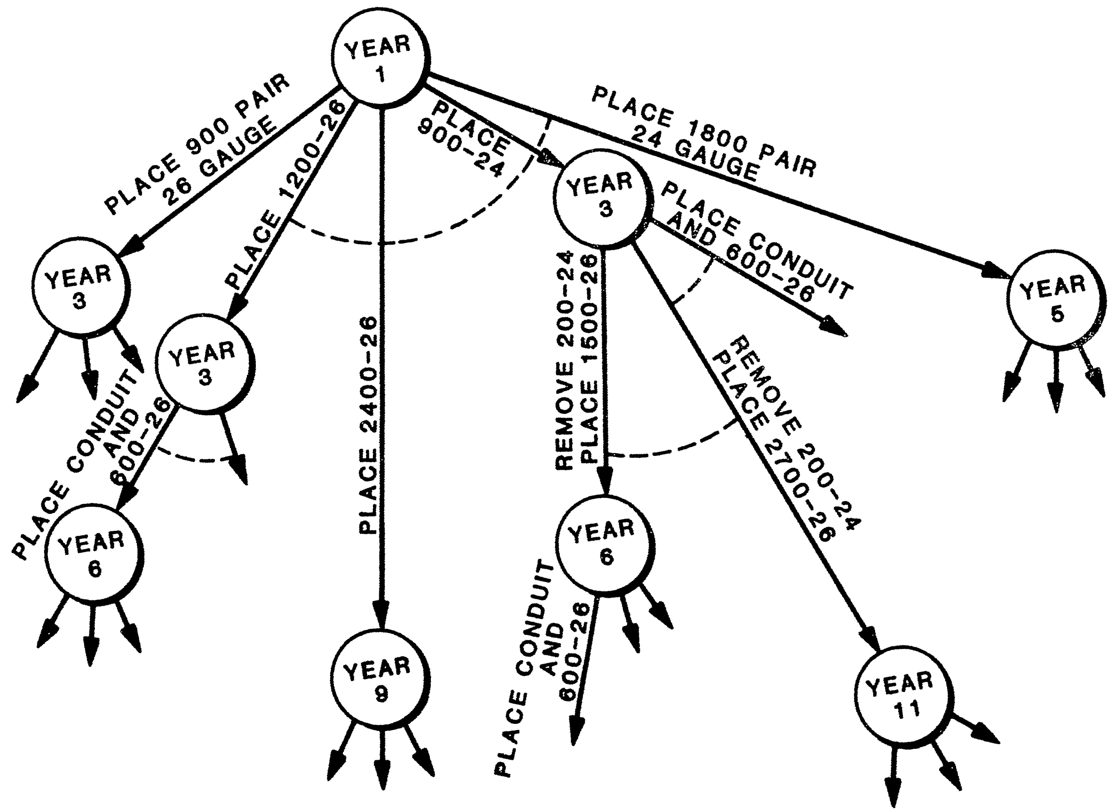


Figure 5. A Decision Tree

by what they called their "elaborate heuristics";

(3) An estimate of the cost of completing the 45-year sequence to infinity using their "tail-end-approximation." For the tail-end-approximation they use McDowell's [30] expression for an infinite stream.

In 1979 Robert L. Smith [41] considered the problem of selecting capacity additions from a finite set of possible facility sizes to meet demand at a single location over an infinite horizon. The solution approach used by Smith is dynamic programming. He uses an example application in the long haul transmission facilities in the nationwide intercity telephone network. The model proposed considers that each expansion is to be chosen from a finite set of possible additions, and that fixed costs may be associated with each allowable capacity addition. One of the characteristics of the model is that it considers that the demand grows exponentially and that all significant capacity sensitive costs occur at the time when the capacity is augmented.

L. Smith bases his mathematical model on two lemmas and three theorems that he uses along with an algorithm, OFNPS of the Western Electric Company to design the algorithm and obtain his findings. His main result, based on the "turnpike theorem" (used also by Shapiro [38]) is that under his assumptions the optimal policy is characterized as one in which the least average cost facility is the only facility type installed over the infinite horizon.

Smith's algorithm consists of the following steps:

(1) For all possible pair of facilities, calculate the time at which the following equality holds:

$$\delta_i(t) = \delta_j(t)$$

where

$\delta(t)$ represents a linearized form of the fixed installation cost.

(2) Set

$$\tilde{t} = \max_{i,j} t_{ij}$$

where

t_{ij} = time at which the facility j intersects with facility i.

(3) Establish a threshold time t* beyond which the last average facility precedes all others:

$$t^* = \max_i t_{ij}^*$$

In other words, make t* as the time at which the facility with min δ_j intersects with the facility i having the larger time, $T_i(t)$.

(4) Use the Western Electric algorithm to obtain the sequence of installations to cover from time 0 to time t*.

(5) Add the cost of installing turnpike facilities indefinitely to each possible truncated sequence in (4).

From the articles reviewed, only two, [19 and 36], deal specifically with the case of primary cables, and none with secondary cables. Of course, any one of the algorithms developed for long-haul, metropolitan, or feeder cables can be adapted to the case of principal or secondary networks; the problem is that due to the vast number of spans of primary and secondary cables to be analyzed for each planning cycle, a solution becomes too costly and/or practically infeasible.

Research Goals and Specific Objectives

Relevant Assumptions Considered

Approaches like dynamic programming or the Freidenfelds and McLaughlins branch-and-bound algorithm [19] have been used with good results to solve the problem of capacity addition in telephonic areas such as trunk cables, long haul facilities, and exchange equipment. In some cases these approaches have also been used, with poor results, in the principal cables network and in underground conducts. These unsatisfactory results in primary network are due to economic and practical aspects rather than theoretical limitations.

This can be explained by recalling that a telephone cables network is formed by branches (cables) and nodes (points in which a cable is sliced into smaller cables or jointed to another cable), disposed in a tree-like configuration and that, on average, for each telephone exchange there are approximately 200 branches for principal network and 3500 for secondary network (see Appendix A) to be analyzed, each planning cycle for addition of capacity. The result is that the number of branches to be analyzed is large (for Mexico, this is in the order of 900,000 and growing each year [see Appendix A]). As a result, analysis by computer using a technique like those cited above may become economically or practically infeasible. This situation is more critical in developing countries like Mexico, where the availability of computers and specialized people required to design, modify, run, etc., these programs is extremely limited.

For this reason, this research concentrates on finding a solution to the capacity expansion problem in principal and secondary cables, using an approach different than dynamic programming or Freidenfelds and McLaughlin's algorithm. The models will incorporate several important aspects that none of the articles searched in the literature have included, like inflation, increase in the value of the material that is recovered when the plant is replaced, and maximum percentage of occupation allowed (i.e., how many pairs used of the total installed), Also, it will incorporate into the analysis two very important aspects: the effect of the change in technology and the stochastic nature of the demand.

Priorities Set for the Objectives

Summarizing, the objectives to be pursued in this research, in descending order of importance, are:

(1) Design a theoretically well supported methodology to be used for determining the best policy of expansion in primary and secondary cables, without using an algorithm that routinely requires the use of a computer each time the analysis of expansion is made.

(2) Evaluate the effects of inflation and deflation in the decision making process of expanding cable telephone networks.

(3) Evaluate the effects of considering the stochastic nature of demand.

(4) Evaluate the effects of the changes in technology.

(5) Evaluate the effects of varying the percentage of occupation in cable telephone networks.

CHAPTER II

METHODOLOGY

Delineation of the Methodology to Use

The principal feature of most capacity expansion problems is that they entail the minimization of a function that is highly linked to economics-of-scale. This is particularly true in the telephone industry. Economics of scale often lead to an objective function which is not convex, and most formulations cannot be solved in closed form without making simplifying assumptions. Most authors recognize in their models the considerable uncertainty associated with each assumption. As a result, their effort has gone into obtaining feasible approximate solutions, an approach that is perfectly valid to solve real problems like that of telephone cable capacity expansion. This research will develop a model for capacity cable expansion that is mathematically tractable but not over simplified.

For this reason, the solution approach taken by Coleman and York [9], Giglio [22], Rapp [34, 35], and Reisman and Buffa [37] was followed. Their approach consists of designing a present worth cash flow equation for the investments, expenditures, salvage values, etc. From this equation, an optimal expression can be developed which will provide the means to perform sensitivity analysis on the relevant parameters.

Initially in this research, the modeling and the calculations will be made as though the future were known with certainty. Later, this assumption will be relaxed when demand is described by a probability distribution and when sensitivity analysis is performed on the optimal value (minimum cost). Finally, the results from the sensitivity analysis will provide a basis for developing a set of simple policies to be used in the decision making process regarding the capacity expansion for primary and secondary cables.

Development of the Model for the Case of Installing a Capacity to Satisfy One Time Demand

The aspects and assumptions considered are:

(1) Initial investment. This concept covers purchase, delivery, and installation costs.

(2) Useful life of the plant installed. Considered equal for the first and subsequent installations.

(3) Replacement of the installation by another facility at the end of its useful life.

(4) Salvage value. Net value, after dismantling costs.

(5) Operation costs. Assumed as incurred at the end of the year.

(6) Maintenance costs. Assumed as incurred at the end of the year.

(7) Cost of capital. Same all the time (this assumption is relaxed later).

(8) Inflation. Considered as the increment in cost for each element (such as installation, operation, and maintenance).

(9) Deflation. Considered as the increment in value of the recovered material when dismantling the old facility (such as copper and lead).

This objective will be to minimize the net present costs (at the time t=0 when the decision will be made). The planning horizon is infinite and compounded by spans of equal length, each span matching the useful life of the plant installed.

Therefore, let

C_0 = cost of installation at time t = 0

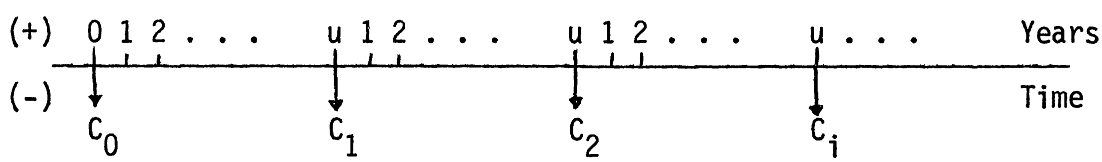
C_1 = cost of the first substitution after the useful life of the facility installed at t = 0

.
.
.

C_i = cost of the J^{th} substitution after the useful life of the facility installed at t = i-1

u = useful life, expressed in years, of each installation.

The corresponding cash flow for these installation costs is:



So, the net present value of the installation costs is:

$$C_{TI} = C_0 + \sum_{i=1}^{n} C_i(1+r)^{-iu}, \ . \ . \ . \qquad (1.1)$$

where

n = number of times the substitution is considered

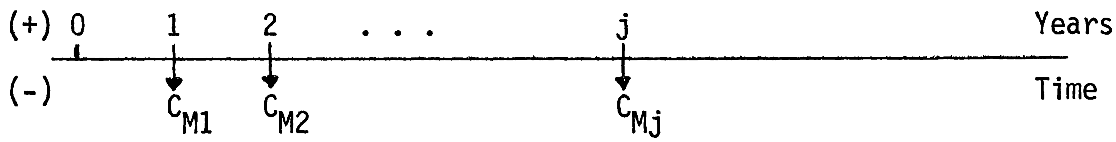
i = i^{th} installation (realized at the end of the useful life of the $(i-1)^{th}$ installation

r = cost of capital (expressed in decimal form).

Now, considering the operation and maintenance costs as one (a similar assumption is made in the telephone industry), let

C_{Mj} = expected operation and maintenance cost for the j^{th} year.

The cash flow for this concept is:



Therefore, the net present value of the operation and maintenance costs is:

$$C_{TM} = \sum_{j=1}^{(n+1)u} C_{Mj}(1+r)^{-j} \quad . . . \qquad (1.2)$$

Looking at the salvage costs, let

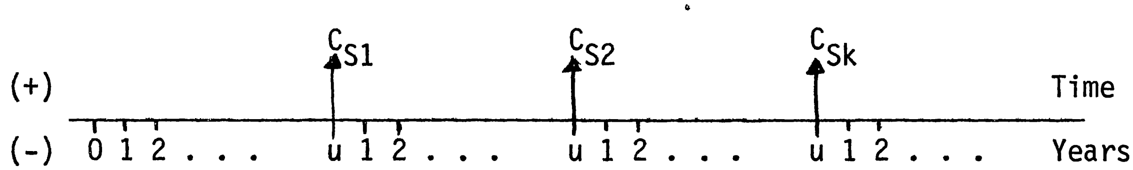
C_{S1} = salvage net value of the first facility, installed at t = 0, and replaced after its useful life.

C_{S2} = salvage net value of the second facility, installed at t = u.

.
.
.

C_{Sk} = salvage net value of the k^{th} facility, installed at t=(k-1)u.

The salvage costs cash flow can be represented as:



Consequently, the net present value of the salvage costs is:

$$C_{TS} = -\sum_{k=1}^{(n+1)} C_{Sk}(1+r)^{-ku} \quad . . . \qquad (1.3)$$

Now, the total net present value can be written as:

$$C_T = C_{TI} + C_{TM} + C_{TS},$$

or

$$C_T = C_o + \sum_{i=1}^{n} C_i(1+r)^{-iu} + \sum_{j=1}^{(n+1)u} C_{Mj}(1+r)^{-j}$$

$$- \sum_{k=1}^{(n+1)} C_{Sk}(1+r)^{-ku} \quad . . . \qquad (1.4)$$

To incorporate the inflation and deflation into the model, the following expressions can be written:

$$C_i = C_o(1+R)^{iu}$$

$$C_{Mj} = \mu C_o(1+\alpha)^j$$

$$C_{Sk} = \varepsilon C_o(1+\beta)^{ku},$$

where

R = inflation rate for the cost of facility installed

α = increment rate on the maintenance and operation cost

β = increment rate for the value of the material forming the facility

μ = percentage (to express operation and maintenance costs as a part of the installation cost)

ε = percentage (to express salvage value as a part of the installation cost).

So, Equation (1.2) becomes:

$$C_T = C_o + \sum_{i=1}^{n} C_o \frac{(1+R)^{iu}}{(1+r)^{iu}} + \sum_{j=1}^{(n+1)u} \mu C_o \frac{(1+\alpha)^j}{(1+r)^j} - \sum_{k=1}^{(n+1)} \varepsilon C_o \frac{(1+\beta)^{ku}}{(1+r)^{ku}} .$$

Simplifying this expression,

$$C_T = C_o + \sum_{i=1}^{n} C_o \rho^{iu} + \sum_{j=1}^{(n+1)u} \mu C_o \gamma^j = \sum_{k=1}^{(n+1)} \varepsilon C_o \theta^{ku} ,$$

where

$$\rho = \frac{1+R}{1+r} ; \qquad \gamma = \frac{1+\alpha}{1+r} ; \quad \text{and} \qquad = \frac{1+\beta}{1+r} .$$

Therefore,

$$C_T + C_o \; 1 + \left[\sum_{i=1}^{n} \rho^{iu} + \mu \sum_{j=1}^{(n+1)u} \gamma^j = \varepsilon \sum_{k=1}^{(n+1)} \theta^{ku} \right] \quad . \; . \; . \qquad (1.5)$$

Now, evaluating the summations, let

$$\sum_{i=1}^{n} \rho^{iu} = s$$

then

$$s = \rho^u + \rho^{2u} + \rho^{3u} + . \; . \; . + \rho^{nu} ,$$

and

$$s\rho^u = \rho^{2u} + \rho^{3u} + \rho^{4u} + . \; . \; . + \rho^{(n+1)u} .$$

Continuing this approach

$$s - s\rho^{u} = \rho^{u} - \rho^{(n+1)u}$$

$$s(1-\rho^{u}) = \rho^{u} - \rho^{(n+1)u}$$

$$s = \frac{\rho^{u}(1-\rho^{n+1})}{1 - \rho^{u}}$$

Although it can happen for a short period of time that $\rho > 1$, most of the time ρ must be <1 for a firm to survive. Therefore, it is assumed that:

$$\rho^{u} < 1$$

So, ρ^{n+1} decreases in value when n increases; as a result,

$$\lim_{n\to\infty} \rho^{n+1} = 0$$

Consequently, as n becomes large,

$$s = \frac{\rho^{u}}{1 - \rho^{u}}$$

and

$$\sum_{i=1}^{n} \rho^{iu} = \frac{\rho^{u}}{1 - \rho^{u}}$$

Now, a similar approach will be used to simplify the following expression:

$$\sum_{j=1}^{(n+1)u} \gamma^{j}$$

Let

$$\sum_{j=1}^{(n+1)u} \gamma^{j} = s$$

$$s = \gamma^{u} + \gamma^{2u} + \gamma^{3u} + \ldots + \gamma^{(n+1)u}$$

$$\gamma^{u}s = \gamma^{2u} + \gamma^{3u} + \gamma^{4u} + \ldots + \gamma^{(n+2)u}$$

$$s\text{-}s\ \gamma^{u} = \gamma^{u} - \gamma^{(n+2)u}$$

$$s(1-\gamma^{u}) = \gamma^{u}(1-\ ^{n+2})$$

$$s = \frac{\gamma^{u}(1-\gamma^{n+2})}{1-\gamma^{u}}$$

Making the same assumptions for γ, as for ρ

$$\lim_{n\to\infty} \gamma^{n+2} = 0$$

So

$$s = \frac{\gamma^{u}}{1-\gamma^{u}},$$

or

$$\sum_{j=1}^{(n+1)u} \gamma^{j} = \frac{\gamma^{u}}{1-\gamma^{u}}$$

Proceeding as above for $\sum_{k=1}^{n+1} \theta^{ku}$:

$$\sum_{k=1}^{(n+1)} \theta^{ku} = \frac{\theta^{u}}{1-\theta^{u}}$$

Therefore, Equation (1.5) can be expressed as:

$$C_T = C_o\left(1 + \frac{\rho^u}{1 - \rho^u} + \mu\,\frac{\gamma^u}{1 - \gamma^u} - \varepsilon\,\frac{\theta^u}{1 - \theta^u}\right) \quad . . . \qquad (1.6)$$

Now make:

$$1 + \frac{\rho^u}{1 - \rho^u} + \mu\,\frac{\gamma^u}{1 - \gamma^u} - \varepsilon\,\frac{\theta^u}{1 - \theta^u} = \lambda$$

C_T can then be expressed as

$$C_T = \lambda\, C_o \qquad . . . \qquad (1.7)$$

Development of the Model For the Case of Linearly Increasing Demand

Let τ represent regular intervals of time at which the capacity is increased. The present cost for the first installation and subsequent substitutions is λC_o. After a period τ, another augmentation to the capacity is made with cost $\lambda\, C_a$, where C_a represents the first installation cost of the facility installed τ years after t=o. The net present value of this additional cost is:

$$\lambda C_a (1 + r)^{-\tau}$$

Then, for the first augmentation after the initial installation, the present cost at t=o, is:

$$\lambda C_a\,\frac{(1+R)^\tau}{(1+r)^\tau}$$

or

$$\lambda C_a \rho^\tau$$

Similarly, for the second augmentation (at t=2τ) the present cost at t=o is:

$$\lambda C_a \rho^{2\tau}$$

Proceeding in the same manner for the third, fourth, etc., augmentations, the expression for the total cost at t=o, becomes:

$$C_{To} = \lambda C_o + \lambda C_a \rho^{\tau} + \lambda C_a \rho^{2\tau} + \ . \ . \ . + \lambda C_a \rho^{n\tau}, \qquad (2.1)$$

or

$$C_{To} = \lambda \left(C_o + \sum_{i=1}^{n} C_a \rho^{i\tau} \right)$$

Now, evaluating the summation:

$$\sum_{i=1}^{n} \rho^{i\tau} = s$$

$$s = \rho^{\tau} + \rho^{2\tau} + \rho^{3\tau} + \ . \ . \ . + \rho^{n\tau}$$

$$\rho^{\tau} s = \rho^{2\tau} + \rho^{3\tau} + \rho^{4\tau} + \ . \ . \ . + \rho^{(n+1)\tau}$$

$$s - \rho^{\tau} s = \rho^{\tau} - \rho^{(n+1)\tau}$$

$$s(1-\rho^{\tau}) = \rho^{\tau} - \rho^{(n+1)\tau}$$

$$s = \frac{\rho^{\tau} - \rho^{(n+1)}}{1 - \rho^{\tau}}$$

Again, since:

$$\lim_{n \to \infty} \rho^{(n+1)\tau} = 0,$$

$$s = \frac{\rho^{\tau}}{1 - \rho^{\tau}}, \text{ and}$$

$$C_{To} = \lambda \left(C_o + C_a \frac{\rho^{\tau}}{1 - \rho^{\tau}} \right) \ . \ . \ . \qquad (2.2)$$

Assuming that the initial demand at t=o is d_o, and that the annual increment of demand is d_a; the total demand at t years, will be

$$D_t = d_o + d_a t$$

For this demand, the capacity will be increased at regular intervals of τ years. Considering that the initial installation will handle a demand of $d_o + d_a\tau$ and that the following expressions will handle a demand of $d_a\tau$ at τ intervals, C_o and C_a can be expressed as:

$$C_o = K(d_o + d_a\tau)$$

$$C_a = Kd_a\tau$$

where K is the cost of the elements of the facility that provide one unit of capacity. Therefore, Equation (2.2) becomes:

$$C_{To} = \lambda\left[k(d_o + d_a\tau) + kd_a\tau\,\frac{\rho^\tau}{1 - \rho^\tau}\right] \quad . . . \qquad (2.3)$$

Now, for the case for which this model is going to be used, telephone cable expansion, it is possible to get an expression for the cost of cables by using regression analysis. Let

$$K = \beta_o + \beta_1\, p$$

where β_o and β_1 are the parameters that identify each group of cables (primary or secondary cables). K would be expressed in dollars per unit of length. The number of pairs in a cable is represented by p. In this fashion, the cost for the period τ can be written as:

$$K(d_o + d_a\tau) = \beta_o + \beta_1(d_o + d_a\tau)$$

For the following periods:

$$K\ d_a\tau = \beta_o + \beta_1 d_a\tau$$

Equation (2.3) can now be written as:

$$C_{To} = \lambda\left[\beta_o + \beta_1(d_o + d_a\tau) + (\beta_o + \beta_1\ d_a\tau)\ \frac{\rho^\tau}{1 - \rho^\tau}\right] \tag{2.4}$$

This last expression can be simplified as follows:

$$\frac{C_{To}}{\lambda\beta_1 d_a} = \frac{\beta_o}{\beta_1 d_a} + \frac{d_o}{d_a} + \tau + \frac{\rho^\tau}{1 - \rho^\tau}\left[\frac{\beta_o}{\beta_1 d_a} + \tau\right]$$

Multiplying by β_o,

$$\frac{\beta_o C_{To}}{\lambda\beta_1 d_a} = \frac{\beta_o^2}{\beta_1 d_a} + \frac{\beta_o d_o}{d_a} + \beta_o\left[\tau + \frac{\rho^\tau}{1 - \rho^\tau}\left(\frac{\beta_o}{{}_1 d_a} + \tau\right)\right]$$

Letting

$$\delta = \frac{\beta_o}{\beta_1 d_a}$$

and substituting into the above expression,

$$\frac{C_{To}}{\lambda}\ \delta = \delta\beta_o + \delta\beta_1 d_o + \beta_o\left[\tau + \frac{\rho^\tau}{1 - \rho^\tau}\ (\delta + \tau)\right],$$

or

$$C_{To} = \lambda\ (\beta_o + \beta_1 d_o) + \lambda\ \frac{\beta_o}{\delta}\left[\tau + \frac{\rho^\tau}{1 - \rho^\tau}\ (\delta + \tau)\right]\ \ .\ .\ . \tag{2.5}$$

For a specific d_a, different values of τ will result in different values for C_{To}. Therefore, the next step is to find which value of minimizes C_{To}.

$$\frac{dC_{To}}{d\tau} = \lambda \frac{\beta_o}{\delta} \cdot \frac{d}{d\tau}\left[\tau + \frac{\rho^\tau}{1 - \rho^\tau}(\delta + \tau)\right]$$

$$= \frac{\lambda\beta_o}{\delta}\left\{\frac{\rho^\tau}{1-\rho^\tau}\left[1 + \left(\frac{\beta_o}{\beta_1 d_a} + \tau\right)\ln\rho\right] + \frac{\rho^\tau}{1-\rho^\tau}\frac{\left(\frac{\beta_o}{\beta_1 d_a} + \tau\right)\rho^\tau \ln\rho}{1 + \rho^\tau} + 1\right\}$$

Setting $\frac{dC_{to}}{d\tau} = 0$,

$$\frac{\rho^\tau}{1-\rho^\tau}\left[1 + \left(\frac{\beta_o}{\beta_1 d_a} + \tau\right)\ln\rho\right] + \frac{\rho^\tau}{1-\rho^\tau}\frac{\left(\frac{\beta_o}{\beta_1 d_a} + \tau\right)\rho^\tau \ln\rho}{1 - \rho^\tau} = -1$$

Collecting terms,

$$\frac{\beta_o}{\beta_1 d_a} = -\frac{1}{\left(1 + \frac{\rho^\tau}{1 - \rho^\tau}\right)\ln\rho}\left(\frac{1}{\frac{\rho^\tau}{1 - \rho^\tau}} + 1\right) - \tau$$

Again, letting

$$\delta = \frac{\beta_o}{\beta_1 d_a}$$

and substituting into the above expression, the optimal value δ^* may be expressed as:

$$\delta^* = \frac{1}{\frac{\rho^\tau}{1 - \rho^\tau}\ln\rho} - \tau ,$$

$$\delta^* = \left[\frac{\beta_o}{\beta_1 d_a}\right]^* = -\frac{1 - \rho^\tau}{\rho^\tau \ln\rho} - \tau \quad . \; . \; . \qquad (2.6)$$

To complete the test for optimality, the sufficient condition

$$\frac{d^2 C_{To}}{d\,\tau^2} > 0 \quad . . . \tag{2.7}$$

was tested. It was found that for the common values of the parameters used in the telephone industry, Equation (2.7) holds. This completes the test for a local minimum.

CHAPTER III

POSTOPTIMALITY ANALYSES

Calculation of Cable Cost Parameters

The unit costs for telephone cables can be represented accurately by the parameters of the simple regression model

$$k = \beta_0 + \beta_1 p ,$$

where β_0 and β_1 are the parameters by which a group of cables can be identified. The number of pairs in a cable is p. The number of different types of cables used in a primary and secondary cable telephone network can be large. For instance, in Mexico the common types used are shown in Table IV. For a description of these cables, see Appendix B.

TABLE IV

COMMON TYPES OF TELEPHONIC CABLES USED IN MEXICO FOR PRIMARY AND SECONDARY NETWORKS

TAF(0.4) 10- 600 Ps	EKD(0.4) 50-600 Ps
TAF(0.5) 50- 600 Ps	EKI(0.4) 10-100 Ps
TAF(0.64) 50- 300 Ps	EKE(0.4) 10-100 Ps
TAF(0.9) 50- 300 Ps	EKE(0.5)150-300 Ps
TAP(0.4) 10- 300 Ps	ASP(0.4) 10-300 Ps
TAP(0.4) 300-2400 Ps	ASP(0.5) 10-300 Ps
TAP(0.5) 150-1200 Ps	ASP(0.64)10-300 Ps
TAP(0.64) 50- 300 Ps	ASP(0.9) 10-100 Ps
TAP(0.9) 50- 450 Ps	

Fortunately, to draw conclusions on the method proposed, it is not necessary to analyze each of those types; since 91% of the total amount of cable used is formed by types ASP(0.5) 10-300 Ps, TAP(0.4) 10-300 Ps, TAP(0.4) 300-2400 Ps, and TAP(0.5) 150-1200 Ps. Therefore, it was considered sufficient to analyze only these types. The regression analysis was performed using the Statistical Analysis System (SAS); obtaining the values shown in Table V.

TABLE V

PARAMETERS CALCULATED FOR THE COMMON TYPES OF CABLES USED IN MEXICO FOR PRIMARY AND SECONDARY TELEPHONE NETWORKS

Type of Cable	β_0	β_1
ASP(0.4) 10- 300 Ps	22759.56	505.74
TAP(0.4) 10- 300 Ps	48072.48	650.59
TAP(0.4) 100-2400 Ps	52444.82	429.98
TAP(0.5) 150-1200 Ps	44316.65	567.49

Net Present Value (NPV) vs. Extent of Extension For Different Demand Values

To attain the main objective of this research--develop a methodology to help in the decision making process of expanding the primary and secondary telephone cable networks--the first step was to analyze the behavior of Equation (2.5). This equation represents the net present value (NPV) of the cash flow associated with the expansion of the cable networks to satisfy an annual demand of pairs. To accomplish this, the computer program, CURVES, listed in Table XVIII of Appendix G was designed. For a specified demand and a cable type, this program generates the net present values corresponding to different extents of extension values. A sample of the results produced by this program can be seen in Table VI.

The results obtained from CURVES was used to construct Figure 6 and Appendix C. These figures represent outcomes for secondary telephone cables of the type ASP(0.4) 10-300 Ps. Using these figures, it is possible to determine (for a specific demand and type of cable) how cost changes when the time between installations is varied. For instance, from Table VI and Figure 6, it can be seen that if the time between installations is too short, less than one year, the resulting net present value is high; but if τ increases, the cost reduces up to a point where it reaches its minimum value. If τ is further increased beyond the time that yields the minimum cost, then the cost begins to increase again. Therefore, these curves show a shape in which, with the exception of the time of the minimum cost, two values of τ that will result in the same cost. This permits setting upper and lower bounds around the optimal value and simplifies the sensitivity analysis of the cost when varying the time between augmentations. Curves for other common types of cables are shown in Appendix C.

The lower and upper bounds are not symmetrical with respect to the minimum value τ^* than to the right. This suggests that for a pre-established value over the minimum cost, the better planning policy would involve a longer time span rather than for a shorter one. That

TABLE VI

SAMPLE PAGE OF THE RESULTS GIVEN BY THE CURVES PROGRAM

PAGE 16

NET PRESENT VALUE OF THE SERIE OF COSTS ASSOCIATED WITH EXPANDING THE CAPACITY OF THE TELEPHONE CABLES NETWORK WITH CABLES OF THE TYPE : TAP (C.4) 10-300 PAIRS. , AT DIFFERENT TAU INTERVALS OF TIME.

*** NPV IS IN THOUSANDS, MONEY IS IN 1981 VALUE *** CALCULATIONS MADE FOR AN ANNUAL DEMAND OF : 100.00 PAIRS.

VALUE OF THE PARAMETERS CONSIDERED FOR THIS RUN : COST OF CAPITAL : 0.15 ; MAINTENANCE : 0.05
INFLATION : 0.10 ; DEFLATION : 0.15

TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV
0.1	10097.	2.6	1650.	7.2	1593.	12.2	1730.	17.2	1910.	24.0	2189.	36.5	2773.
0.2	5665.	2.7	1641.	7.4	1597.	12.4	1736.	17.4	1917.	24.5	2211.	37.0	2798.
0.3	4190.	2.8	1633.	7.6	1601.	12.6	1743.	17.6	1925.	25.0	2233.	37.5	2823.
0.4	3454	2.9	1627.	7.8	1605.	12.8	1750.	17.8	1933.	25.5	2255.	38.0	2848.
0.5	3014.	3.0	1618.	8.0	1609.	13.0	1757.	18.0	1941.	26.0	2277.	38.5	2873.
0.6	2721.	3.2	1607.	8.2	1614.	13.2	1763.	18.2	1949.	26.5	2299.	39.0	2899.
0.7	2514.	3.4	1597.	8.4	1619.	13.4	1770.	18.4	1956.	27.0	2322.	39.5	2924.
0.8	2358.	3.6	1589.	8.6	1624.	13.6	1777.	18.6	1964.	27.5	2344.	40.0	2950.
0.9	2239.	3.8	1583.	8.8	1629.	13.8	1784.	18.8	1972.	28.0	2367.	40.5	2975.
1.0	2143.	4.0	1578.	9.0	1634.	14.0	1791.	19.0	1980.	28.5	2390.	41.0	3001.
1.1	2066.	4.2	1575.	9.2	1639.	14.2	1798.	19.2	1988.	29.0	2413.	42.0	3053.
1.2	2002.	4.4	1572.	9.4	1645.	14.4	1805.	19.4	1996.	29.5	2436.	43.0	3105.
1.3	1948.	4.6	1570.	9.6	1650.	14.6	1813.	19.6	2004.	30.0	2460.	44.0	3157.
1.4	1903.	4.8	1569.	9.8	1656.	14.8	1820.	19.8	2013.	30.5	2483.	45.0	3210.
1.5	1864.	5.0	1569.	10.0	1662.	15.0	1827.	20.0	2021.	31.0	2507.	46.0	3263.
1.6	1830.	5.2	1569.	10.2	1667.	15.2	1834	20.2	2029.	31.5	2530.	48.0	3371.
1.7	1801.	5.4	1570.	10.4	1673.	15.4	1842.	20.4	2037.	32.0	2554.	50.0	3479.
1.8	1775.	5.6	1571.	10.6	1679.	15.6	1849.	20.6	2045.	32.5	2578.	52.0	358[illegible].
1.9	1753.	5.8	1572.	10.8	1685.	15.8	1857.	20.8	2053.	33.0	2602.	54.0	3700.
2.0	1733.	6.0	1574.	11.0	1691.	16.0	1864.	21.0	2062.	33.5	2626.	56.0	3812.
2.1	1715.	6.2	1577.	11.2	1698.	16.2	1872.	21.5	2083.	34.0	2650.	60.0	4039.
2.2	1699.	6.4	1579.	11.4	1704.	16.4	1879.	22.0	2104.	34.5	2675.	70.0	4622.
2.3	1685.	6.6	1582.	11.6	1710.	16.6	1887.	22.5	2125.	35.0	2699.	80.0	5222.
2.4	1672.	6.8	1586.	11.8	1717.	16.8	1894.	23.0	2146.	35.5	2724.	90.0	5834.
2.5	1661.	7.0	1589.	12.0	1723.	17.0	1902.	23.5	2167.	36.0	2748.	100.0	6454.

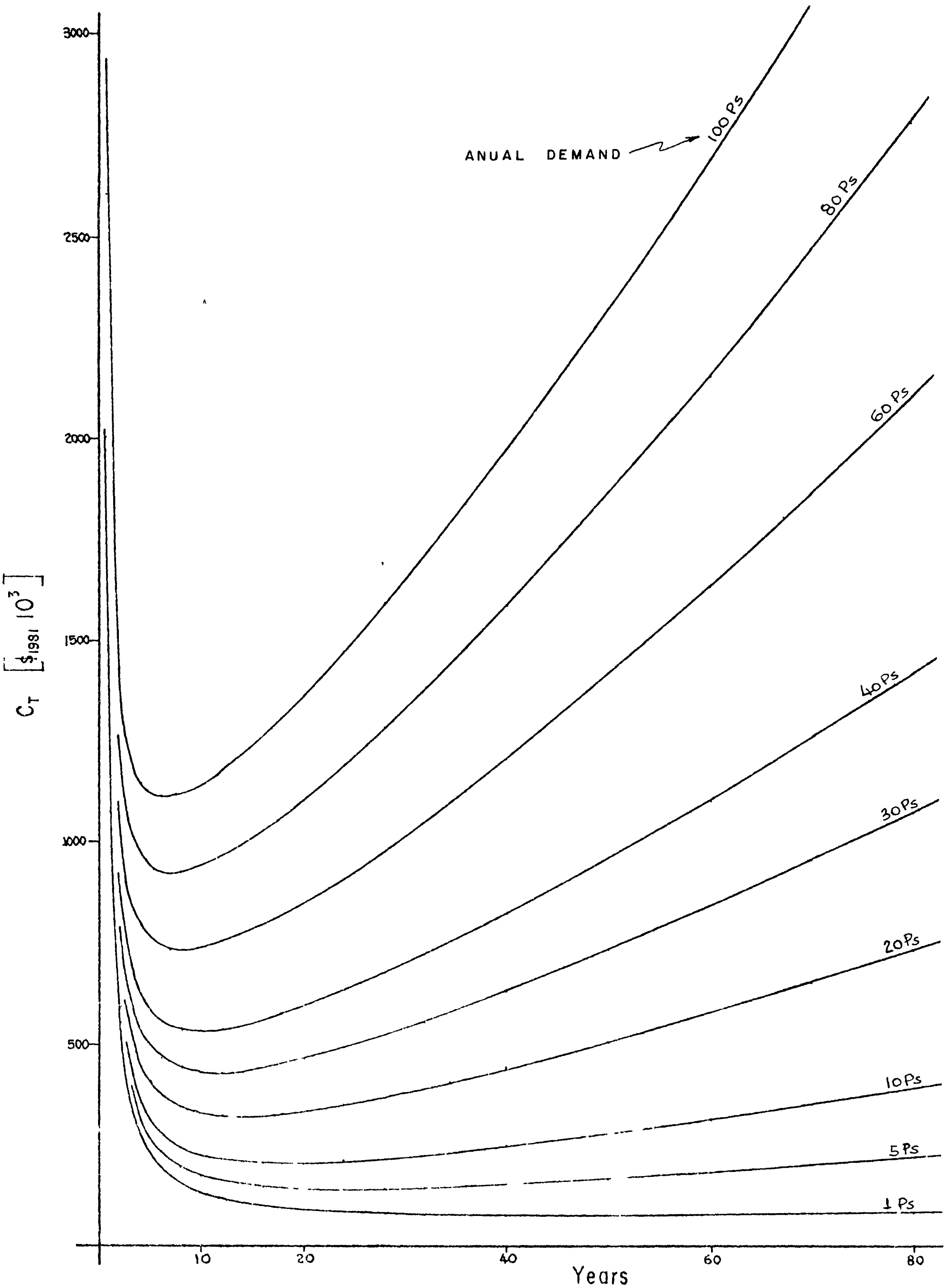


Figure 6. Extent of Extension and Its Net Present Value For Secondary Telephone Cables of the Type ASP(0.4) 10-300 Pairs

is, the cost is the same for extent of extensions of three and ten years, it may be better to plan the installation to last ten, and not three years. This concept is used and explained more fully in succeeding pages.

Values of Demand and Corresponding Extent of Extension to Get the Minimum Net Present Value (NPV)

Equation (2.6) relates the values of demand and time between installations which bear the minimum cost. This implies that if the annual demand (d_a) and the time (τ) of the extent of extension are known, it is possible to know the capacity corresponding to this pair of values by using the equation:

$$\text{Capacity} = d_a \cdot \tau \qquad \ldots \qquad (3.1)$$

To gain insight into two aspects: (1) to know what is the optimal extent of extension and its matching demand for cables in use, as well as for those not in current use; and (2) to have another way to prove that Equation (2.6) fulfills both the necessary and sufficient conditions for optimality, a program F(DA)F(TA), was designed to tabulate values of demand and time between installations. In this program, listed in Table XIX of Appendix G, the values F(DA) and F(TA) correspond with the left hand side and right hand side of Equation (2.6), respectively.

By comparing values in Table VII with the optimal values presented in Figure 6 and in Figures 14-16 of Appendix C, it was possible to compare the optimal values from two sources: From the program CURVES

TABLE VII

EXAMPLE OF PRODUCT GIVEN BY THE F(DA)F(TA) PROGRAM

CALCULATION OF RELATIONS BETWEEN CA, F(DA), F(TA), TA AND CAPACITY

DATA CONSIDERED FOR THIS RUN : COST OF CAPITAL : 0.1600 , INFLATION : 0.1000

TAP (0.4) 10-300 PAIRS. BETA ZERO : 48072.50 BETA ONE : 650.60

DA	F(DA)	F(TA)	TA	CAPACITY		DA	F(DA)	F(TA)	TA	CAPACITY
0.05	1477.79	1476.85	83.40	4.17	*	1.30	56.84	56.84	33.01	42.91
0.10	738.90	738.48	71.25	7.13	*	1.35	54.73	54.67	32.55	43.94
0.15	492.60	492.30	64.39	9.66	*	1.40	52.78	52.75	32.13	44.98
0.20	369.45	369.39	59.67	11.93	*	1.45	50.96	50.88	31.71	45.97
0.25	295.56	295.40	56.09	14.02	*	1.50	49.26	49.24	31.33	46.99
0.30	246.30	246.06	53.23	15.97	*	1.55	47.67	47.63	30.95	47.96
0.35	211.11	210.94	50.87	17.80	*	1.60	46.18	46.15	30.58	48.94
0.40	184.72	184.65	48.87	19.55	*	1.65	44.78	44.78	30.24	49.90
0.45	164.20	164.11	47.13	21.21	*	1.70	43.46	43.44	29.90	50.84
0.50	147.78	147.58	45.59	22.79	*	1.75	42.22	42.20	29.58	51.77
0.55	134.34	134.17	44.23	24.33	*	1.80	41.05	41.00	29.26	52.63
0.60	123.15	123.01	43.01	25.80	*	1.85	39.94	39.89	28.96	53.58
0.65	113.68	113.62	41.91	27.24	*	1.90	38.89	38.87	28.68	54.50
0.70	105.56	105.44	40.89	28.62	*	1.95	37.89	37.88	28.40	55.39
0.75	98.52	98.48	39.97	29.98	*	2.00	36.94	36.90	28.12	56.25
0.80	92.36	92.32	39.11	31.29	*	2.05	36.04	36.01	27.86	57.12
0.85	86.93	86.87	38.31	32.56	*	2.10	35.19	35.14	27.60	57.97
0.90	82.10	82.06	37.57	33.81	*	2.15	34.37	34.34	27.36	58.83
0.95	77.78	77.70	36.87	35.02	*	2.20	33.59	33.56	27.12	59.67
1.00	73.89	73.89	36.23	36.23	*	2.25	32.84	32.79	26.88	60.49
1.05	70.37	70.33	35.61	37.39	*	2.30	32.13	32.10	26.66	61.33
1.10	67.17	67.12	35.03	38.53	*	2.35	31.44	31.42	26.44	62.14
1.15	64.25	64.24	34.49	39.66	*	2.40	30.79	30.75	26.22	62.94
1.20	61.57	61.56	33.97	40.76	*	2.45	30.16	30.15	26.02	63.76
1.25	59.11	59.06	33.47	41.83	*	2.50	29.56	29.56	25.82	64.56

and from Equation (2.6). For example, in Table VII it can be seen that for a demand of one pair per year, the values of F(DA) and F(TA) are equal at TA = 36.23 years. This means that the optimal extent of extension for an annual demand of one pair, is 36.23 years. This result matches with the minimum value shown in the curve for one pair (1 Ps.) of Figure 6. Comparison shows conclusively that Equation (2.6) fulfills the necessary conditions for a minimum cost. Another use of this program is that it was used as a subroutine in several of the programs described later to calculate minimum costs.

Policies of Expansion For Optimal and Suboptimal Net Present Value (NPV) For Different Demand Values

After developing a simplified procedure to help in the decision making process regarding the primary and secondary cables capacity expansion problem, the next step was to perform a sensitivity analysis on the optimum, by varying the value of the extent of extension, τ. As observed when describing the program CURVES for a value of demand and for a pre-established cost greater than the optimal, there are two values of τ which give that cost. Using this basis, a program, PERCENT, was designed to perform the above mentioned sensitivity analysis. This program is listed in Table XX of Appendix G. Also, an example of the results of the program is shown in Table VIII.

For a specific value of annual demand, the program PERCENT yields tables which allow the network designer to read the values of the extent of extnesion that give the optimal policy, as well as the corresponding values of time and capacity of cable for different

TABLE VIII

EXAMPLE OF PRODUCT GIVEN BY THE PERCENT PROGRAM

VALUES OF TAU (INFERIOR AND SUPERIOR) AND THEIR CORRESPONDENT CAPACITY FOR A NPV GREATER THAN THE OPTIMAL, IN DIFFERENT PERCENTAGES, FOR THE GROUP OF CABLES : TAP (0.4) 10-300 PAIRS.

*** COST IN THOUSANDS ***				CORRESPONDENT VALUES FOR A DEVIATION FROM THE OPTIMAL COST, OF :											
ANNUAL DEMAND	O P T I M A L			1.0 PERCENTAGE				5.0 PERCENTAGE				10.0 PERCENTAGE			
	TAU	CAP.	COST	TLEFT	CAP.	TRIGHT	CAP.	TLEFT	CAP.	TRIGHT	CAP.	TLEFT	CAP.	TRIGHT	CAP.
0.1	71.3	7.1	22.9	56.3	5.6	92.3	9.2	43.0	4.3	130.9	13.1	35.6	3.6	173.1	17.3
0.2	59.7	11.9	24.8	48.4	9.7	74.3	14.9	37.8	7.6	98.5	19.7	31.7	6.3	122.7	24.5
0.3	53.2	16.0	26.4	43.6	13.1	65.2	19.6	34.4	10.3	84.2	25.3	29.0	8.7	102.4	30.7
0.4	48.9	19.5	27.9	40.4	16.1	59.5	23.8	32.1	12.8	75.7	30.3	27.1	10.8	90.9	36.3
0.5	45.6	22.8	29.3	37.8	18.9	55.2	27.6	30.1	15.0	69.6	34.8	25.5	12.7	82.8	41.4
0.6	43.0	25.8	30.7	35.8	21.5	51.8	31.1	28.6	17.2	65.0	39.0	24.2	14.5	77.0	46.2
0.7	40.9	28.6	32.0	34.1	23.9	49.1	34.4	27.3	19.1	61.5	43.0	23.1	16.2	72.5	50.7
0.8	39.1	31.3	33.2	32.6	26.1	46.9	37.5	26.1	20.9	58.5	46.8	22.2	17.8	68.7	55.0
0.9	37.6	33.8	34.5	31.4	28.2	45.0	40.5	25.2	22.6	56.0	50.4	21.4	19.2	65.8	59.2
1.0	36.2	36.2	35.7	30.2	30.2	43.4	43.4	24.3	24.3	53.8	53.8	20.6	20.6	63.0	63.0
1.5	31.3	47.0	41.2	26.2	39.3	37.3	56.0	21.0	31.5	46.1	69.2	17.9	26.9	53.9	80.9
2.0	28.1	56.2	46.4	23.5	47.0	33.5	67.0	18.9	37.8	41.5	83.0	16.0	32.0	48.3	96.6
2.5	25.8	64.5	51.3	21.6	54.0	30.8	77.0	17.3	43.3	38.2	95.5	14.7	36.8	44.4	111.0
3.0	24.0	72.1	56.0	20.0	60.1	28.8	86.5	16.0	48.1	35.6	106.9	13.6	40.9	41.4	124.3
3.5	22.6	79.1	60.5	18.8	65.8	27.2	95.2	15.0	52.5	33.6	117.6	12.7	44.5	39.2	137.2
4.0	21.4	85.6	64.9	17.8	71.2	25.8	103.2	14.2	56.8	31.8	127.2	12.0	48.0	37.2	148.8
4.5	20.4	91.8	69.2	16.9	76.1	24.6	110.7	13.5	60.8	30.4	136.8	11.4	51.3	35.6	160.2
5.0	19.5	97.6	73.5	16.2	81.1	23.5	117.6	12.8	64.1	29.3	146.6	10.8	54.1	34.3	171.6
5.5	18.8	103.2	77.6	15.6	85.6	22.6	124.1	12.3	67.4	28.2	154.9	10.4	57.0	33.0	181.3
6.0	18.1	108.6	81.7	14.9	89.4	21.9	131.4	11.8	70.8	27.3	163.8	9.9	59.4	32.1	192.6
6.5	17.5	113.6	85.7	14.4	93.5	21.3	138.3	11.4	74.0	26.5	172.1	9.6	62.3	31.1	202.0
7.0	16.9	118.6	89.7	13.9	97.6	20.5	143.8	11.0	77.3	25.7	180.2	9.2	64.7	30.1	211.0
7.5	16.5	123.5	93.6	13.6	101.7	20.1	150.5	10.7	80.0	25.1	188.0	9.0	67.2	29.5	221.0
8.0	16.0	128.0	97.5	13.1	104.8	19.4	155.2	10.3	82.4	24.4	195.2	8.6	68.8	28.8	230.4
8.5	15.6	132.6	101.4	12.8	108.8	19.0	161.5	10.0	85.0	23.8	202.3	8.4	71.4	28.2	239.7

deviations from the optimal cost. In Table VIII the deviations considered were 2, 5, and 10%. These percents are arbitrary and are provided to the program as data. A 10% allowance over the minimum was chosen in this research to demonstrate the methodology proposed. Therefore, when looking for a way of providing the policy to follow for a threshold value of demand and a stated maximum deviation from the minimum cost, tables such as Table VIII can provide the solution sought.

Nevertheless, for each type of cable the amount of tables generated for the most common range of values of demand is in the order of 15, so it was thought convenient to simplify the presentation of the results. This was achieved by building a nomogram that summarizes the values of those 15 or more tables into one figure. Nomograms for the four most commonly used types of cables in primary and secondary networks are shown in Figure 7 and Figures 17-19, Appendix D.

Implemented in these nomograms is the relation of the gain of subscribers, the percentage of occupation planned, and the corresponding annual demand of pairs. The relation between gain, percentage of occupation and demand of pairs will be explained later in this thesis when analyzing the sensitivity of the percentage of occupation and its effect on cost. For the moment it can be considered as though the nomograms were formed only by the five right-most scales.

As an example of the application of these nomograms, consider the case of having an annual demand of 25 pairs per year on a route of principal caller which must use cables of the type TAP(0.4). Twenty-five will be the threshold value to enter on scales "demand" of Figure 7. As can be seen, the two scales "demand" are identical. They were constructed in this manner in order to provide an easy way of

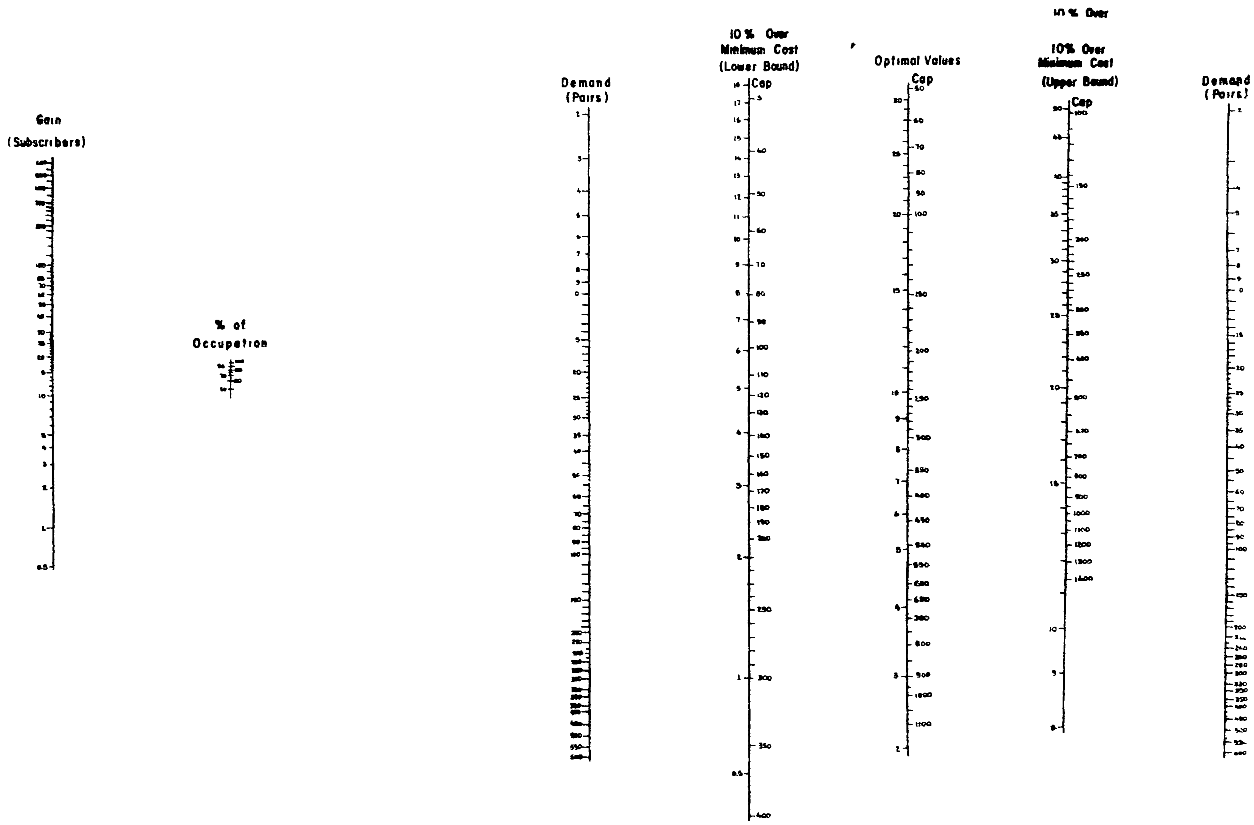


Figure 7. Extent of Extension for Primary Cables of the Type TAP(0.4) 100-2400 Pairs as a Function of the Annual Increment of Subscribers (Gain), the Percentage of Occupation and the Annual Demand of Pairs (da) Correspondent, Which Gives the Optimal Policy of Extension, and Variations Which Increment the Minimum Cost in 10%

reading the nomogram. So, by drawing a straight line between both "demand" scales at the desired value of demand (in this example 25), one can read at the same time the optimal policy on the scale "optimal values" and the policies that will yield a deviation of 10% over the minimum cost on the "lower bound" and "upper bound" scales. The scales labeled "lower bound" and "upper bound" were named in this manner because they correspond to the bounds on the extent of the extensions that provide the guarantee that the minimum cost will not be exceeded by some pre-specified percentage.

Getting back to the example, from Figure 7 it can be seen that for 25 pairs of demand, the optimal policy is to install a cable of 305 pairs each 12.2 years. For policies that raise the minimum cost by 10%, one can also read on Figure 7 that the installation should correspond to 570 pairs each 27.8 years or 154 pairs each 6.1 years, for the upper and lower bound, respectively. However, when making a decision the network designer would round the theoretical to practical values. For instance, the designer would choose 300, 600, and 150 pairs for the optimal, upper bound, and lower bound, respectively. For practicality, the error resulting from rounding is not significant. This can easily be proved by using the results given by the program CURVES or directly by evaluating the increase in cost from Figure 7.

If the policy given for the firm is to accept at most a deviation of the 10% over the minimum value, then the designer might choose an expansion plan involving a cable of 600 pairs. As will be explained later, there are other reasons to support the selection of the policy given by the upper bound over the selection of the policy given by the lower bound.

Net Present Value vs. Extent of Extension For Each Cable

An important aspect of telephone cable capacity planning is linked to the question of how related are the extent of extension using a specific cable and the associated net present value. That is, what is the cost of the policy of installing a specified cable every τ years. Equations (2.5) and (3.1) provide the means to analyze this relation.

For this purpose, a computer program CABLES, listed in Table XXI, Appendix G, was designed. The product of this program are tables, such as Table IX. In these tables, it is possible to read the net present value of the series of costs associated with expanding the capacity of the telephone cable netowrks, using cables of the type and capacity indicated in the heading of the table.

Figures 8 and 20-22, Appendix E, were constructed using the values obtained from the program CABLES. In these figures it can be seen that for small values of τ, the cost is high. Also, when τ increases, the present value decreases rapidly and then trends asymptotically to a final value. The information gained from the analysis of the relation between τ and the net present value of expanding the network allowed the calculation of the range of demands associated with an increment in cost over the minimum. This concept is explained later when describing the program BOUNDS.

TABLE IX

EXAMPLE OF THE VALUES GENERATED WITH THE PROGRAM CABLES

NET PRESENT VALUE OF THE SERIE OF COSTS ASSOCIATED WITH EXPANDING THE CAPACITY OF THE TELEPHONE CABLES NETWORK WITH CABLES OF THE TYPE : TAP (C.4) 10-300 PAIRS. , AT DIFFERENT TAU INTERVALS OF TIME.

*** NPV IS IN THOUSANDS, MONEY IS IN 1981 VALUE ***   CALCULATIONS MADE FOR A CABLE OF CAPACITY OF : 10 PAIRS.

VALUE OF THE PARAMETERS CONSIDERED FOR THIS RUN : COST OF CAPITAL : 0.16 ; MAINTENANCE : 0.05 ; BETA0 = 48073.
INFLATION : 0.10 ; DEFLATION : 0.15 ; BETA1 = 651.

TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV	TAU	NPV
0.1	10096.5	2.6	414.7	7.2	168.3	12.2	112.1	17.2	89.3	24.0	74.2	36.5	62.5
0.2	5061.7	2.7	400.3	7.4	164.6	12.4	110.9	17.4	88.7	24.5	73.5	37.0	62.2
0.3	3383.4	2.8	387.0	7.6	161.0	12.6	109.6	17.6	88.1	25.0	72.8	37.5	61.9
0.4	2544.3	2.9	374.7	7.8	157.7	12.8	108.4	17.8	87.5	25.5	72.1	38.0	61.7
0.5	2040.8	3.0	363.1	8.0	154.5	13.0	107.3	18.0	86.9	26.0	71.4	38.5	61.4
0.6	1705.2	3.2	342.2	8.2	151.5	13.2	106.1	18.2	86.3	26.5	70.8	39.0	61.2
0.7	1465.4	3.4	323.7	8.4	148.6	13.4	105.0	18.4	85.8	27.0	70.2	39.5	61.0
0.8	1285.6	3.6	307.3	8.6	145.9	13.6	104.0	18.6	85.2	27.5	69.6	40.0	60.7
0.9	1145.8	3.8	292.6	8.8	143.2	13.8	102.9	18.8	84.7	28.0	69.1	40.5	60.5
1.0	1034.0	4.0	279.4	9.0	140.7	14.0	102.0	19.0	84.2	28.5	68.6	41.0	60.3
1.1	942.4	4.2	267.5	9.2	138.4	14.2	101.0	19.2	83.7	29.0	68.1	42.0	59.9
1.2	866.2	4.4	256.6	9.4	136.1	14.4	100.0	19.4	83.2	29.5	67.6	43.0	59.5
1.3	801.6	4.6	246.7	9.6	133.9	14.6	99.1	19.6	82.7	30.0	67.1	44.0	59.2
1.4	746.3	4.8	237.7	9.8	131.8	14.8	98.2	19.8	82.2	30.5	66.7	45.0	58.9
1.5	698.4	5.0	229.3	10.0	129.8	15.0	97.4	20.0	81.7	31.0	66.2	46.0	58.6
1.6	656.5	5.2	221.6	10.2	127.9	15.2	96.5	20.2	81.3	31.5	65.8	48.0	58.0
1.7	619.5	5.4	214.5	10.4	126.0	15.4	95.7	20.4	80.8	32.0	65.4	50.0	57.5
1.8	586.6	5.6	207.9	10.6	124.2	15.6	94.9	20.6	80.4	32.5	65.1	52.0	57.1
1.9	557.2	5.8	201.7	10.8	122.5	15.8	94.2	20.8	80.0	33.0	64.7	54.0	56.7
2.0	530.7	6.0	196.0	11.0	120.9	16.0	93.4	21.0	79.6	33.5	64.3	56.0	56.4
2.1	506.7	6.2	190.6	11.2	119.3	16.2	92.7	21.5	78.6	34.0	64.0	60.0	55.8
2.2	485.0	6.4	185.6	11.4	117.8	16.4	92.0	22.0	77.6	34.5	63.7	70.0	54.8
2.3	465.1	6.6	180.9	11.6	116.3	16.6	91.3	22.5	76.7	35.0	63.4	80.0	54.3
2.4	446.9	6.8	176.4	11.8	114.9	16.8	90.6	23.0	75.8	35.5	63.0	90.0	53.9
2.5	430.1	7.0	172.2	12.0	113.5	17.0	89.9	23.5	75.0	36.0	62.8	100.0	53.7

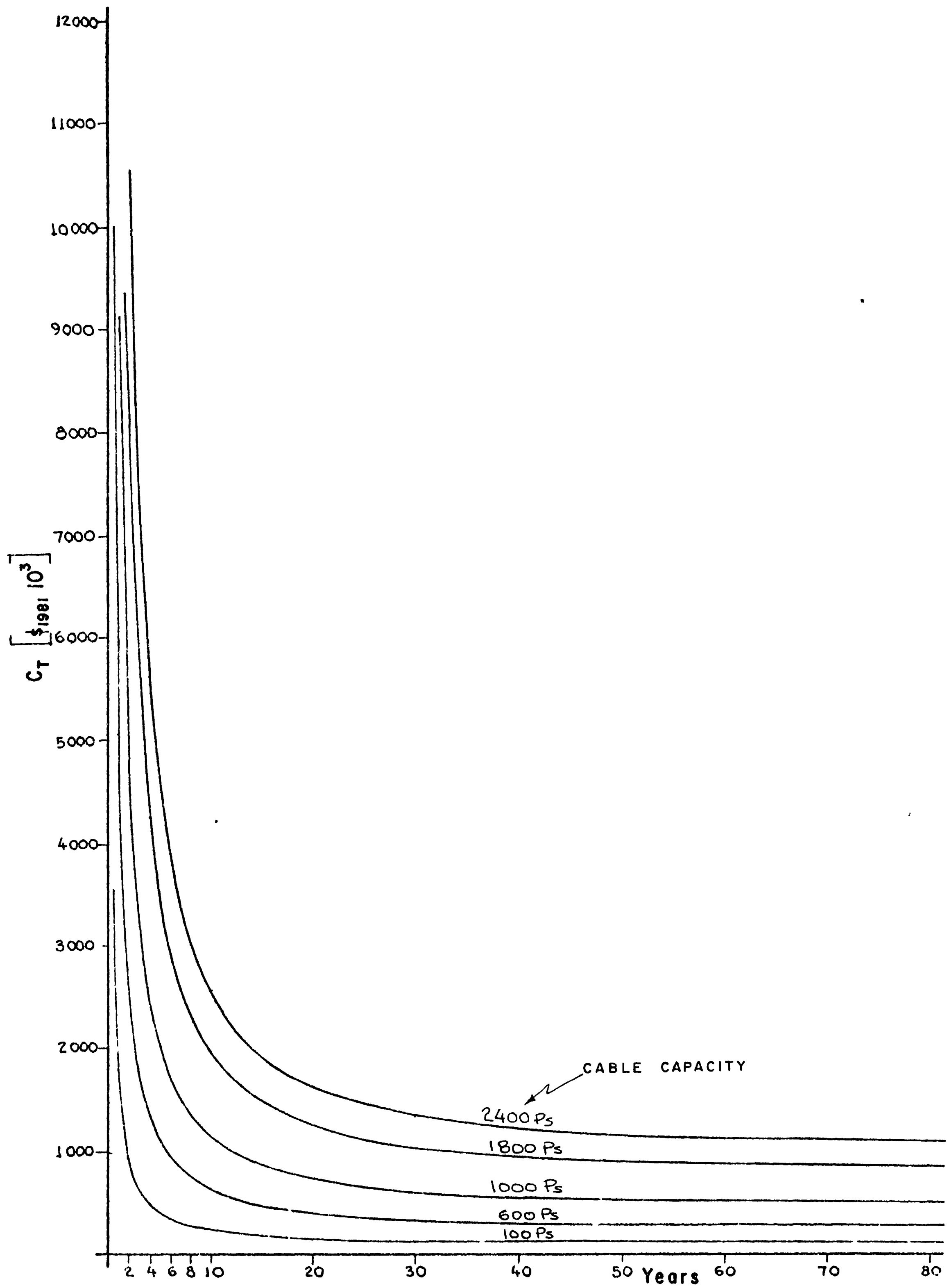


Figure 8. Net Present Value (NPV) vs. Time Between Installations of Primary Cables of the Type TAP(0.4) 100-2400 Pairs

Range of Demand Values to Produce a Net Present Value Which is at Most a Pre-Specified Percent Over the Minimum

Perhaps the uncertainty of demand is the factor that contributes most significantly to making capacity expansion a very difficult problem. If the future additional capacity needs were known with certainty, the network planner could simply apply an optimal policy like that dictated by Equation (2.6). Unfortunately, this is not the case in a real situation. In reality only an estimate of demand is known; therefore, there will be an error or an unknown deviation.

At the moment of decision making, it would be very convenient for the network designer to be able to evaluate what would be the cost of protecting a desired deviation from the original estimation. After the decision is made, the cost of installation becomes a burden cost, and the question to answer is what will be the real cost of this policy if the real demand differs from the original estimate.

To answer this question, two possible cases must be analyzed: (1) the real demand result was smaller than estimated, and (2) the demand was greater than estimated. In the first case, the implication is that the cable will last longer than planned and a penalty cost will be paid as opportunity cost. In the second case, the cable will last a shorter time than planned, so the cost will be increased. As can be seen in Figures 8 and 20-22 in Appendix E, as τ becomes smaller the cost increases. It is clear that the worst situation is that in which the real result was greater than expected, since this implies the installation of another cable. This is not the case when the real result was a smaller demand, since the cable will last longer, and it will not be necessary to install another cable. Both cases are undesirable, but the network designer must be more concerned with the case in which the result was greater than projected.

To evaluate this situation, a program, BOUND, was designed. The logic of this program is: Given a threshold value of demand, to attain the optimal policy a correspondent optimal cable is selected, then given a pre-specified maximum deviation from the minimum cost, the matching demand for that cost over the minimum is calculated. In a graphical way this corresponds in Figure 9 of going from point 1 to point 2 to point 3, and finally to points 4 and 5. In other words, for the example shown in Figure 9, the procedure is as follows: For a demand of 10 pairs per year it is determined (using Equation (2.6)) that the optimal policy is to install every 14.9 years, a cable of 150 pairs which will produce a minimum cost, C_1*, of 231.7 x 10^3 monetary units. But since the firm is willing to accept a deviation of 10% over the minimum, then it can be acceptable to incur a cost of 1.1 x C_0* or 254.1 x 10^3 monetary units, which corresponds to using a cable of 150 pairs and incurring an annual demand of 11.4 pairs per year. In other words, the cable will last 13.1 years and not the 14.9 years originally calculated.

The program BOUND is listed in Table XXII in Appendix G. Table X is an example of output from this program. The result provided by this program gives a way of calculating the range of demand values to guarantee that when installing a specific cable the maximum deviation from the minimum cost will be a pre-accepted percentage. For instance, from Table X it can be seen that for a cable of 100 pairs and a maximum allowed deviation from the minimum cost of 5%, the demand does not have

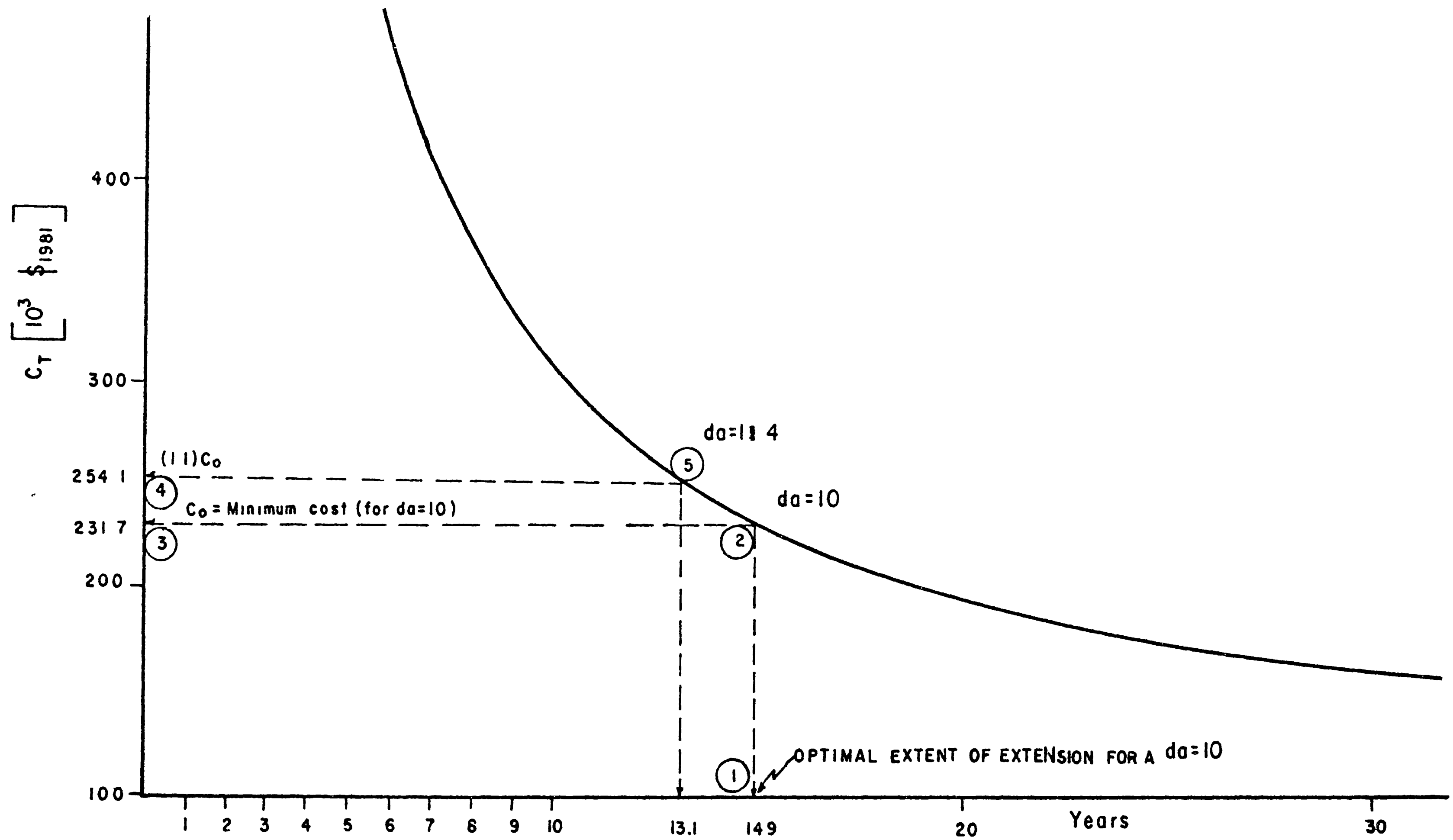


Figure 9. Net Present Value of Extension With a Cable of 150 Pairs of the Type TAP(0.5), vs. Estent of Extension

TABLE X

EXAMPLE OF VALUES GENERATED BY THE PROGRAM BOUND

CALCULATION OF DEMANDS AND CORRESPONDENT STAGE OF EXTENSION (TAU) TO PRODUCE A NET PRESENT VALUE WHICH IS GREATER THAN THE MINIMUM COST BY THE INDICATED PERCENTAGES, FOR THE GROUP OF CABLES : TAP(0.4) 10-300 PAIRS.

CABLE OF (PAIRS)	VALUES THAT GIVE OPTIMAL POLICY FOR THIS CABLE		VALUE OF DEMAND (UPPER BOUND) AND CORRESPONDENT TAU THAT INCREASE THE MINIMUM COST BY 5.%		10.%		25.%		50.%		75.%		100.%		150.%	
	DEMAND	TAU	DEMAND	TAU	DEMAND	TAU	DEMAND	TAU	DEMAND	TAU	DEMAND	TAU	DEMAND	TAU	DEMAND	TAU
10.	0.16	62.63	0.21	47.54	0.25	39.63	0.36	27.90	0.51	19.44	0.66	15.12	0.81	12.42	1.09	9.20
20.	0.41	48.39	0.50	39.84	0.58	34.45	0.79	25.27	1.11	18.00	1.42	14.12	1.72	11.66	2.32	8.68
30.	0.75	29.96	0.87	24.31	0.99	20.22	1.31	22.93	1.81	16.64	2.28	13.16	2.75	10.92	3.68	8.17
40.	1.17	34.33	1.33	30.17	1.48	27.05	1.92	20.92	2.60	15.41	3.26	12.28	3.91	10.23	5.21	7.69
50.	1.65	30.21	1.86	26.95	2.05	24.40	2.61	19.20	3.49	14.32	4.36	11.48	5.23	9.60	6.93	7.25
60.	2.22	27.04	2.46	24.37	2.70	22.23	3.39	17.72	4.50	13.36	5.59	10.77	6.67	9.03	8.77	6.85
70.	2.86	24.51	3.15	22.25	3.43	20.41	4.27	16.44	5.62	12.51	6.92	10.13	8.22	8.52	10.83	6.48
80.	3.57	22.43	3.92	20.48	4.25	18.87	5.23	15.33	6.82	11.75	8.39	9.55	9.96	8.06	13.04	6.15
90.	4.35	20.69	4.75	18.98	5.13	17.55	6.27	14.36	8.15	11.07	10.01	9.03	11.85	7.64	15.53	5.84
100.	5.21	19.21	5.66	17.69	6.11	16.40	7.43	13.50	9.56	10.46	11.68	8.56	13.86	7.26	18.14	5.56
110.	6.13	17.94	6.65	16.56	7.15	15.39	8.67	12.73	11.13	9.92	13.52	8.14	15.97	6.91	20.81	5.31
120.	7.13	16.82	7.73	15.57	8.29	14.50	9.98	12.05	12.73	9.43	15.54	7.76	18.26	6.59	23.65	5.08
130.	8.21	15.84	8.85	14.70	9.49	13.71	11.41	11.43	14.54	8.98	17.58	7.40	20.66	6.30	26.84	4.86
140.	9.35	14.97	10.09	13.91	10.79	13.00	12.88	10.88	16.43	8.57	19.79	7.08	23.24	6.04	30.28	4.66
150.	10.57	14.20	11.37	13.21	12.15	12.36	14.50	10.37	18.30	8.20	22.24	6.78	26.11	5.79	33.75	4.48
160.	11.86	13.50	12.75	12.58	13.62	11.78	16.17	9.91	20.39	7.86	24.63	6.51	28.85	5.56	37.25	4.31
170.	13.22	12.86	14.21	12.00	15.16	11.25	17.97	9.49	22.63	7.54	27.37	6.26	32.00	5.35	41.34	4.15
180.	14.65	12.29	15.74	11.48	16.77	10.77	19.81	9.10	24.87	7.25	30.07	6.03	35.04	5.16	45.15	4.01
190.	16.16	11.76	17.34	11.00	18.43	10.33	21.81	8.75	27.30	6.98	32.98	5.81	38.30	4.98	49.22	3.87
200.	17.73	11.28	19.00	10.56	20.25	9.92	23.87	8.42	29.95	6.73	35.85	5.61	41.85	4.81	53.64	3.74

to exceed 5.66 pairs per year. From Table X it can also be seen that the optimal cost will be obtained if the annual demand is for 5.2 pairs per year. That is, the cost for this example will be between the optimum and a cost that is 5% greater, provided that the demand is $5.2 \le da \le 5.66$. In the following pages an approach will be presented to evaluate the net present value associated with protecting a desired level of uncertainty in the demand.

CHAPTER IV

STOCHASTIC NATURE OF THE DEMAND AND ITS EFFECTS ON POLICIES OF EXPANSION

A general consensus of the people involved in capacity expansion planning is that the level of success in this activity depends mainly on the completeness of the information available at the time of making a decision regarding how to invest the resources available for expanding the capacity of a plant. As mentioned previously, the information related to the future needs of additional capacity is believed to be the most difficult to obtain, due to its stochastic nature. It is so difficult to handle this aspect that the usual procedure followed for most of the researchers working with capacity expansion is to assume that demand is deterministic.

Since it is not possible with the present capabilities of analysis to predict with certainty the outcome of future events, at least it is desirable to evaluate the cost of protecting certain levels of that outcome. That is, in terms of this research, it would be desirable to quantify the cost of providing a capability in the telephone network such that only a pre-established percent of the new subscribers will not be provided with service because of lack of enough capacity. This aspect is carefully considered by most management of telephone systems, and it is customary that a great amount of resources are applied to obtain the best information possible regarding future needs.

Nevertheless, it is common that most post mortem analyses display discouraging results when comparing what was constructed based on those predictions with what was the real outcome. In the following two sections, a proposal will be presented on how to evaluate the cost of protecting a desired level of uncertainty in the demand.

Analysis of the Estimated and the Resulting Real Demand

The usual procedure followed by most administrations of telephone companies is to delegate the function of forecasting the demand to a specialized group of people, generally in the area of commercial duties. These forecasted needs are then given to the technical people for their use in the planning and construction of additions to the telephone plant. In Mexico, this is the procedure followed, and data gathered from Mexico was used to present the approach described in this thesis.

The analysis procedure was to first identify the way in which the predictions were made, and second to analyze what was the real outcome. So, data was collected on how many times an increment of one, two, three, etc., new subscribers were predicted. The histogram in Figure 10 depicts this information. Similarly, the histograms of Figures 23-27 shown in Appendix I, were constructed for the real increment of new subscribers. With these histograms, the next step was to visualize the shape of the distribution of the predictions and the real outcomes. It was hypothesized that both predicted and real demands of the data follow a normal distribution. This was confirmed by using the Kolmogorov-Smirnov Test-of-good-fitness implemented in the Statistical Analysis System (SAS). Figure 11 was drawn to visually

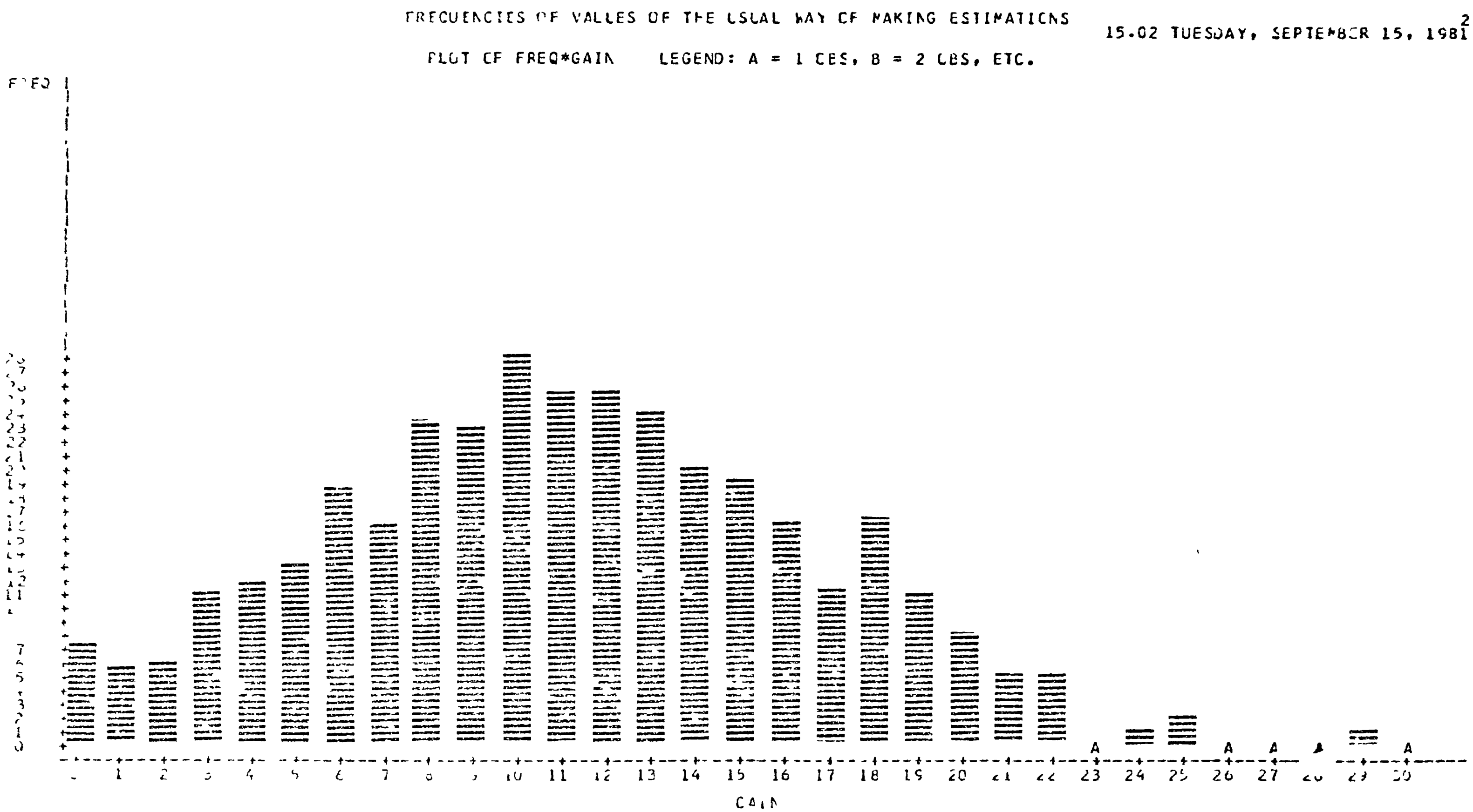


Figure 10. Frequencies of Values of the Usual Way of Making Estimations

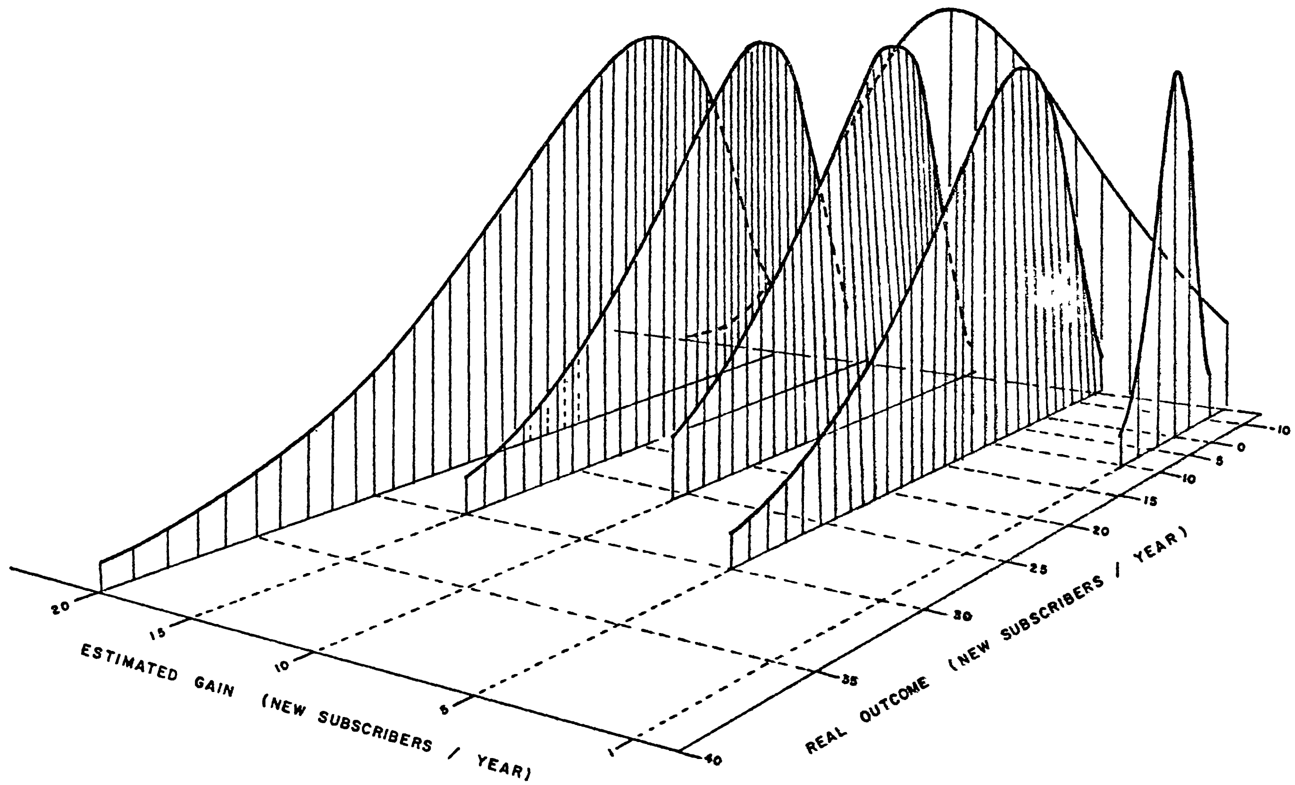


Figure 11. Distribution of Estimated and Real Annual Gain of New Subscribers

depict these results. Table XI shows the parameters calculated for these distributions.

TABLE XI

PARAMETERS OF THE DISTRIBUTION OF ESTIMATED AND REAL ANNUAL GAIN OF NEW SUBSCRIBERS

Distribution for	Mean μ	Std. Deviation σ
Estimated gain	11.18	5.38
Real gain when one new subscriber was estimated	0.11	4.69
Real gain when five new subscribers were estimated	4.71	10.15
Real gain when ten new subscribers were estimated	5.82	10.60
Real gain when fifteen new subscribers were estimated	9.04	10.08
Real gain when twenty new subscribers were estimated	11.94	11.68

Cost Associated With a Policy of Expansion to Provide Protection For a Desired Level of Uncertainty on the Resulting Real Demand

Once the distributions of the estimated and real demand were identified, the next step consisted in linking these results with the cost of different policies of expansion to protect a desired level of the possible real outcomes. Since at this point of the research, it was known how to evaluate optimal and suboptimal policies and associated costs, a program UNCERT (listed in Table XXIII of Appendix G) was designed to calculate costs associated with different values of uncertainty.

The logic followed in the program UNCERT was to first calculate for the threshold demand--in this case, the predicted value--the minimum cost associated with that threshold value of demand. In this program, the optimal cost for the threshold demand was CMIN. The following step consisted of calculating for every integer value in the distribution of the assumed real outcomes, the correspondent optimal cost, which was RCMIN, for that value of demand. Next the program calculated the percent that RCMIN attained over the minimum CMIN. Also, since the distribution of the outcomes were known, the level of uncertainty matching each value in the distribution was calculated and included as part of the result. The resulting product of this program is shown in Table XII.

It is pertinent to mention here a comment on the shape of the distribution of the demands estimated and their associate real outcomes. The conclusion is that even though it is known that the demand on telephone service is discrete in value, the error of considering the distribution as continuous is not significant. The author strongly believes in this fact and agrees with Naddor [32] that in cases like the one treated in this research, the shape and nature of discreteness of the random variable will not alter drastically the conclusions of

TABLE XII

EXAMPLE OF VALUES GENERATED BY THE PROGRAM UNCERT

RELATION BETWEEN THE COST OF AN EXPANSION POLICY FOR A NETWORK WITH CABLES OF THE TYPE : ASP(0.4) 10-300PS.
TO SECURE THE UNCERTANITY LEVELS SHOWN, FOR A THRESHOLD ESTIMATED DEMAND OF : 5.0 PAIRS.

REAL DEMAND	CORRESPONDENT LEVEL OF UNCERTANITY	OPTIMAL COST (RCMIN) FOR THIS REAL DEMAND (THOUSANDS OF 1980S MEXICAN PESOS)	% (RCMIN) IS OVER THE MINIMUM COST CORRESPONDENT TO AN OPTIMAL POLICY FOR THIS THRESHOLD DEMAND
1.0	34.601	2.83	-56.89
2.0	37.916	3.87	-40.90
3.0	41.322	4.62	-26.51
4.0	44.794	5.70	-12.97
5.0	48.307	6.55	0.00
6.0	51.833	7.38	12.57
7.0	55.345	8.18	24.84
8.0	58.816	8.97	36.85
9.0	62.219	9.74	48.67
10.0	65.529	10.51	60.32
11.0	68.725	11.26	71.82
12.0	71.785	12.01	83.20
13.0	74.654	12.74	94.46
14.0	77.437	13.48	105.63
15.0	80.003	14.20	116.71
16.0	82.385	14.92	127.71
17.0	84.580	15.64	138.64
18.0	86.585	16.35	149.57
19.0	88.403	17.06	160.30
20.0	90.040	17.76	171.05
21.0	91.500	18.47	181.74
22.0	92.794	19.16	192.35
23.0	93.932	19.86	202.99
24.0	94.924	20.55	213.55

the results. As Naddor [32] proved, the values of importance are the values of the mean and the variance of the distributions.

CHAPTER V

AN OVERVIEW OF THE EFFECT OF CHANGE IN TECHNOLOGY OVER THE POLICY OF CAPACITY EXPANSION OF PRIMARY AND SECONDARY TELEPHONE CABLES

The action of making predictions of future events like the forecasting of the effects of technological change of primary and secondary telephone network, is not and probably never will be an exact science. However, the utilization of some present techniques raises the opportunity of improving the reliability in this forecasting activity.

The most common mathematical model for forecasting technological substitution considers the case where a new product or technology replaces the old product over a period of time. The form in which this process of substitution is generally characterized is by a slow initial rise followed by a more rapid growth up to a point in which the rate of growth decreases as it approaches a value of saturation. The first to point out this pattern of growth were Raymond Pearl and Reed [33] in 1924, when observing some biological phenomena. They represented this growth by the S-shaped curve (see Figure 12) now known as the Pearl or logistic curve.

Pearl and Reed's observations led them to postulate the logistics growth law:

$$\frac{dN}{dt} = kN\left(1 - \frac{N}{M}\right) \tag{5.1}$$

where k is constant, M is the upper bound on population, N is the number of individuals at a certain point of time, and $1 - \frac{N}{M}$ represents the action of environmental resistance. That is, as N trends to M, the growth rate approaches zero. The assertion that the shape of substitution tends to follow the Pearl curve has been supported by numerous empirical evidence. For instance, see Sharif and Kabir [39], Blackman [3], and others in the journal Technological Forecasting and Social Change.

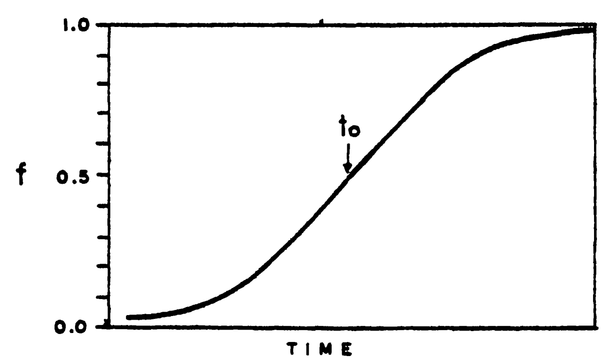


Figure 12. Pearl or Logistic Curve

Fisher and Pry [18], using the Pearl curve as a model for underlying the substitution of technology, transformed Equation (5.1) into the form:

$$\frac{df}{dt} = kf(1 - f), \tag{5.2}$$

where f is the fraction of the market captured by the new product, t is the time, and k is a constant defined as the annual growth rate of the fractional market share of the new product during the first few years of substitution (obtained from historical data). If t_0 denotes the time at which the fractional substitution reaches midpoint, then, f = 0.5. Integrating Equation (5.2), the logistic curve Equation (5.3) is obtained:

$$\frac{1}{1 - f} = \exp k\ (t - t_0) \tag{5.3}$$

Equation (5.3) represented on semilog paper has a linear form as can be seen in Figure 13. With this background, it is reasonable to state as an hypothesis that the substitution of the multipair telephone cable by another technology will follow the model used by Fisher and Pry. At present the new technology that may replace the multipair cable is optical fibers which permits sending of a large number of circuits using a single fiber.

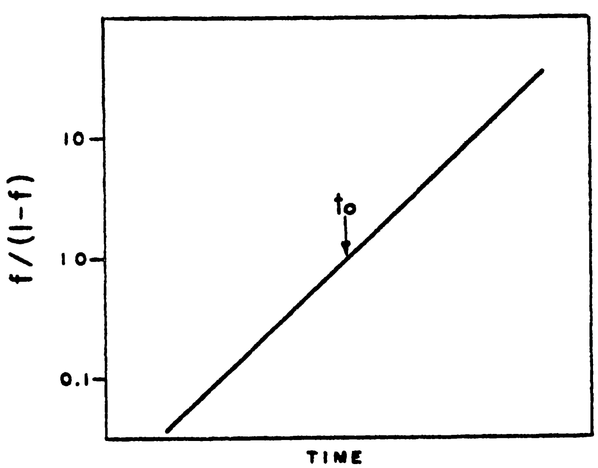


Figure 13. General Form of the Fisher and Pry Substitution Model Function

From the experience documented in the literature regarding the transition from one technology, the slope of the curve before the first inflection point is rather flat. This reflects the fact that during the initial years, the new technology must overcome the lack of knowledge, resistance of consumers, sustain contract arrangements based on the old technology, overcome high cost due to small production, and resolve problems of developing, installing, testing, and learning to use the new product. In the latter phases of the substitution, the change increases as the product becomes accepted, economies of scale are achieved, and the learning period comes to an end. This process usually takes a longer period of time in places where resources are more limited, as in the case of developing countries like Mexico.

The usage of optical fibers was proposed some 40 years ago. At the present time this technology still has serious practical problems. At the moment, they are being tested in trunk circuits between urban telephone exchanges. This is because this new technology requires sophisticated equipment at the transmission and reception points and telephone exchange buildings provide good protection for such equipment. In addition, telephone exchanges are places where a large amount of circuits start and/or end. This is not the case in primary or secondary networks where one of the transmission/reception points is the telephone exchange and the other side of the circuit is formed by thousands of transmitters/receivers; that is, the telephone set itself.

For these reasons, the author of this thesis believes that it will take some time for this technology to take over the primary and secondary cables. Another reason to support this thinking is that in primary and secondary networks the number of branches and their tree-like configuration will require solving the problem of making this multiseparation of circuits in each branch. The probelm of separating circuits on a branch complicates the change of technology due to the usual constant requirements of the tree configuration as a normal activity in the expanding process. Experience in changes of technology in telephone networks has shown that this change is more difficult when dealing with multipair telephone cables. This can be supported by historical cases of digital transmission using existing cables and the use of coaxial cables. The concepts of these new technologies--digital transmission and coaxial cables--began conceptually at the beginning of the century, and even now are not in common usage in primary and secondary cables. These two new technologies are struggling to capture the long distance and trunk networks.

Even though the conditions are "unfavorable" for a rapid change in the technology used in primary and secondary networks, we should continuously observe technological advances in optical transmission or any other new technology. This observation will allow us to be prepared and to make the appropriate adjustments in the decision making process concerning capacity expansion in primary and secondary cables. In this research, this progress was observed by building a good record of the progress of these possible changes. This was done by plotting on semilogarithmic paper points in time and their corresponding penetration of the new technology into the market of primary and secondary networks. Then, using some method like that described by the model of Fisher and Pry, calculate the span of time, $t_o - t$. When the optimal time of extension (determined by the methodology proposed in this thesis) is greater than $t_o - t$, it is time to make a detailed analysis and see if installing cables which will last less than the time calculated as optimal is justified.

A final observation regarding change of technology in multipair cables pertains to the case of a small annual demand. In this case the augmentations must last longer; conversely, for greater demands, the extent of extension must be shorter. This observation suggests that for small demands the change of technology apparently must take place first in networks with cables of small capacities. Paradoxically it is in this part of the network where the arrangements due to normal expansion process are more frequent, a fact that will cause a greater reluctance to making changes. On the other hand, for larger demands, the cables have a greater capacity and their optimal extent of extension must last a shorter time, so it seems that changes in new technology may take place first in primary rather than in secondary cables.

CHAPTER VI

EFFECT OF INFLATION ON OPTIMAL POLICY

Inflation is a major concern in any financial adventure, and its influence must be analyzed carefully to avoid consequences which may be catastrophic from the economic point of view. In the present case of planning the capacity expansion of the telephone plant, this is true and for that reason an analysis of the influence of inflation on the optimal policy was thought to be appropriate to include in this thesis. Consequently, a program called INFLA listed in Table XXIV of Appendix G was designed and used to perform sensitivity analyses condidering inflation.

The logic of INFLA is to first calculate for a given value of ρ [$\rho = (1 + R)/(1 + r)$] the correspondent optimal cost C*. This term will be used as a basis to compare values of C, and C* will also be used to compare the various values of C. INFLA was used to study the effect of changing (all other parameters kept constant) on the optimal cost. By varying the value of the ratio ρ below and above a fixed threshold ρ^*, for which, using Equation (2.6), its correspondent C* was calculated.

A summary of results taken from tables like Table XIII, which is an example of the product generated by INFLA, is presented in Table XIV. As can be observed from Table XIV, by varying ρ the cost presents two kinds of behavior. To discuss these results, define:

$$\rho^{(-)} < \rho^* < \rho^{(+)} ,$$

TABLE XIII

EXAMPLE OF THE PRODUCT OF PROGRAM INFLA

RELATION BETWEEN THE COST OF AN EXPANSION POLICY FOR A NETWORK OF THE TYPE : TA(0.4) 10-300 PAIRS.
AND DIFFERENT VALUES OF THE RATIO RHO = (1. + INFLA) / (1. + INTER)
IN THIS RUN, THE VALUE OF RHO TAKEN AS BASIS, WAS 0.9483 , WITH A MINIMUM COST(CMIN) OF 24064.7
OTHER CONSTANTS CONSIDERED ARE : DEMAND = 0.2 TAU OPTIMAL = 83.8 .

RHO	COST(CINF) FOR THIS VALUE OF RHO	% CINF IS OVER CMIN
0.1000	8594.	-64.3
0.2000	8594.	-64.3
0.3000	8594.	-64.3
0.4000	8594.	-64.3
0.5000	8594.	-64.3
0.6000	8594.	-64.3
0.7000	8595.	-64.3
0.8000	8665.	-64.0
0.8100	8698.	-63.9
0.8200	8744.	-63.7
0.8300	8810.	-63.4
0.8400	8903.	-63.0
0.8500	9036.	-62.5
0.8600	9224.	-61.7
0.8700	9496.	-60.6
0.8800	9865.	-59.0
0.8900	10396.	-56.8
0.9000	11150.	-53.7
0.9050	11641.	-51.6
0.9100	12229.	-49.2
0.9150	12936.	-46.2
0.9200	13790.	-42.7
0.9250	14828.	-38.4
0.9300	16096.	-33.1
0.9350	17661.	-26.6

TABLE XIII (Continued)

RELATION BETWEEN THE COST OF AN EXPANSION POLICY FOR A NETWORK OF THE TYPE : TAF(0.4) 10-300 PAIRS.
AND DIFFERENT VALUES OF THE RATIO RHO = (1. + INFLA) / (1. + INTER)
IN THIS RUN, THE VALUE OF RHO TAKEN AS BASIS, WAS 0.9463 , WITH A MINIMUM COST(CMIN) OF 24064.7
OTHER CONSTANTS CONSIDERED ARE : DEMAND = 0.2 TAU OPTIMAL = 63.6

RHO	COST(CINF) FOR THIS VALUE OF RHO	% CINF IS OVER CMIN
0.9400	19612.	-18.5
0.9450	22080.	-8.2
0.9500	25256.	4.9
0.9550	29438.	22.3
0.9600	35108.	45.9
0.9650	43096.	79.1
0.9700	54954.	128.4
0.9750	73837.	206.8
0.9800	107147.	345.2
0.9850	175976.	631.2
0.9900	363633.	1411.1
0.9910	441024.	1732.7
0.9920	546200.	2178.0
0.9930	703044.	2821.5
0.9940	939353.	3803.4
0.9950	1327461.	5416.2
0.9960	2034958.	8356.2
0.9970	3548360.	14645.1
0.9980	7829016.	32433.2
0.9985	13780460.	57164.2
0.9986	15788280.	65507.7
0.9987	18274700.	75839.9
0.9988	21403150.	88840.0
0.9989	25421340.	105537.5
0.9990	30699320.	127465.9

TABLE XIV

SUMMARY OF A SAMPLE OF RESULTS GENERATED WITH PROGRAM INFLA

Deviations From the Minimum Cost, For the Threshold Values of ρ* and Capacity Cables Shown When Varying ρ

ρ	ρ* = 0.9483		ρ* = 0.7000		ρ* = 0.4000	
	10 Ps.	100 Ps.	10 Ps.	100 Ps.	10 Ps.	100 Ps.
0.1000	-64.3	-76.4	-3.4	-36.0	-3.4	-30.8
0.2000	-64.3	-76.4	-3.4	-36.4	-3.1	-23.3
0.3000	-64.3	-76.4	-3.4	-33.9	-2.3	-13.4
0.4000	-64.3	-76.4	-3.4	-31.0	0.0	0.0
0.5000	-64.3	-76.4	-3.3	-25.8	4.7	18.9
0.6000	-64.3	-76.4	-2.6	-17.7	13.9	47.5
0.7000	-64.3	-76.3	0.0	0.0	32.0	95.3
0.8000	-64.0	-75.8	10.0	35.7	72.4	191.3
0.8500	-62.5	-74.0	24.0	73.4	115.9	289.9
0.9000	-53.7	-64.7	60.1	151.2	213.8	506.3
0.9350	-26.6	-33.9	138.2	324.6	410.7	331.2
0.9500	4.9	6.6	223.1	503.1	620.9	1384.4
0.9600	45.9	64.5	332.9	733.8	892.6	1970.6
0.9700	128.4	192.2	556.4	1205.2	1447.4	3169.9
0.9800	345.2	563.0	1153.6	2474.1	2939.2	6406.2
0.9850	631.2	1086.8	1949.9	4177.9	4940.4	10760.3
0.9900	1411.1	2591.9	4138.3	8890.0	10470.4	22823.1
0.9920	2178.0	4120.8	6300.3	13565.3	15954.2	34805.4
0.9950	5416.2	10764.0	15464.4	33460.4	39278.1	85849.4

where ρ^* is a fixed value of ρ for which an optimal cost C* is calculated using Equation (2.6). From Table XIV it can be seen that below ρ^*, C* is improved. That is, the cost corresponding to a value of $\rho^{(-)}$ is lower than C*, the "optimal." When $\rho^{(-)}$ decreases from ρ^*, the differential savings in cost first decreases a relatively small percentage below C*; after which, it remains practically constant. It can be observed that beyond a value of $\rho^{(-)}$ no further savings are obtained. On the other hand, when ρ^+ goes above ρ^*, the value of C* increases sharply. The marginal cost for values of $\rho^{(+)}$, as Table XIII shows, grows very rapidly. The behavior described has the same form for calculation made for cables of different capacities but the effect of ρ^* on C* is more significant for cables of larger capacities. All this suggests that when dealing with financial investments in capacity expansion of primary and secondary cables, the aspect that must be observed carefully is to avoid letting ρ grow beyond ρ^*, especially when planning the installation of cables of large capacities.

The influence of inflation, as incorporated in the model presented here, is linked with the cost of capital. That is, ρ is not only controlled by the value of the inflation but also by the cost of the capital. In the complex economic system in which a telephone company is involved, it is known that all the relations among the components of the economic system are governed by interactions which must be respected. Failing to do so, may cause serious trouble to the firm.

One consequence is that the firm must be prepared to react accordingly to the variations in inflation. If the inflation raises, the cost of capital must be also set accordingly to a value which guarantees no deterioration of the well being of the company. Table XV

TABLE XV

SOME VALUES OF THE RATIO (1 + INFLATION RATE)/(1 + COST OF CAPITAL)

VALUES OF THE RATIO (1. + INFLATION RATE) / (1. + COST OF CAPITAL)

VALUES OF THE RATIO (1. + INFLATION RATE) / (1. + COST OF CAPITAL)

INFLATION RATE

COST OF CAPITAL	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
0.05	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.10	0.5000	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.15	0.3333	0.6667	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.20	0.2500	0.5000	0.7500	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.25	0.2000	0.4000	0.6000	0.8000	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.25	0.2000	0.4000	0.6000	0.8000	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.30	0.1667	0.3333	0.5000	0.6667	0.8333	******	******	******	******	******	******	******	******	******	******	******	******	******	******
0.35	0.1429	0.2857	0.4286	0.5714	0.7143	0.8571	******	******	******	******	******	******	******	******	******	******	******	******	******
0.40	0.1250	0.2500	0.3750	0.5000	0.6250	0.7500	0.8750	******	******	******	******	******	******	******	******	******	******	******	******
0.45	0.1111	0.2222	0.3333	0.4444	0.5556	0.6667	0.7778	0.8889	******	******	******	******	******	******	******	******	******	******	******
0.50	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000	******	******	******	******	******	******	******	******	******	******
0.55	0.0909	0.1818	0.2727	0.3636	0.4545	0.5455	0.6364	0.7273	0.8182	0.9091	******	******	******	******	******	******	******	******	******
0.60	0.0833	0.1667	0.2500	0.3333	0.4167	0.5000	0.5833	0.6667	0.7500	0.8333	0.9167	******	******	******	******	******	******	******	******
0.65	0.0769	0.1538	0.2308	0.3077	0.3846	0.4615	0.5385	0.6154	0.6923	0.7692	0.8462	0.9231	******	******	******	******	******	******	******
0.70	0.0714	0.1429	0.2143	0.2857	0.3571	0.4286	0.5000	0.5714	0.6429	0.7143	0.7857	0.8571	0.9286	******	******	******	******	******	******
0.25	0.0714	0.1429	0.2143	0.2857	0.3571	0.4286	0.5000	0.5714	0.6429	0.7143	0.7857	0.8571	0.9286	******	******	******	******	******	******
0.75	0.0667	0.1333	0.2000	0.2667	0.3333	0.4000	0.4667	0.5333	0.6000	0.6667	0.7333	0.8000	0.8667	0.9333	******	******	******	******	******
0.80	0.0625	0.1250	0.1875	0.2500	0.3125	0.3750	0.4375	0.5000	0.5625	0.6250	0.6875	0.7500	0.8125	0.8750	0.9375	******	******	******	******
0.85	0.0588	0.1176	0.1765	0.2353	0.2941	0.3529	0.4118	0.4706	0.5294	0.5882	0.6471	0.7059	0.7647	0.8235	0.8824	0.9412	******	******	******
0.90	0.0556	0.1111	0.1667	0.2222	0.2778	0.3333	0.3889	0.4444	0.5000	0.5556	0.6111	0.6667	0.7222	0.7778	0.8333	0.8889	0.9444	******	******
0.95	0.0526	0.1053	0.1579	0.2105	0.2632	0.3158	0.3684	0.4211	0.4737	0.5263	0.5789	0.6316	0.6842	0.7368	0.7895	0.8421	0.8947	0.9474	******

was constructed as an easy reference to visualize how changes for different rates of inflation and costs of capital. The term ρ can be considered as the percentage that the amount (1 + inflation rate) is of the amount (1 + cost of capital) so program INFLA can be used by the company to set a policy for the value of ρ. In other words, if the company detects an increase in inflation, the cost of capital can be changed accordingly to maintain the value of ρ.

On the other hand, if the inflation rate decreases, the value of ρ will decrease; consequently, the company will experience an improvement in its financial situation. Of course this is valid for all industries. It is easily understood that if the rate of inflation is low, everybody benefits. The utilization of program INFLA can be a good source of information to help in the re-evaluation of the cost of capital each time inflation changes. Also, it may be used to perform simulations in order to generate in advance possible courses of action for different variations of inflation and cost of capital.

CHAPTER VII

SENSITIVITY OF OPTIMAL POLICY ON THE CHANGE OF THE PERCENTAGE OF OCCUPATION OF THE PLANNED CAPACITY

The policy relating to the percentage of occupation of the telephone network is another important concern of the administration of telephone systems. Occupation is the percentage of the telephone network that is utilized to provide telephone service. The percentage that is not utilized for regular service is reserved for emergencies, substitution of faulty circuits, repairs, etc. Therefore, if in a secondary network the policy is to have a 70% occupation, this means that on the average seven out of each ten secondary pairs will be used to connect telephone services and the remaining three pairs will be used for the items mentioned above. This area of telephone network planning is open for research because not much has been done in this respect. To study occupation in a telephone network is not easy, since in addition to the items just mentioned, aspects like the type of configuration of the network, the stochastic nature of the demand, the change of technology, the risk of having lack of network, etc., must also be considered. However, it is useful to incorporate in this research as an extension of the methodology presented a way of evaluating how the cost is altered by changing from one occupation policy to a different one. In this regard, a program, OCCUPA, listed in

Table XXV of Appendix G was designed.

Program OCCUPA generates the percentages that the cost is increased by going from an occupation policy of (A)% to an occupation policy of (B)%. The logic behind program OCCUPA is: For a gain threshold value and a percentage [(A) or (B)] of occupation, calculate the correspondent demand. This is calculated simply by using the relation:

$$\text{Amount of pairs demanded} = \frac{\text{Gain of new subscribers}}{\text{Percentage of occupation}}$$

Then for this amount of pairs, the correspondent minimum cost is calculated. In this fashion, calculations are performed for all of the gain and (A)% and (B)% values provided to the program as data. The next step consists of calculating the relative values of one minimum cost (associated with a specific percentage of occupation) with respect to the other minimum costs. Finally, the results of all those comparisons are presented in tables like Table XVI.

After running program OCCUPA several times and analyzing the results, a summary of selected values was constructed. This summary is presented in Table XVII. By observing the values in this table, it can be seen that regardless of the gain of subscribers, if an (A)% occupation policy is changed to a (B)% occupation policy where $(A)\% < (B)\%$, the cost is improved. On the contrary, if $(A)\% > (B)\%$, then the cost is increased. This is easily understood, since if the new policy adopted is to increase the percentage of occupation, this implies a small amount of pairs are required; consequently, a smaller cost is incurred. On the other hand, if the percentage of occupation is reduced, then the amount

TABLE XVI

EXAMPLE OF THE VALUES GENERATED BY PROGRAM OCCUPA

TABULATION OF THE % THAT THE COST IS INCREASED BY GOING FROM AN OCCUPATION POLICY OF (A)%,
TO AN OCCUPATION POLICY OF (E)%.

CALCULATIONS MADE IN THIS RUN WERE FOR THE GROUP OF CABLES . 3AP(0.4) 10-300 PAIRS.
AND A GAIN OF 20.0 SUBSCRIBERS.

E(%)

(A)%	0.50	0.55	0.60	0.65	0.67	0.68	0.69	0.70	0.71	0.72
0.50	0.00	-7.38	-13.57	-18.88	-20.77	-21.68	-22.57	-23.43	-24.27	-25.09
0.55	7.56	0.00	-6.69	-12.40	-14.46	-15.44	-16.40	-17.33	-18.24	-19.12
0.60	15.71	7.17	0.00	-6.12	-8.32	-9.38	-10.40	-11.40	-12.37	-13.32
0.65	23.25	14.16	6.52	0.00	-2.35	-3.47	-4.56	-5.63	-6.66	-7.67
0.67	26.[illegible]1	16.90	9.[illegible]3	2.40	0.00	-1.19	-2.27	-3.36	-4.42	-5.45
0.68	27.6[illegible]	18.26	10.[illegible]5	3.60	1.16	0.00	-1.13	-2.23	-3.31	-4.35
0.69	29.14	19.62	11.61	4.[illegible]8	2.32	1.15	0.00	-1.11	-2.20	-3.26
0.70	31.60	20.96	12.87	5.96	3.48	2.29	1.13	0.00	-1.10	-2.16
0.71	3[illegible].04	22.[illegible]1	14.12	7.14	4.62	3.42	2.25	1.11	0.00	-1.08
0.72	33.[illegible]9	23.64	15.37	8.21	5.77	4.55	3.36	2.21	1.09	0.00

TABLE XVII

SELECTED VALUES FROM TABLE XVI GENERATED BY PROGRAM OCCUPA

Percent that the cost is increased by going from an occupation policy of (A)% to an occupation policy of (B)% for different values of gain of new subscribers.

	Gain = 0.5 (B)%			Gain = 10.0 (B)%			Gain = 20.0 (B)%			Gain = 30.0 (B)%		
(A)%	0.60	0.70	0.90	0.60	0.70	0.90	0.60	0.70	0.90	0.60	0.70	0.90
0.50	-5.60	-9.76	-15.58	-12.51	-21.64	-34.14	-13.57	-23.43	-36.84	-14.08	-24.28	-38.12
0.60	0.00	-4.41	-10.58	0.00	-10.43	-24.72	0.00	-11.40	-26.92	0.00	-11.87	-27.98
0.65	2.41	-2.10	-8.42	5.92	-5.13	-20.26	6.52	-5.63	-22.16	6.81	-5.87	-23.07
0.70	4.61	0.00	-6.45	11.65	0.00	-15.95	12.87	0.00	-17.52	13.47	0.00	-18.28
0.72	5.44	0.79	-5.71	13.89	2.00	-14.26	15.37	2.21	-15.69	16.09	2.31	-17.38
0.74	6.24	1.56	-4.99	16.10	3.98	-12.60	17.84	4.40	-13.88	18.70	4.61	-14.51
0.76	7.02	2.30	-4.30	18.28	5.94	-10.96	20.29	6.58	-12.09	21.29	6.89	-12.65
0.78	7.70	3.02	-3.63	20.43	7.87	-9.34	22.72	8.73	-10.32	23.85	9.15	-10.80
0.80	8.50	3.71	-2.98	22.56	9.77	-7.73	25.12	10.86	-8.56	26.40	11.39	-8.96
0.85	10.22	5.36	-1.43	27.77	14.44	-3.81	31.04	16.10	-4.23	32.68	16.93	-4.44
0.90	11.83	6.90	0.00	32.83	18.97	0.00	36.84	21.23	0.00	38.84	22.36	0.00

of pairs demanded is greater, implying a larger cost.

Using tables like Table XVI, it is possible to evaluate exactly the change in cost that a change in policy will generate for a specific gain and specific (A) and (B) percentages of occupation. At any rate, from Table XVII the following rule of thumb can be deduced: "The difference between the cost of a policy of occupation of (A)% and the cost of a policy of occupation of (B)% will be approximately the value of the difference of (A)% - (B)%." Of course, this is only a rough value. The exact value can be obtained by using program OCCUPA.

Another way of drawing conclusions on how the change of the percent of occupation affects the capacity expansion policy is by using the three first columns of the nomograms shown in Figure 7, and Figures 17 to 19. These figures allow the network designer to determine varying the percentage of occupation and the demand of pairs affects the extent of extension. Also, it is possible to evaluate the effects on the minimum cost of various demands and percentages of occupation.

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Investments in capacity expansion have both a theoretical and practical side, and are of interest to managers, engineers, operation researchers, politicians, economists, etc. Therefore, it is possible to find applications in a wide range of fields. The problem of capacity expansion arises when the capacity of some facility must be augmented in an "optimal" way with the objective of satisfying demand for such a facility. The telephone industry is one of the many which confronts the problem of capacity expansion. Here, a telephone network is designed to provide the means of interconnecting elements that transmit and receive information from the users of the system. The needs for telephone service are positively correlated with the number of users, and since the number of users increases with time, the telephone system must also increase its capacity with the passage of time in order to be able to provide the solicited service. This requires making successive investments and it is not always simple to determine what is the best procedure.

From the literature it can be learned that there have been several serious attempts to handle this problem using different approaches. In the telephone industry, the problem of capacity expansion embraces several items, each one of those parts even though highly linked with the other, has its own problems and characteristics. Consequently, the solution to one part may not be suitable for another. This has been supported by experience which suggests that the solution found for one part of the network, for example, long distance trunks, has not been applied successfully in the exterior cables plant. The external part of the telephone plant is formed by primary and secondary cables, cables that run in a tree-like form from the telephone exchange building to the telephone set. This "tree" is generally composed of numerous branches, thousands in a typical telephone exchange area; consequently, most of the techniques applied with good results to telephone exchanges, long-haul systems and even trunk cables between exchanges, are not adequated for primary or secondary cables. Most of these inadequacies are of a practical nature rather than theoretical. That is, it is not always economically feasible to apply a dynamic programming algorithm to all the branches forming the primary and secondary networks. These inadequacies are more dominant in developing countries.

In most countries, the solution given for the capacity expansion problem of primary and secondary cables is to state a fixed number of years that an extension of this type of cables must last. For example, in Mexico, the plans for expansion in primary and secondary cables are for three and five years, respectively. However, due to several years of experience and from some "post mortem" calculations, it is believed that these policies must be restudied, because in some cases the cost actually paid is several times higher than the optimum. Since it is common to talk in the telephone industry of annual investments in the order of thousands of millions of units of money, the impact of a good or bad decision regarding capacity expansion may be also in the order of thousands of millions of units of money.

The main aim of the present research was to develop a methodology for determining in a simplified manner the economical policies of expansion for primary and secondary cables without the routine use of a computer. Other objectives were to incorporate into the analysis aspects like inflation, stochastic aspect of the demand, change of technology, and percentage of occupation; aspects that have been considered very little or not at all in previous works.

The research started with the introduction of some of the terminology used in the telephone industry. Next, it proceeded with a brief description of a typical telephone network, describing the types of switching systems, the structure of the facilities network, and the telephone expansion process and its problems. After this, the background of the study was presented by first discussing the general problem of capacity expansion, followed by an exposition of some of the fields in which capacity expansion planning has been studied, the diverse assumption considered in the literature, the computational tools used in the literature, and the different methods/techniques that have been used to approach a solution for the capacity expansion problem in the telephone industry. Next, the research goals and specific objectives for this research were explained; the priorities set for those objectives were also discussed.

Chapter II develops the basis of the methodology used, starting with a description of the formulation of a mathematical model for the case of installing capacity to satisfy one-time demand. Then a model for the case of linearally increasing demand was presented, and later he relation between the demand and the time between augmentations that yield the minimum cost was presented. Next, since the methodology developed is to be implemented in Mexico, where support for this research was provided, estimates of the cables cost parameter were made using linear regression and real data from Mexico. After this, a computer program, CURVES, was explained. This program generates a set of values that relate specified values of demand to the net present value of various extent of extension values. Also, output from the program CURVES was used to draw a set of figures to illustrate how the net present value and the extent of extension are related.

A program, F(DA)F(TA), was explained which tabulates series of values that relate demand and time between installations. This program was designed to gain insight into two aspects: (1) to know what is the optimal extent of extension and its matching demand for cables in use as well as for those not in use; and (2) to have another way to prove the necessary and sufficient conditions for optimality.

The next step was to design a computer program, PERCENT, which was used to perform sensitivity analysis on the optimum solution by varying the extent of extension. Results obtained from PERCENT were used to develop nomograms, which satisfy the main objective of this research. Implemented in these nomograms is the relation of the gain of subscribers, the percentage of occupation planned, the corresponding annual demand of pairs, and the optimal and suboptimal policies.

The following step was to analyze how the net present value associated with a specific cable is affected by varying the extent of extension. A program, CABLES, was designed and used to answer this question. From the results obtained, a set of figures were constructed corresponding to the types of cables most commonly used.

Next, a procedure was developed for determining demand values which result in a net present value which is at most a pre-specified percent over the minimum. In doing this, a computer program, BOUND, was designed. The results provided by this program give a way of calculating the range of demand values which guarantee that when installing a specific cable, the maximum deviation from the minimum cost will be a preaccepted percentage.

After which, the stochastic nature of demand and its affect on policies of expansion was studied. An analysis of the estimated and the observed real demand was performed. The probability distributions of these demands were identified. A figure was constructed to present in one glance how the estimated and the real demands behave.

Once the distributions of the estimated and real demand were identified, the next step consisted of linking these results with the cost of different policies of expansion in order to protect a desired level of the possible real outcomes. This was attained by designing a program, UNCERT, which calculates for a determined probability distribution of demand, the cost resulting for different values of uncertainty.

Next, an overview of the effect of change in technology over the policy of capacity expansion of primary and secondary telephone cables, was discussed. A proposal on how this problem can be handled is also presented.

Later, the effect of inflation on optimal policies was discussed. For that purpose, a program called INFLA was designed and used to perform sensitivity analyses of an inflation related parameter. Results of such analyses are presented in tabular form, and the behavior of the variation was discussed.

Finally, an analysis of the sensitivity of the optimal policy on the change of the percentage of occupation of the planned capacity was performed. In doing so, a program, OCCUPA, was designed. Results of this analyses were presented in tabular form. The program OCCUPA facilitates the calculation of the cost that is incurred from going from an occupation policy of (A)% to an occupation policy of (B)%.

Conclusions

From the results obtained, the following findings can be identified:

(1) Equation (2.5) states that the economic extent of extension is independent of the constant λ. This implies that the optimal policy for a specified type of cable remains the same regardless of the value of the

a) salvage value of the facility that is replaced,

h) useful life of the plant installed,

c) operation costs,

d) maintenance costs, and

e) increment in the value of the recovered material.

(2) For a specified value of demand, the shape of the relationship between the extent of extension and its net present value is, in general, very flat around the optimal values. Therefore, if an optimal policy is planned, it is possible to vary significantly the length of the extent of extensions without altering drastically the increment in the minimum cost. This can be easily confirmed by looking at the nomograms in Figures 7, and 17-19.

(3) By looking at Figures 6 and 14-16 it can be concluded that the length of the extent of extension (for the particular case of Mexico) should be changed because time periods of three and five years do not represent the optimal policy for installing primary and secondary cables.

(4) By applying the policies given in the nomograms shown in Figures 6 and 14-16 the length of the extension does not have to be a fixed number of years. Because, using these nomograms, it is possible to optimally plan the extent of extension for each branch.

(5) It is possible to evaluate the cost of protecting different levels of uncertainty in demand without changing the current procedure of determining demand; that is, without taking away this activity from the personnel that currently have this duty. Estimates made by different persons will also have errors.

(6) The effect of inflation on the optimal policy is not significant provided that any change experienced in the rate of inflation is followed by a suitable change in the cost of capital. Therefore, management should try to keep unaltered the value of the ratio:

$$\rho = \frac{1 + \text{rate of inflation}}{1 + \text{cost of capital}}$$

The value of ρ should never be allowed to increase, because, if the value of ρ is increased, costs to the firm are sharply increased.

(7) The optimal policy is not very sensitive to different percentages of occupation. A rule of thumb in this respect can be stated as "the difference between the cost of a policy of occupation of an (A)% and the cost of a policy of occupation of (B)% will have approximately the value of the difference of (A)% - (B)%."

Recommendations

Two kinds of recommendations can be made: general recommendations for any telephone company administration and recommendations for the Mexican telephone company.

General recommendations are:

(1) Construct nomograms as those shown in Figures 7 and 17-19 to provide simplified aids to the network designer for planning primary and secondary networks.

(2) Use the conclusions obtained in the section related to the study of inflation and its effects on the optimal policy for establishing the cost of capital.

(3) Perform research relating to the change of technology and its implications on the telephone cable networks.

Recommendations to the Mexican telephone company, in addition to the general recommendations mentioned above, are:

(1) Use the methodology presented in this research to revise the way of planning the capacity extension of primary and secondary cable networks. It has been shown that the current way of planning these networks can be significantly improved and the savings achieved may be very significant.

(2) Test this hypothesis by choosing areas of service as similar as possible. Use these areas to experiment and get the results of the effects of two "treatments": (1) to continue using the current policy (base treatment), and (2) to change to the "new" policy dictated by this research. This will provide the scienfific basis for acceptance or rejection of the proposed methodology.

It is evident to the author that great improvement can be made by eliminating from the current use, cables of small capacity--10, 20, and 30 pairs. Also, it can be concluded from observing the nomograms in Figures 7 and 17-19, that the optimal extent of extension for small cables is fairly large. For example, in the type of cable (AS)(0.4), 10-300 pairs) most often used in secondary networks, the optimal demand for a cable of 10 pairs is less than 0.2 pairs per year, and the optimal extent of extension is greater than 50 years. Similarly, for a cable of 20 pairs, the demand is approximately 0.5 pairs per year and 40 years for the extent of extension. For a cable of 30 pairs, the optimal demand is less than one pair per year and the extent of extension is approximately 30 years. These values are for the <u>optimal</u> policy; however, if a small deviation from the optimal is allowed, these values become even greater. This suggests that installation of small capacities is inappropriate; since, when making estimations into the future, longer planning horizons result in greater uncertainty in those predictions. Consequently, the probability of installing another small cable before its optimal time is very high. Therefore, this will force the continual repeating of the payment for lack of economies of scale.

If the recommendations stated here are followed, it is implied that the extent of extension policy will be increased. The action of making additions last longer will result in significant related savings, such as the following:

(1) Subdivision of existing areas will be less necessary; therefore, the records and administrative efforts associated with the subdivision of an area will be reduced significantly.

(2) If the cables to be installed are of larger capacity, a better utilization of the underground conducts will be achieved.

(3) A lesser number of trips per unit of time will be required to do to the same place for studying and installing capacity additions.

(4) By having a network with cables of larger capacities, the total maintenance and operation costs will be reduced.

(5) The methodology proposed allows working with ranges of values as estimates of demands. This provides flexibility to the people charged with furnishing these estimations. They can supply their estimations as ranges rather than fixed amounts.

(6) By eliminating the use of cables of small capacities, the stock of different cables is reduced; consequently, the problems associated with carrying and controlling the inventory and fabrication of telephone cables will be reduced.

A possible area for future research would be the study of demand distributions in addition to the normal, which was investigated in this research. Another area might be the development of models representing the transition from small time periods between capacity augmentation to long time periods. These models might involve some multiobjective optimization techniques because many factors would need to be considered, such as new labor needs and new equipment requirements.

REFERENCES

[1] Bell Telephone Laboratories. "Engineering and Operations in the Bell System." Bell Telephone Laboratories, Inc. Prepared by members of the Technical Staff and the Technical Publication Department, Bell Laboratories, N.J., 1979.

[2] Bellman, R., and S. Dreyfus. Applied Dynamic Programming. Princeton, N.J.: University Press, 1962.

[3] Blackman, A. Wade. "The Market Dynamics of Technological Substitutions." Technological Forecasting and Social Change, 6, No. 3 (1974), pp. 41-63.

[4] Butcher, W. S., Y. Y. Haimes, and W. D. Hall. "Dynamic Programming for the Optimal Sequencing of Water-Supply Projects." Water Resources Research, 5 (1960), pp. 1196-1204.

[5] Consultative Committee of the International Telegraph and Telephone Company (CCITT). "Local Network Planning." International Communication Union, Geneva (1979), p. 9.

[6] Chenery, Hollis B. "Overcapacity and the Acceleration Principle." Econometrica, 20, No. 1 (1952), pp. 1-28.

[7] Clapham, J. C. R. "Economic Life of Equipment." Operation Research Quarterly, 8 (1957), pp. 181-190.

[8] Clark, Paul G. "The Telephone Industry: A Study in Private Investment." Studies in the Structure of the American Economy: Theoretical and Empirical Explorations in Input-Output Analysis. Fair Lawn, N.J.: Oxford University Press, 1953, pp. 243-294.

[9] Coleman, John R., and Robert York. "Optimum Plant Design for a Growing Market." Industrial and Engineering Chemistry, 56, No. 1 (January, 1964), pp. 28-34.

[10] Dale, K. M. "Dynamic Programming Approach to the Selection and Timing of Generation Plant Additions." Proceedings IEE, 113, No. 5 (May, 1966), pp. 803-811.

[11] Doulliez, P. J., and M. R. Rao. "Capacity of a Network With Increasing Demands and Arcs Subject to Failure." Operation Research, 19, No. 4 (July-August, 1971), pp. 905-915.

[12] Doulliez, P. M., and M. R. Rao. "Optimal Network Capacity Planning: A Shortest Path Scheme." Operation Research, 23 (1975), pp. 810-818.

[13] Erlenkotter, D. "Optimal Plant Size With Time-Phased Imports." In Investments for Capacity Expansion. Ed. A. S. Manne. Cambridge, Mass.: M.I.T. Press, 1967, p. 157.

[14] Erlenkotter, D., and Alan S. Manne. "Capacity Expansion for India's Nitrogenous Fertilizer Industry." Management Science, 14, No. 10 (June, 1968), pp. B-533-B-572.

[15] Erlenkotter, D. "Sequencing Expansion Projects." Operation Research, 21, No. 2 (March-April, 1973), pp. 542-553.

[16] Erlenkotter, D. "A Dynamic Programming Approach to Capacity Expansion and Specialization." Management Science, 21 (1974), pp. 360-362.

[17] Erlenkotter, D. "Capacity Planning for Large Multilocation Systems: Approximate and Incomplete Dynamic Programming Approaches." Management Science, 22 (1975), pp. 274-285.

[18] Fisher, J. C., and R. H. Pry. "A Simple Substitution Model of Technological Change." Technological Forecasting and Social Change, 3 (1971), pp. 75-88.

[19] Freidenfelds, John, and C. D. McLaughlin. "A Heuristic Branch-and-Ground Algorithm for Telephone Feeder Capacity Expansion." Operation Research, 27 (1979), pp. 567-582.

[20] Fong, C. O., and M. R. Rao. "Capacity Expansion With Two Producing Regions and Concave Costs." Management Science, 22, No. 3 (November, 1975), pp. 331-339.

[21] Giglio, Richard J. "Stochastic Capacity Models." Management Science, 17, No. 3 (November, 1970), pp. 174-184.

[22] Giglio, Richard J. "A Note on the Deterministic Capacity Problem." Management Science, 19, No. 9 (May, 1973), pp. 1096-1099.

[23] Hinomoto, Hirohide. "Capacity Expansion With Facilities Under Technological Improvement." Management Science, 11, No. 5 (March, 1965), pp. 581-592.

[24] Kalotay, A. J. "Capacity Expansion and Specialization." Management Science, 20 (1973), pp. 56-64.

[25] Kalotay, A. J. "Two Comments on the Deterministic Capacity Problem." Management Science, 20, No. 9 (May, 1974), p. 1313.

[26] Manne, A. S. "Capacity Expansion and Probabilistic Growth." Econometrica, 29, No. 4 (1961), pp. 632-649.

[27] Manne, A. S., and Arthur F. Vienott, Jr. "Optimal Plant Size With Arbitrary Increasing Time Paths of Demand." In Investments for Capacity Expansion. Ed. A. S. Manne. Cambridge, Mass.: MIT Press, 1967, pp. 178-190.

[28] Manne, A. S. Investments for Capacity Expansion: Size, Location, and Time-Phasing. London: George Allen and Unwin, Ltd., 1967.

[29] McCracken, Daniel D., and William Dorn. Numerical Methods and FORTRAN Programming. New York: John Wiley and Sons, 1964.

[30] McDowell, I. "The Economical Planning Period for Engineering Works." Operation Research, 8 (1960), pp. 533-542.

[31] Morgan, J. T. Telecommunications Economics. 2nd Ed. London: Technicopy Limited, 1976.

[32] Naddor, E. "Sensitivity to Distributions in Inventory Systems." Management Science, 24, No. 16 (1978), pp. 1769-1772.

[33] Pearl, R. The Biology of Population Growth. New York: Alfred A. Knopf, 1925.

[34] Rapp, Y. "Economic Stages of Extension of a Telephone Network Problem." Ericsson Technics, 5 (1939), pp. 87-96.

[35] Rapp, Y. "The Economic Optimum in Urban Telephone Network Problems." Ericsson Technics, 49 (1950), pp. 38-46.

[36] Rapp, Y. "The Use of Dynamic Programming for Planning of Extension of Conduits and Main Cable Networks in a Local Exchange Area." Ericsson Review, 46 (1969), pp. 102-112.

[37] Reisman, Arnold, and Elwood S. Buffa. "A General Model for Investment Policy." Management Science, 8, No. 3 (1962), pp. 304-310.

[38] Shapiro, Jeremy F. "Turnpike Planning Horizons for a Markovian Decision Model." Management Science, 14, No. 5 (January, 1968), pp. 292-300.

[39] Sharif, M. Nawaz, and Chowdhury Kabir. "A Generalized Model for Forecasting Technological Substitution." Technological Forecasting and Social Change, 8, No. 4 (1976), pp. 353-364.

[40] Sinden, Frank W. "The Replacement and Expansion of Durable Equipment." Journal of Social Industrial Applied Math, 8, No. 4 (1976), pp. 353-364.

[41] Smith, Robert L. "Turnpike Results for Single Location Capacity Expansion." Management Science, 25, No. 5 (May, 1979), pp. 474-484.

[42] Srinivasan, T. N. "Geometric Rate of Growth of Demand." In Investments for Capacity Expansion. Ed. A. S. Manne. Cambridge, Mass.: MIT Press, 1967, pp. 151-156.

[43] Telefonos de Mexico. Annual Report, 1972. Telefonos de Mexico, Mexico City, 1972.

[44] Telefonos de Mexico. Annual Report, 1973. Telefonos de Mexico, Mexico City, 1973.

[45] Telefonos de Mexico. Annual Report, 1974. Telefonos de Mexico, Mexico City, 1974.

[46] Telefonos de Mexico. Annual Report, 1975. Telefonos de Mexico, Mexico City, 1975.

[47] Telefonos de Mexico. Annual Report, 1976. Telefonos de Mexico, Mexico City, 1976.

[48] Telefonos de Mexico. Annual Report, 1977. Telefonos de Mexico, Mexico City, 1977.

[49] Telefonos de Mexico. Annual Report, 1978. Telefonos de Mexico, Mexico City, 1978.

[50] Turvey, Ralph, and Dennis Anderson. Electricity Economics: Essays and Case Studies. Baltimore, Maryland: Johns Hopkins University Press, 1977, pp. 184-200.

[51] White, James M. "A Dynamic Model for the Analysis of Expansion." Journal of Industrial Engineering, 17 (1966), pp. 275-281.

APPENDIXES

APPENDIX A

CALCULATION OF THE APPROXIMATE NUMBER OF PRINCIPAL AND SECONDARY CABLES TO BE ANALYZED IN AN AVERAGE SIZE TELEPHONE EXCHANGE AREA

From the 65 telephone exchange areas in Mexico City we have:

Exchange	Lines in 1981	Exchange	Lines in 1981
AP	20,000	PO	34,000
AG	20,000	PC	12,000
AR	10,000	PP	12,000
AT	16,000	QU	18,000
AZ	16,000	RO	40,000
BA	20,000	RA	12,000
BO	8,000	SB	18,000
CA	22,000	SA	20,000
CP	13,000	SJ	15,000
CO	18,000	SC	16,000
CH	18,000	SF	5,000
CI	30,000	SM	20,000
CU	22,000	RS	14,000
DO	28,000	SR	18,000
EA	8,000	ST	26,000
EC	20,000	SO	14,000
ES	8,000	TA	20,000
GU	24,000	TY	35,000
HI	28,000	TE	14,000
IX	38,000	TL	16,000
LA	18,000	TP	16,000
LI	18,000	TC	22,000
MA	38,000	UR	21,000
MG	15,000	VA	25,000
ML	18,000	VL	22,000
ME	12,000	VR	15,000
MI	18,000	VI	40,000
MC	26,000	VE	18,000
MO	34,000	XO	12,000
NA	20,000	ZA	20,000
NE	22,000	ZO	20,000
PD	14,000		
PE	28,000	TOTAL	1,308,000
PI	30,000		

If each district has approximately 200 lines, then in an exchange area there are

$$\frac{1{,}308{,}000}{65} \times \frac{1}{200} = 100.61 = 100 \text{ districts/exchange.}$$

To connect 100 districts to the telephone exchange building it is usually required to have 200 branches; therefore, there are in Mexico City

$$200 \times 65 = 13{,}000 \text{ branches of principal cables.}$$

On the other hand, each district has approximately 350 secondary pairs, so to its district cabinet approximately 40 branches are required. Consequently, in a telephone exchange area there are

$$40 \times 100 = 4{,}000 \text{ branches/exchange}$$

or, in Mexico City

$$4{,}000 \times 65 = 260{,}000 \text{ branches of secondary cables}$$

or a total of

$$13{,}000 + 260{,}000 = 273{,}000 \text{ branches.}$$

Since Mexico City has approximately 30% of the total number of lines, the result for the whole country is

$$\frac{273{,}000}{30} \times 100 = 910{,}000 \text{ branches.}$$

APPENDIX B

DESCRIPTION OF THE TELEPHONIC CABLES USED IN MEXICO

Description of the telephonic cables used in Mexico:

TYPE	DESCRIPTION
TAF	Cable formed by pairs of copper wires insulated individually with paper. On the set of pairs, there is a pipe made of lead, which is covered by a layer of jute, two layers of soft steel, and finally another layer of jute impregnated with adhesive. Wages: 0.40 mm ø (26 AWG) 0.50 mm ø (24 AWG) 0.64 mm ø (22 AWG) 0.91 mm ø (19 AWG) Common Capacities: From 10 to 600 pairs (10-600Ps.).
TAP	Cable formed by pairs of copper wires insulated individually with paper. On the set of pairs there is a pipe made of lead, which in turn is covered by a layer of black, high density, flame retardant polyethylene. Wages: 0.40 mm ø (26 AWG) 0.50 mm ø (24 AWG) 0.64 mm ø (22 AWG) 0.91 mm ø (19 AWG) Common Capacities: From 10 to 2400 pairs (10-2400Ps.).
EKD	Cable formed by pairs of copper wires insulated individually with colored, semirigid polyvinil (PVC). On the set of pairs there is an identification ribbon, a paper layer, and a pipe made of lead. Wages: 0.40 mm ø (26 AWG) Common Capacities: From 50 to 600 pairs (50-600Ps.).
EKI	Cable formed by pairs of copper wires insulated individually with colored, semirigid polyvinil (PVC). On the set of pairs there is an identification ribbon and a cover of brown, thermoplastic vinil. Wages: 0.4 mm ø (26 AWG) Common Capacities: From 10 to 100 pairs (10-100Ps.).
EKE	Cable formed by pairs of copper wires insulated individually with colored, semirigid polyvinil (PVC). On the set of pairs there is a hygroscopic ribbon and a cover of black, high density, flame retardant polyethylene.

TYPE	DESCRIPTION
EKE (Continued)	
	Wages: 0.4 mm ø (26 AWG) 0.5 mm ø (24 AWG)
	Common Capacities: From 10 to 300 pairs (10-100Ps.).
ASP	Same as EKE with the exception that the outer layer contains also a steel cable to support the weight of the cable once the cable is installed.
	Wages: 0.4 mm ø (26 AWG) 0.5 mm ø (24 AWG) 0.64 mm ø (22 AWG) 0.91 mm ø (19 AWG)
	Common Capacities: From 10 to 300 pairs (10-300Ps.).

APPENDIX C

FIGURES FOR EXTENT OF EXTENSION AND ITS NET PRESENT VALUE FOR CABLE TYPES:

TAP(0.4) 10- 300 PAIRS

TAP(0.4) 100-2400 PAIRS

TAP(0.5) 150-1200 PAIRS

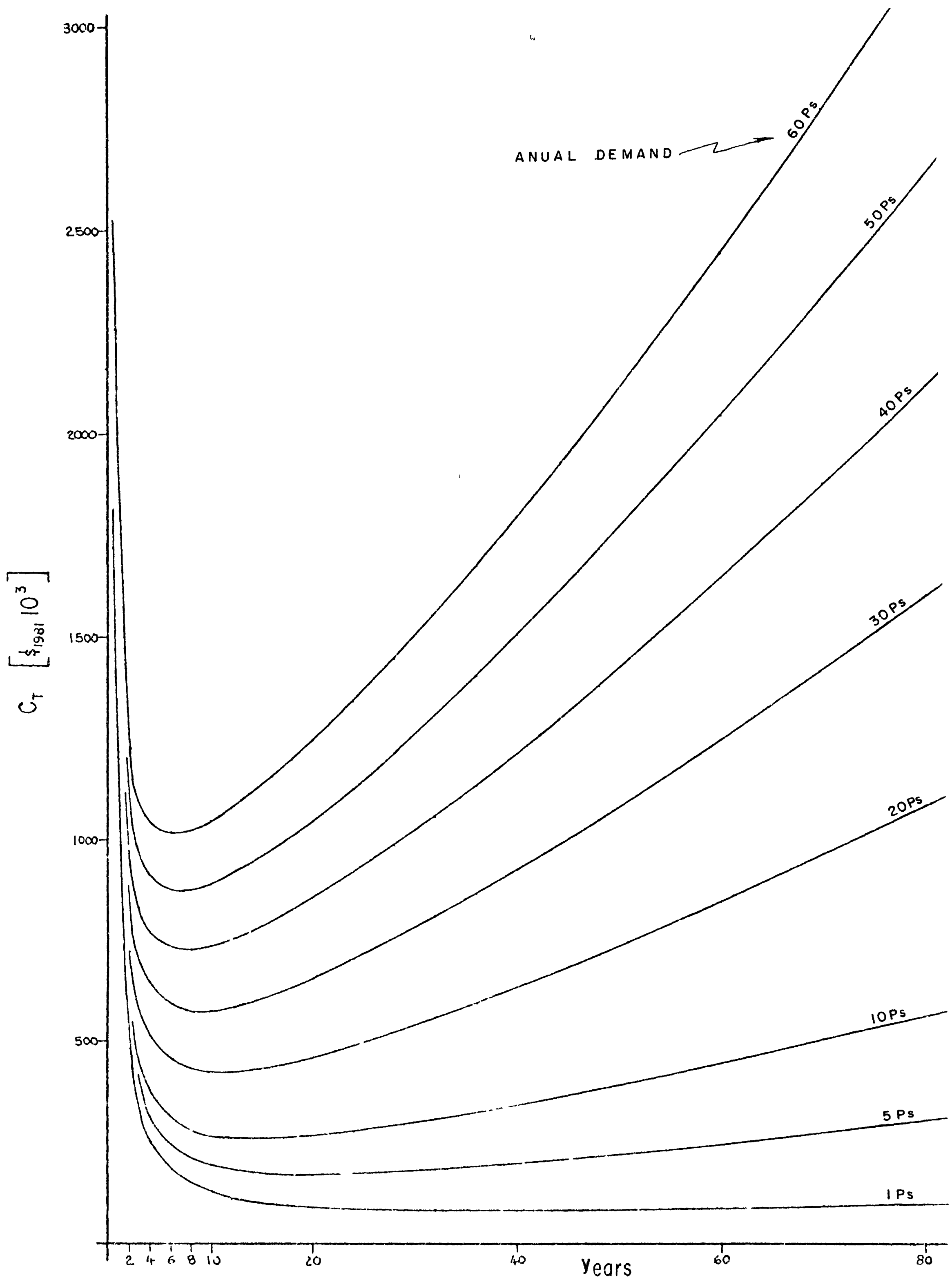


Figure 14. Extent of Extension and Its Net Present Value For Secondary Telephone Cables of the Type TAP(0.4) 10-300 Pairs

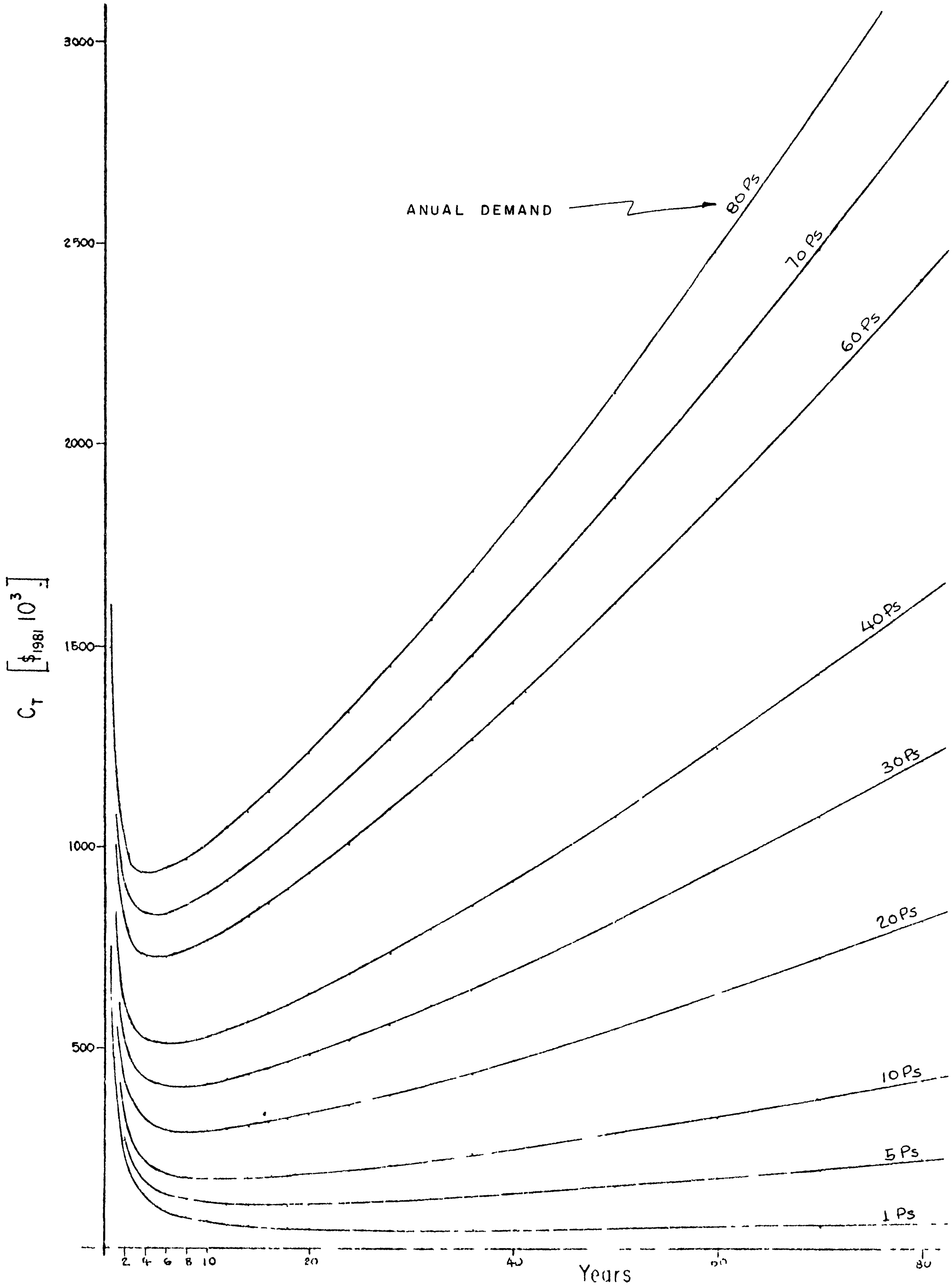


Figure 15. Extent of Extension and Its Net Present Value For Primary Telephone Cables of the Type TAP(0.4) 100-2400 Pairs

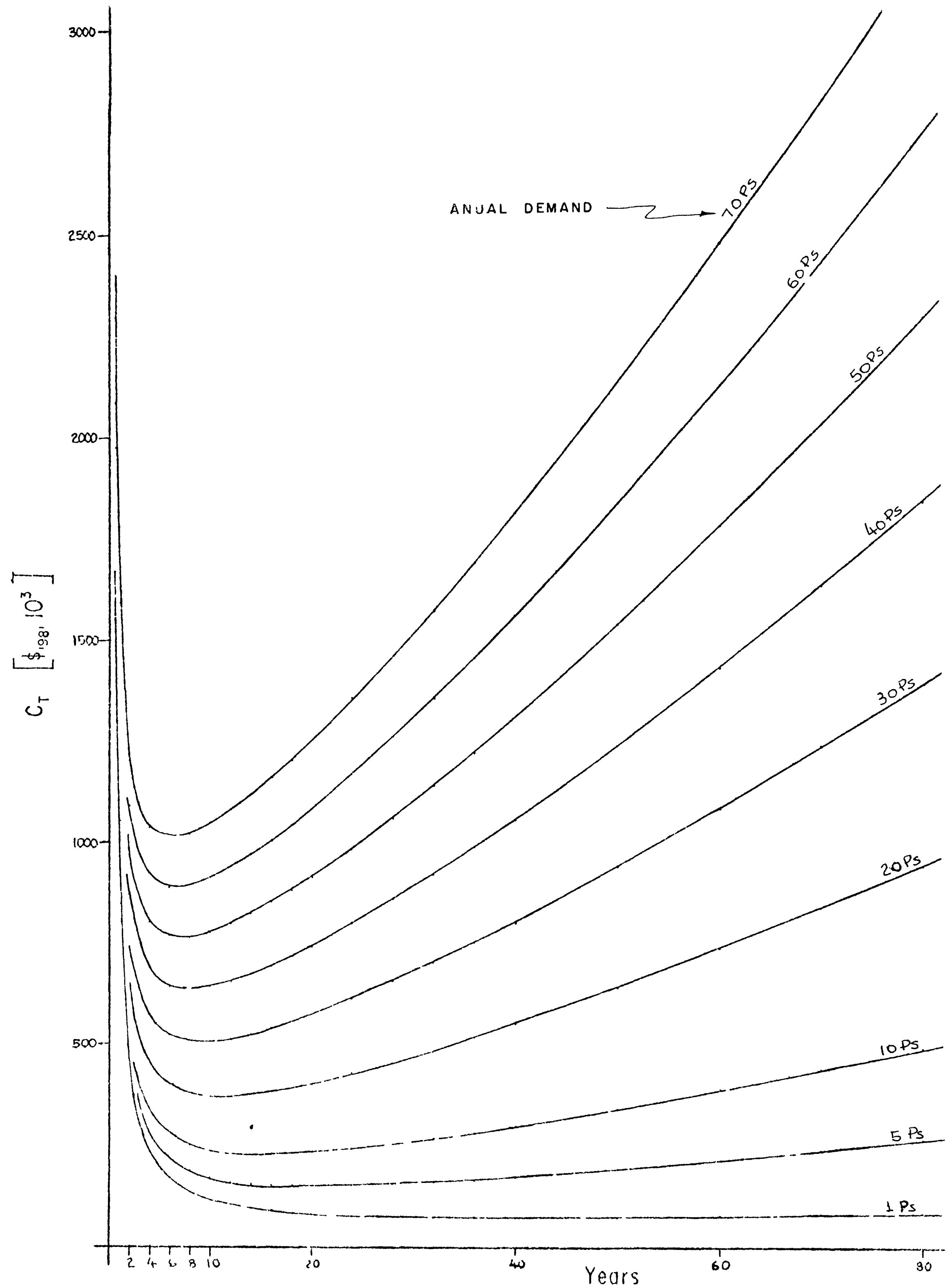


Figure 16. Extent of Extension and Its Net Present Value For Primary Telephone Cables of the Type TAP(0.5) 150-1200 Pairs

APPENDIX D

NOMOGRAMS FOR EXTENT OF EXTENSION, AS A FUNCTION OF THE ANNUAL INCREMENT OF SUBSCRIBERS (GAIN), THE PERCENTAGE OF OCCUPATION AND THE ANNUAL DEMAND OF PAIRS CORRESPONDENT, WHICH GIVES THE OPTIMAL POLICY OF EXTENSION, AND VARIATIONS WHICH INCREMENT THE MINIMUM COST IN 10%, FOR CABLE TYPES:

ASP(0.4) 10- 300 PAIRS

TAP(0.4) 10- 300 PAIRS

TAP(0.5) 150-1200 PAIRS

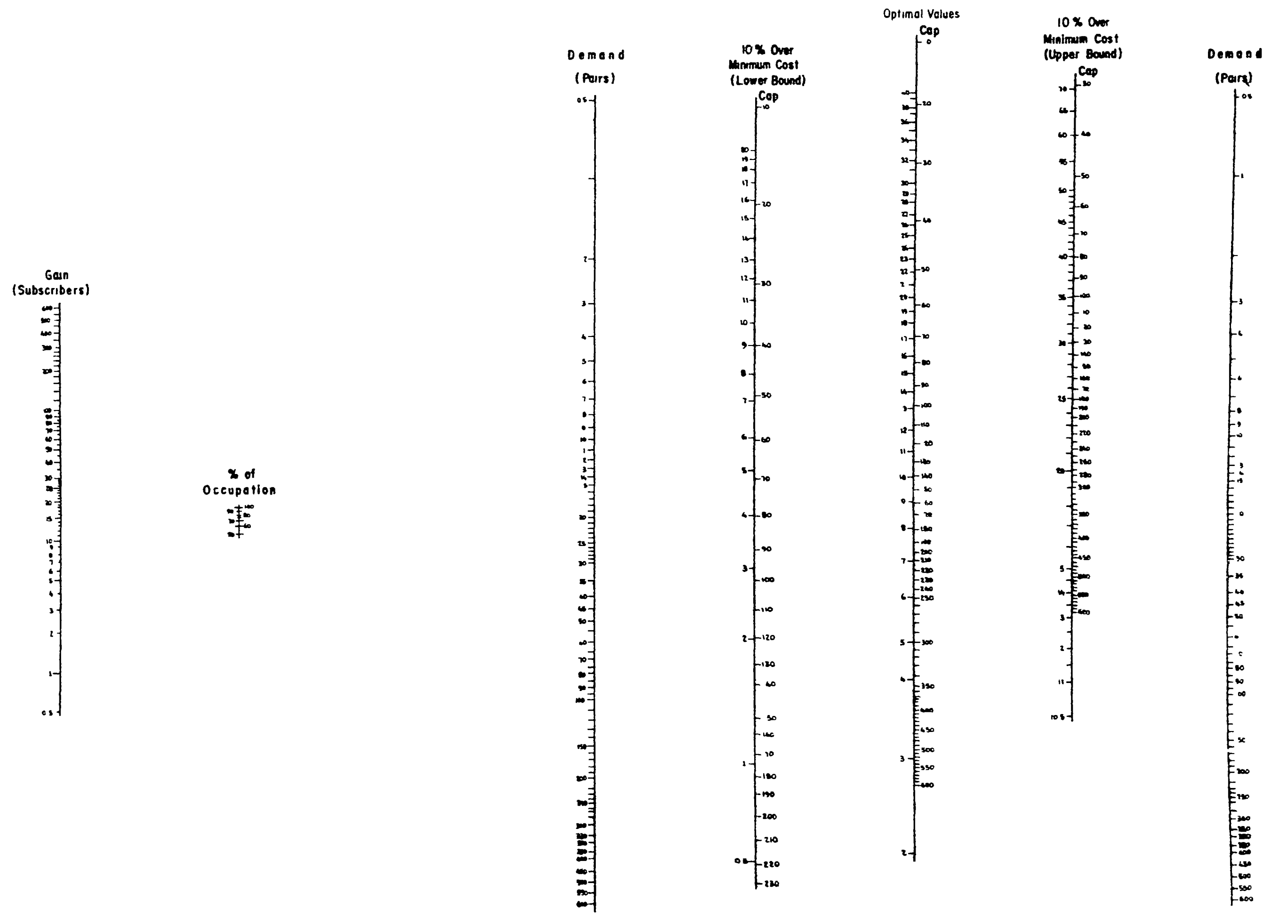


Figure 17. Extent of Extension For Secondary Cables of the Type ASP(0.4) 10-300 Pairs as a Function of the Annual Increment of Subscribers (Gain), the Percentage of Occupation and the Annual Demand of Pairs (da) Correspondent, Which Gives the Optimal Policy of Extension, and Variations Which Increment the Minimum Cost in 10%

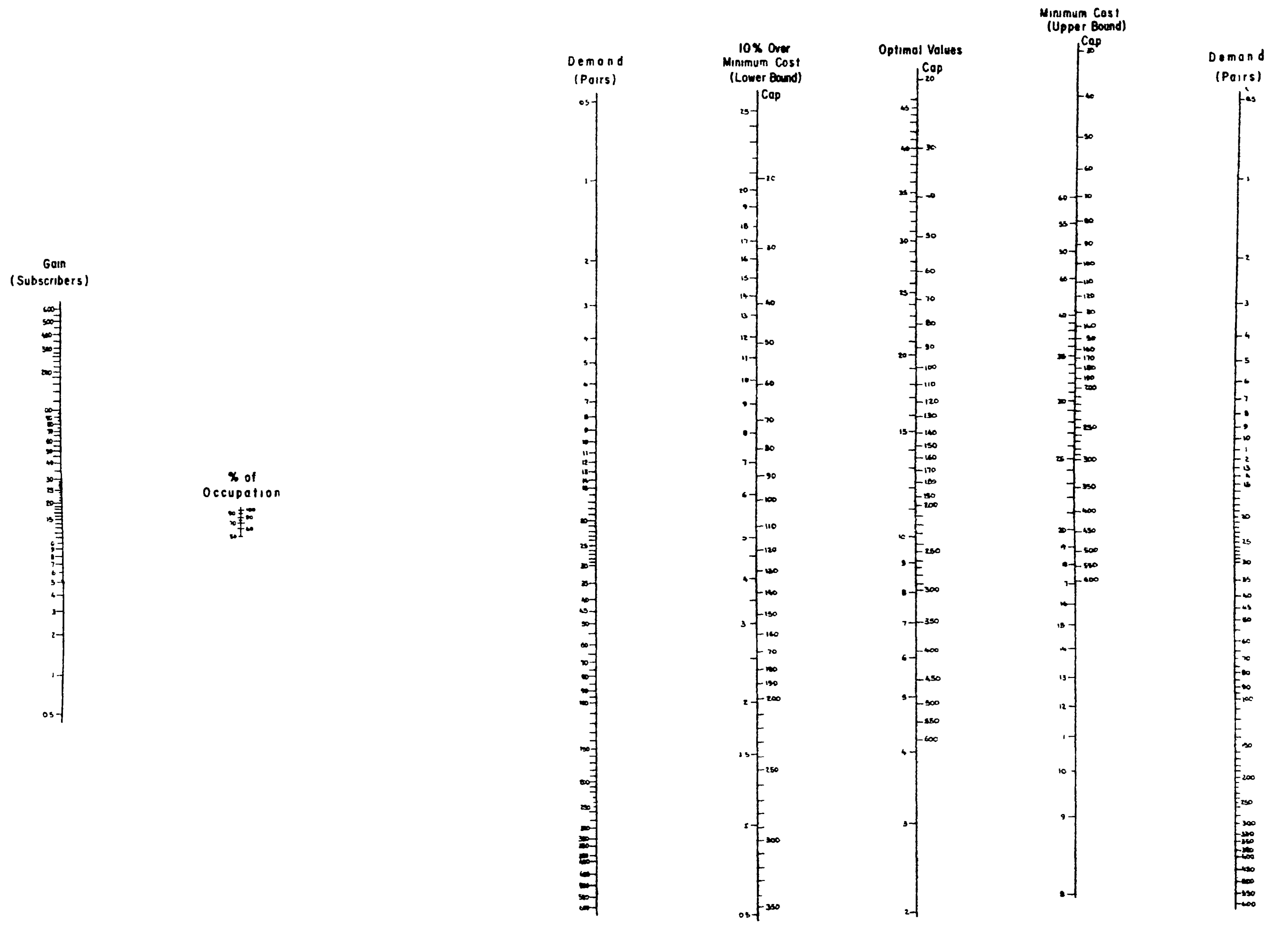


Figure 18. Extent of Extension For Secondary Cables of the Type TAP(0.4) 10-300 Pairs as a Function of the Annual Increment of Subscribers (Gain), the Percentage of Occupation and the Annual Demand of Pairs (da) Correspondent, Which Gives the Optimal Policy of Extension, and Variations Which Increments the Minimum Cost in 10%

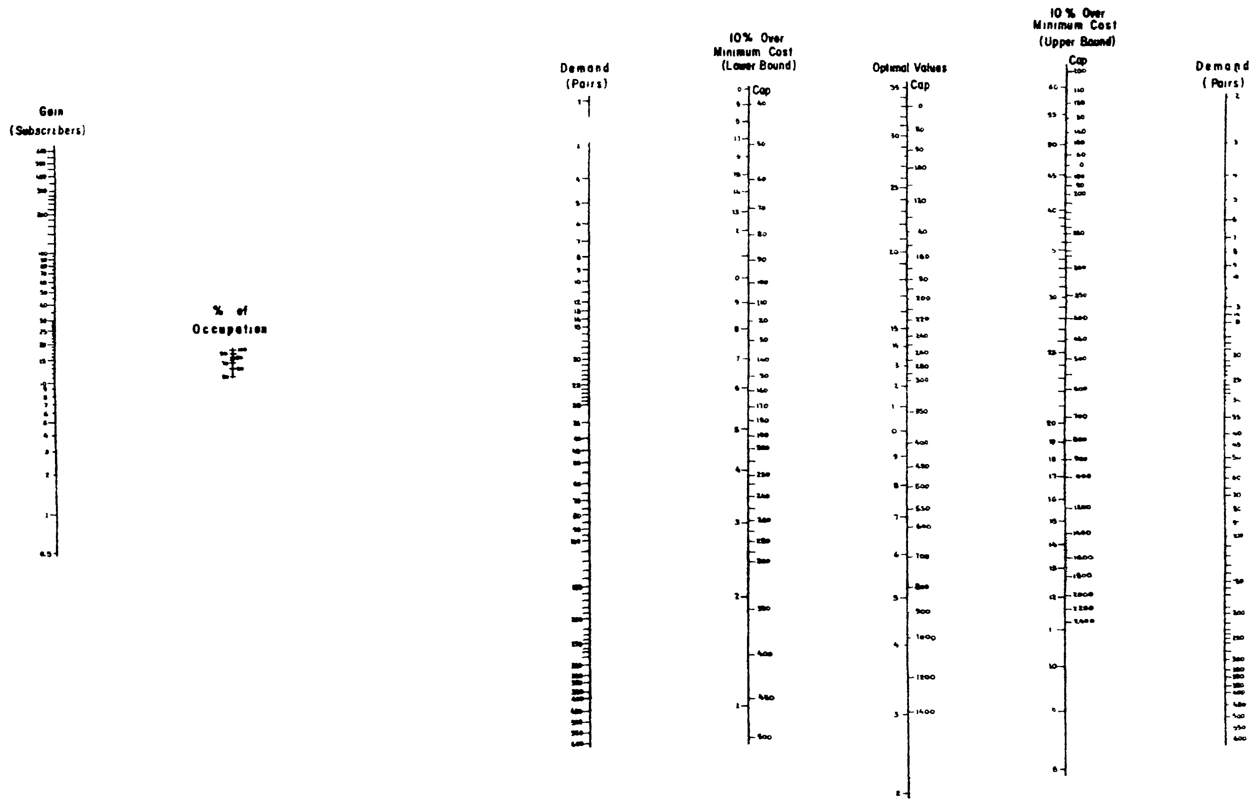


Figure 19. Extent of Extension (τ) For Primary Cables of the Type TAP(0.5) 150-1200 Pairs as a Function of the Annual Increment of Subscribers (Gain), the Percentage of Occupation and the Annual Demand of Pairs (da) Correspondent Which Gives the Optimal Policy of Extension, Variations Which Increment the Minimum Cost in 10%

APPENDIX E

FIGURES FOR NET PRESENT VALUE VS. TIME

BETWEEN INSTALLATIONS OF CABLE TYPES:

ASP(0.4) 10- 300 PAIRS

TAP(0.4) 10- 300 PAIRS

TAP(0.5) 150-1200 PAIRS

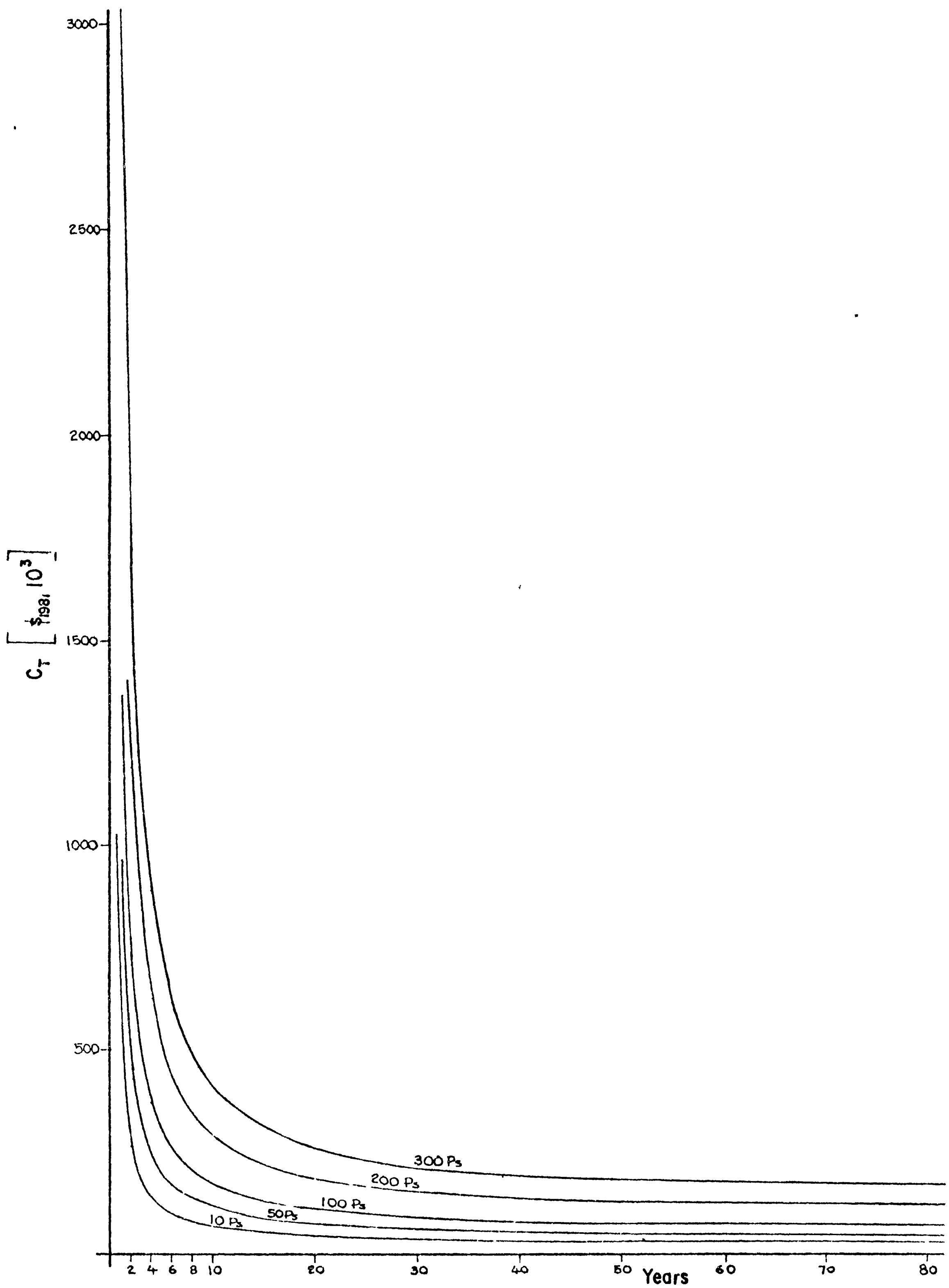


Figure 20. Net Present Value (NPV) vs. Time Between Installations of Secondary Cables of the Type ASP(0.4) 10-300 Pairs

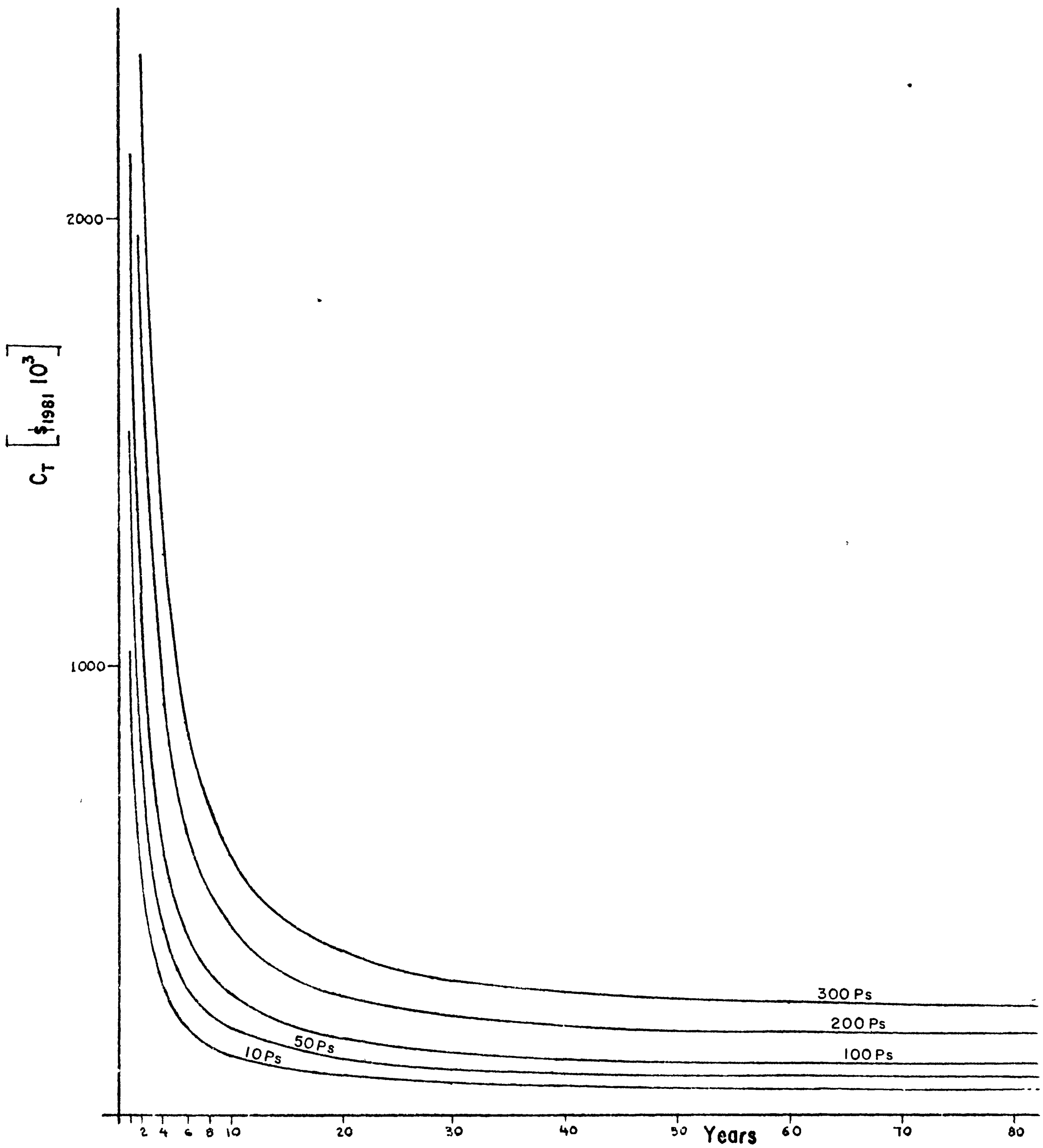


Figure 21. Net Present Value (NPV) vs. Time Between Installations of Secondary Cables of the Type TAP(0.4) 10-300 Pairs

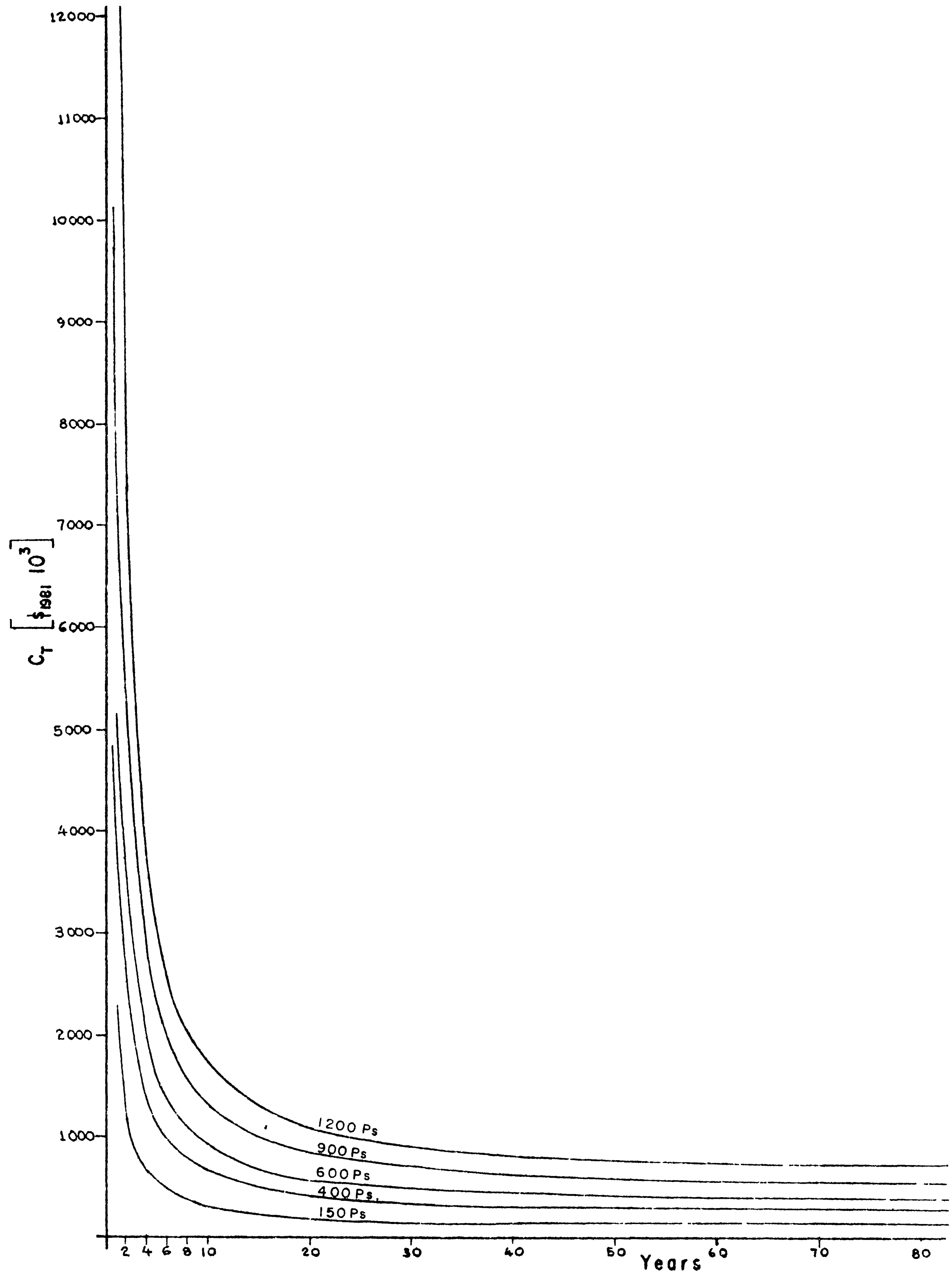


Figure 22. Net Present Value (NPV) vs. Time Between Installations of Primary Cables of the Type TAP(0.5) 150-1200 Pairs

APPENDIX F

HISTOGRAMS OF THE REAL VALUES OF DEMAND

WHEN THE ESTIMATED DEMAND WAS OF:

1 NEW SUBSCRIBER

5 NEW SUBSCRIBERS

10 NEW SUBSCRIBERS

15 NEW SUBSCRIBERS

20 NEW SUBSCRIBERS

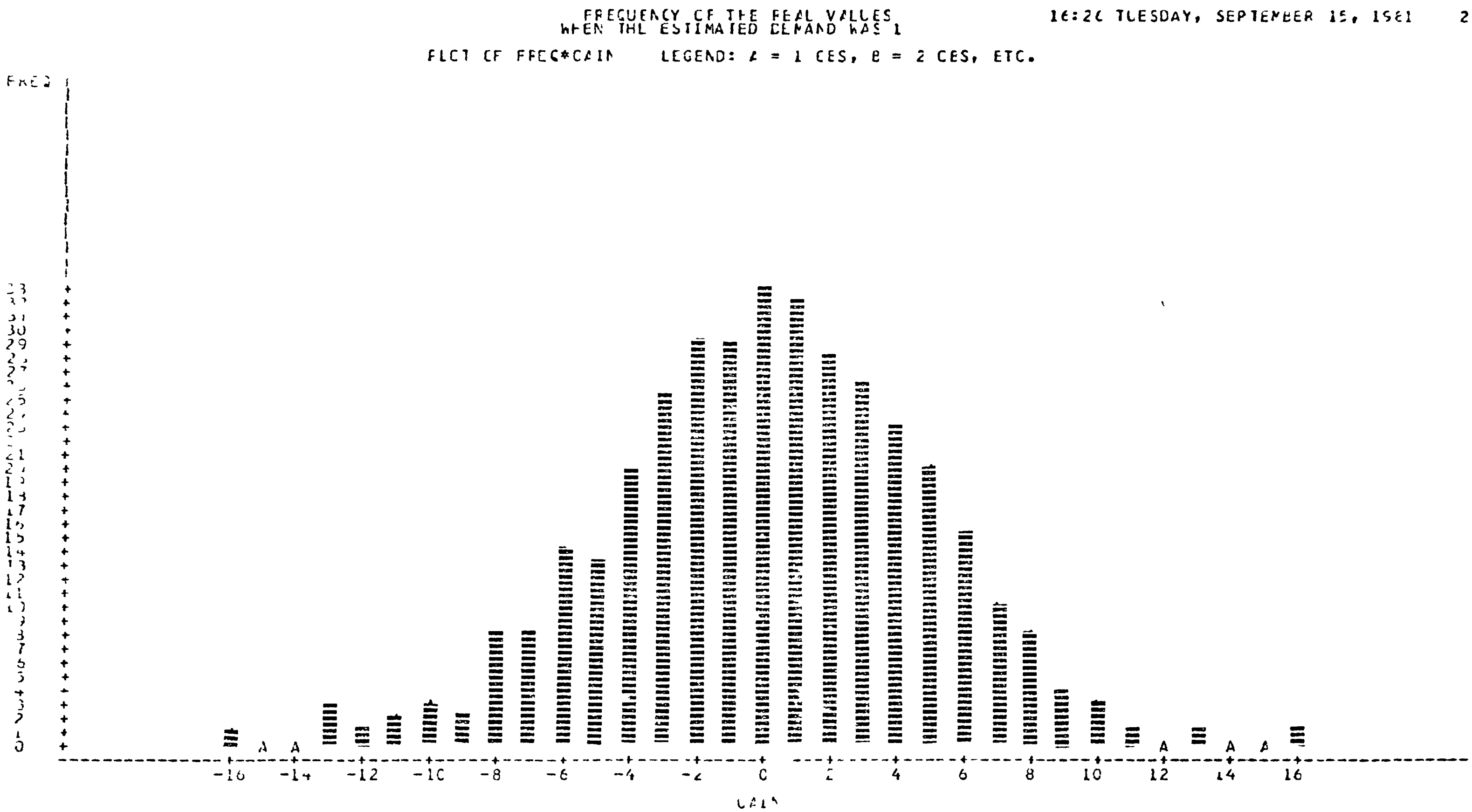


Figure 23. Frequency of the Real Values When the Estimated Demand Was One

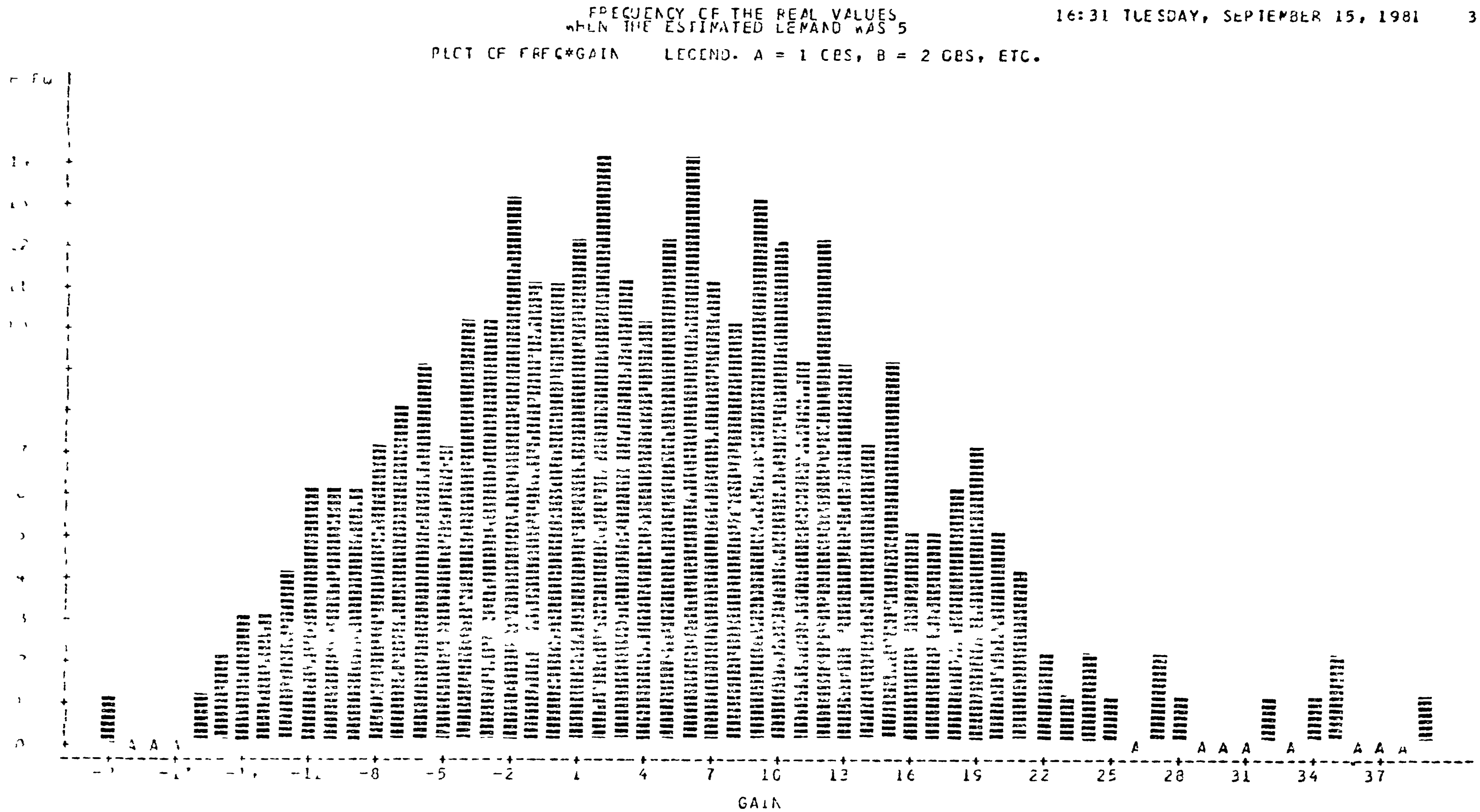


Figure 24. Frquency of the Real Values When the Estimated Demand Was Five

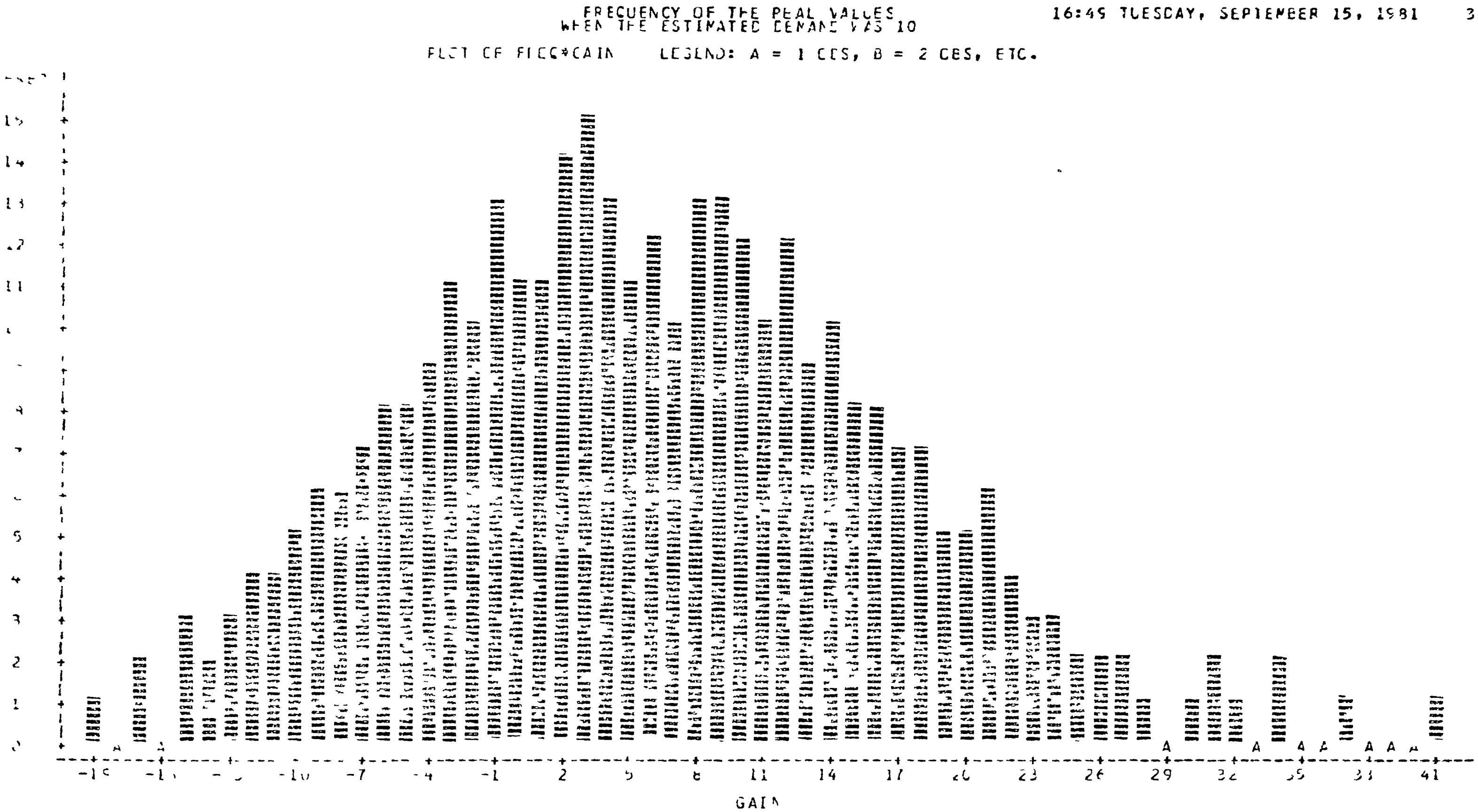


Figure 25. Frequency of the Real Values When the Estimated Demand Was Ten

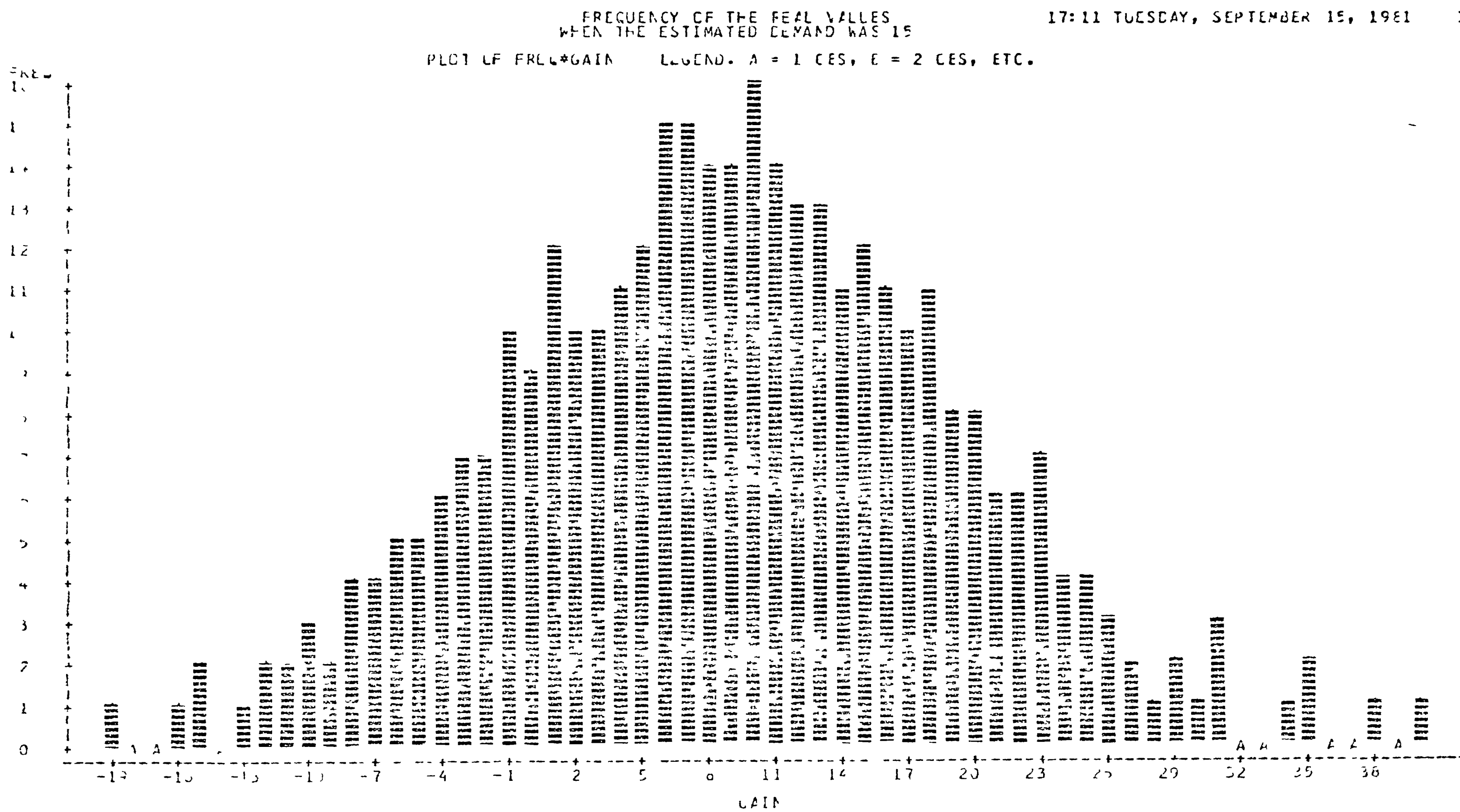


Figure 26. Frequency of the Real Values When the Estimated Demand Was Fifteen

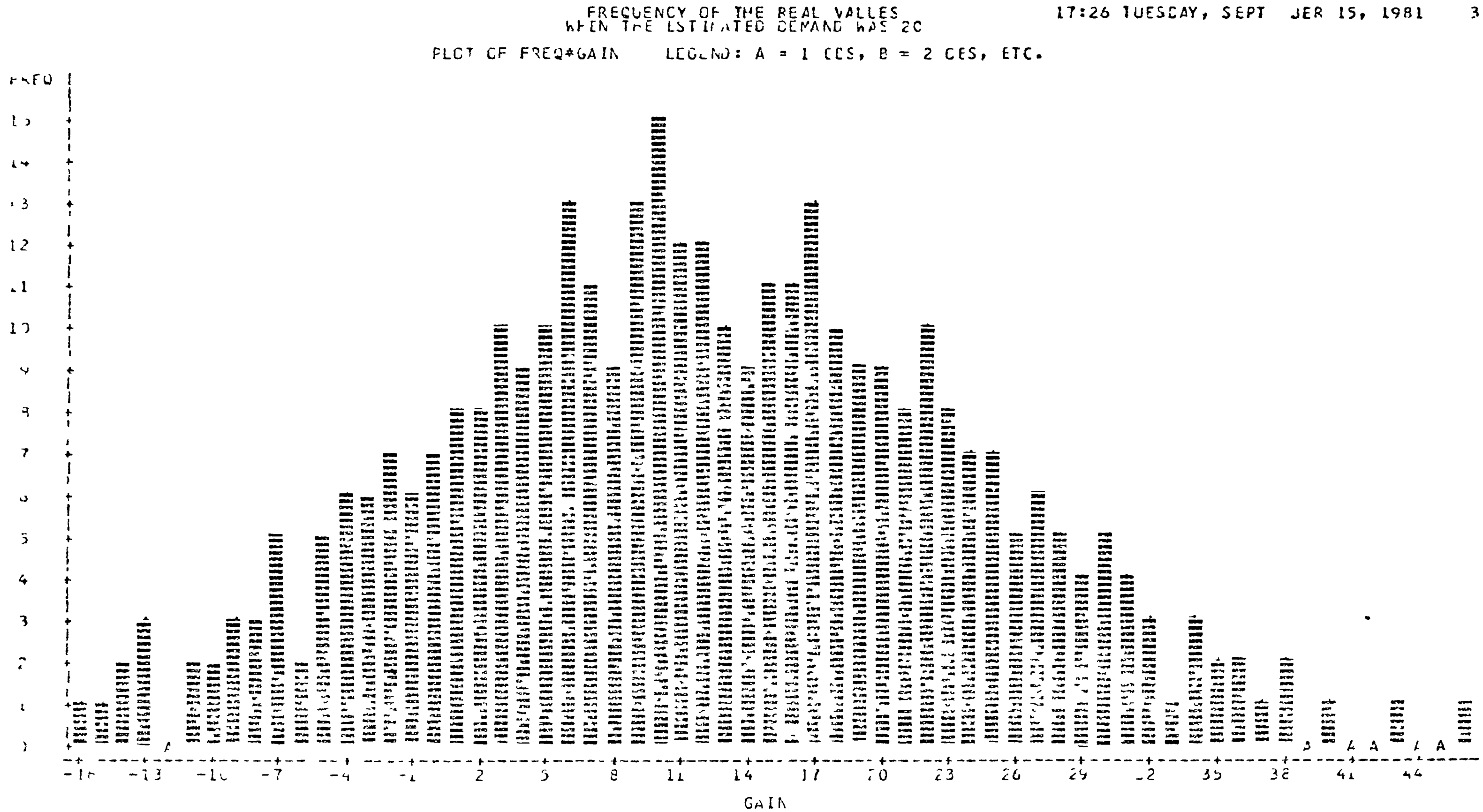


Figure 27. Frequency of the Real Values When the Estimated Demand Was Twenty

APPENDIX G

FORTRAN PROGRAM LISTINGS

TABLE XVIII

FORTRAN SOURCE LISTING OF THE PROGRAM CURVES USED TO CALCULATE THE NET PRESENT VALUE VS. EXTENT OF EXTENSIONS FOR DIFFERENT DEMAND VALUES

```
**********************************************************************
*                                                                    *
*                                                                    *
*   FORTRAN SOURCE LISTING OF THE PROGRAM CURVES USED TO CALCULATE   *
*   THE NET PRESENT VALUE VS. EXTENT OF EXTENSIONS FOR DIFFERENT     *
*   DEMAND VALUES.                                                   *
*                                                                    *
*                                                                    *
**********************************************************************

      DIMENSION DA(30),RESUL(25,14),F(30)
      INTEGER PAGE,P,TYPE(7)
      REAL INFLA,INTER,MANTE,MATR(175,2),LAMDA
C
C READ THE NAME OF THE CABLE
C
      READ(5,1)(TYPE(I),I=1,7)
    1 FORMAT (7A4)
C
C READ DATA ABOUT THE ECONOMY
C
      READ(5,2) INFLA,INTER,AUMAR
    2 FORMAT(3F10.2)
C
C CALCULATION OF RHO AND GAMA FOR THIS TYPE OF CABLE
C
      RHO=(1.+INFLA)/(1.+INTER)
      GAMA=(1.+AUMAR)/(1.+INTER)
C
C READ DATA RELATED TO THE TYPE OF CABLE
C
   40 READ(5,3) NUMDE
    3 FORMAT(I2)
      PAGE=0
      IF(NUMDE)1000,1000,50
   50 READ(5,4) LIFE,VALRE,MANTE,BETAO,BETA1
    4 FORMAT(I5,4F10.2)
C
C CALCULATION OF LAMDA FOR THIS TYPE OF CABLE
C
      X=((1.+MANTE)*RHO**LIFE)/(1.-RHO**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1.-GAMA**LIFE)
      LAMDA=1+X-Y
C
C READ DEMANDS TO BE CONSIDERED IN THIS RUN
C
      READ(5,5)(DA(I),I=1,NUMDE)
    5 FORMAT(16F5.1)
C
C CALCULATION OF F(L) FOR DEMANDS PROVIDED
C
      DO 300 I=1,NUMDE
  300 F(I)=(BETAO/BETA1)/DA(I)
C
C BEGINNING OF THE CALCULATION FOR EACH DEMAND
C
      DO 500 L=1,NUMDE
      DO 110 K=1,30
      TA=K
      TA=TA/10.
      MATR (K,1)=TA
      S=(RHO**TA)/(1.-RHO**TA)
      COST=LAMDA*(BETAO+BETA1*DA(L)*(TA+S*(F(L)+TA)))
      COST=COST/1000.
      MATR(K,2)=COST
```

TABLE XVIII (Continued)

```
  110 CONTINUE
      N=30
      DO 111 K=31,120
      N=N+2
      TA=N
      TA=TA/10
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      COST=LAMDA*(BETAO+BETA1*DA(L)*(TA+S*(F(L)+TA)))
      COST=COST/1000.
      MATR(K,2)=COST
  111 CONTINUE
      N=210
      DO 112 K=121,160
      N=N+5
      TA=N
      TA=TA/10.
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      COST=LAMDA*(BETAO+BETA1*DA(L)*(TA+S*(F(L)+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  112 CONTINUE
      N=41
      DO 113 K=161,165
      N=N+1
      TA=N
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      COST=LAMDA*(BETAO+BETA1*DA(L)*(TA+S*(F(L)+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  113 CONTINUE
      N=46
      DO 114 K=166,170
      N=N+2
      TA=N
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      COST=LAMDA*(BETAO+BETA1*DA(L)*(TA+S*(F(L)+TA)))
      COST=COST/1000.
      MATR(K,2)=COST
  114 CONTINUE
      N=50
      DO 115 K=171,175
      N=N+10
      TA=N
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      COST=LAMDA*(BETAO+BETA1*DA(L)*(TA+S*(F(L)+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  115 CONTINUE
C
C FORMATION OF MATRIX OF RESULTS
C
      DO 220 I=1,25
      RESUL(I,1)=MATR(I,1)
      RESUL(I,2)=MATR(I,2)
      RESUL(I,3)=MATR((I+25),1)
      RESUL(I,4)=MATR((I+25),2)
      RESUL(I,5)=MATR((I+50),1)
      RESUL(I,6)=MATR((I+50),2)
      RESUL(I,7)=MATR((I+75),1)
      RESUL(I,8)=MATR((I+75),2)
      RESUL(I,9)=MATR((I+100),1)
      RESUL(I,10)=MATR((I+100),2)
      RESUL(I,11)=MATR((I+125),1)
      RESUL(I,12)=MATR((I+125),2)
      RESUL(I,13)=MATR((I+150),1)
      RESUL(I,14)=MATR((I+150),2)
  220 CONTINUE
```

TABLE XVIII (Continued)

```
C
C PRINT RESULTS FOR THE DEMAND ANALYZED.
C
      PAGE=PAGE+1
      WRITE(6,20)
      WRITE(6,21) PAGE
      WRITE(6,22)
      WRITE(6,23)(TYPE(I),I=1,7)
      WRITE(6,24) DA(L)
      WRITE(6,25) INTER,MANIF
      WRITE(6,26) INFLA,AUMAR
      WRITE(6,27)
      DO 325 P=1,25
      WRITE(6,28)(RESUL(P,I),I=1,14)
  325 CONTINUE
  500 CONTINUE
C
C GO BACK TO READ AND PROCESS ANOTHER TYPE OF CABLE
C
      GO TO 40
   20 FORMAT('1',' ',/)
   21 FORMAT(' ',115X,'PAGE ',I2)
   22 FORMAT(4X,'NET PRESENT VALUE OF THE SERIE OF COSTS ASSOCIATED WITH
     1 EXPANDING THE CAPACITY OF THE TELEPHONE CABLES NETWORK')
   23 FORMAT(4X,'WITH CABLES OF THE TYPE   ',7A4,', AT DIFFERENT TAU INT
     1ERVALS OF TIME '/)
   24 FORMAT(4X,'*** NPV IS IN THOUSANDS, MONEY IS IN 1981 VALUE ***
     1      CALCULATIONS MADE FOR AN ANNUAL DEMAND OF     ',F6 2,' PAIRS
     2'//)
   25 FORMAT(4X,'VALUE OF THE PARAMETERS CONSIDERED FOR THIS RUN   COST
     1OF CAPITAL    ',F6 2,' ,  MAINTENANCE    ',F6 2)
   26 FORMAT(60X,'INFLATION    ',F6 2,' ,     DEFLATION    ',F6 2/)
   27 FORMAT(5X,7('TAU     NPV       ')/)
   28 FORMAT(3X,7(F5 1,1X,F7.0,3X)/)
 1000 STOP
      END
```

TABLE XIX

FORTRAN SOURCE LISTING OF THE PROGRAM (F(DA)F(TA) USED TO CALCULATE THE VALUES OF DEMAND AND CORRESPONDENT EXTENT OF EXTENSION TO OBTAIN THE MINIMUM NET PRESENT VALUE (NPV)

```
      ******************************************************************
      *                                                                *
      *                                                                *
      *   FORTRAN SOURCE LISTING OF THE PROGRAM F(DA)F(TA) USED TO     *
      *   CALCULATE THE VALUES OF DEMAND AND CORRESPONDENT EXTENT OF   *
      *   EXTENSION TO OBTAIN THE MINIMUM NET PRESENT VALUE (NPV)      *
      *                                                                *
      *                                                                *
      ******************************************************************

      DIMENSION RESUL (35,10)
      INTEGER PAGE,TITLE(40),O
      REAL INFLA,INTER
C
C READ DATA ON ECONOMIC SITUATION
C
      READ (5,1) INFLA,INTER
    1 FORMAT (2F10.4)
C
C READ PARAMETERS FOR THIS GROUP OF CABLES   BETA ZERO AND BETA ONE
C
      READ(5,2) BETAO,BETA1
    2 FORMAT (2F10.2)
C
C READ TYPE OF CABLE AND GROUP OF CABLES TO WHICH
C      THIS PARAMETERS CORRESPOND
C
      READ (5,3) (TITLE(I),I=1,10)
    3 FORMAT(10A4)
C
C CALCULATION AND INITIALIZATION OF CONSTANTS TO USE IN THIS RUN.
C
      MAXCA=300.
      RHO=(1 +INFLA)/(1 +INTER)
      A=1./ALOG(RHO)
      DELTAT = 0 02
      DELDE = 0 05
      DELTD = 0.05
      TA=100
      PAGE=0
      DA=0
C
C CALCULATIONS FOR ONE PAGE
C
  500 PAGE = PAGE + 1
C
C CALCULATION OF THE LEFT HAND SIDE OF THE OPTIMAL EXPRESION
C
      DO 100 K=1,25
      DA = DA + DELDE
C
C CALCULATION OF COLUMNS ONE TO FIVE OF MATRIX RESUL
C
      RESUL (K,1)=DA
      FDA=BETAO / (BETA1 * DA)
      RESUL(K,2)=FDA
C
C CALCULATION OF FTA
C
      KK=0
  220 KK=KK+1
      TA=TA-DELTAT
      S=(RHO**TA)/(1 -RHO**TA)
      FTA=(-A/S)-TA
      IF(FTA-FDA)222,222,223
  223 IF(KK-3000)220,220,301
  222 RESUL (K,3)=FTA
      RESUL (K,4)=TA
      RESUL (K,5)=DA*TA
      TA=TA+4*DELTAT
```

TABLE XIX (Continued)

```
C
C CALCULATION OF COLUMNS SIX TO TEN OF MATRIX RESUL
C
      DAD = DA + 25 * DFLDE
      RESUL(K,6)=DAD
      FDA=BETAO/(BETA1*DAD)
      RESUL (K,7)=FDA
      KK=0
      TAD = TA + 4 * DELTAT
  320 KK=KK+1
      TAD=TAD-DELTAT
      S=(PHO**TAD)/(1.-RHO**TAD)
      FTA=(-A/S)-TAD
      IF(FTA-FDA)322,322,323
  323 IF(KK-3000)320,320,302
  322 RESUL (K,8)-FTA
      RESUL (K,9)=TAD
      RESUL (K,10)=DAD*TAD
  100 CONTINUE
C
C PRINT RESULTS
C
      WRITE(6,4) PAGE
    4 FORMAT ('1',122X,'PAGE',I4)
      WRITE(6,5)
  5   FORMAT ('0',21X,'CALCULATION OF RELATIONS BETWEEN DA, F(DA), F(TA)
     1, TA AND CAPACITY')
      WRITE(6,6) INTER,INFLA
  6   FORMAT ('0',6X,'DATA CONSIDERED FOR THIS RUN   COST OF CAPITAL  -'
     1 ,F8 4,' ,  INFLATION   ',F8 4)
      WRITE (6,7)(TITLE(O),O=1,10),BETAO,BETA1
  7   FORMAT ('0',6X,10A4,10X,' BETA ZERO . ',F11.2,'  BETA ONE   ',F11.
     12/)
      WRITE(6,8)
    8 FORMAT('0',8X,'DA',8X,'F(DA)',6X,'F(TA)',7X,'TA',6X,'CAPACITY ',18
     1X,'DA',8X,'F(DA)',7X,'F(TA)',6X,'TA',6X,'CAPACITY ')
      WRITE(6,9)
    9 FORMAT(' ',132X)
      DO 110 I=1,25
      WRITE(6,10)(RESUL(I,J), J=1,10)
   10 FORMAT('0',5X,F7 2,4X,F7 2,4X,F7 2,4X,F7 2,4X,F7 2,8X,'*',8X,F7 2,
     14X,F7 2,4X,F7 2,4X,F7.2,4X,F7 2)
  110 CONTINUE
C
C IF LAST PAGE DID NOT CONTAINED RESULTS FOR
C AT LEAST 20 MORE PAIRS, INCREASE DELTAT
C
      DIFF = RESUL(25,10) - RESUL(1,5)
      IF(DIFF.LT.20) DELDE = DELDE + DELTD
C
C CHECK FOR TERMINATION *****
C IF THE LAST VALUE IN LAST COLUMN  WAS GREATER THAN MAXCA + 100, STOP.
C
      IF(RESUL(25,10) GE (MAXCA + 100.)) GO TO 1000
C
C INCREMENT LAST TA IN ORDER TO HAVE A HIGHER POINT WHERE TO START
C THE SEARCH FOR THE RHS IN THE CALCULATIONS FOR NEXT PAGE
C
      TA = TA + 4 * DELTAT
      DA = DAD
      GO TO 500
  301 WRITE(6,11)
 11   FORMAT('1',5X,'IT IS REQUIRED TO INCREASE THE LIMIT OF KK, IN COL.
     1 1')
  302 WRITE(6,12)
 12   FORMAT('1',5X,'IT IS REQUIRED TO INCREASE THE LIMIT OF KK, IN COL
     1 2')
 1000 STOP
      END
```

TABLE XX

FORTRAN SOURCE LISTING OF THE PROGRAM PERCENT USED TO PROVIDE POLICIES OF EXPANSION FOR OPTIMAL AND SUBOPTIMAL NET PRESENT VALUE (NPV) FOR DIFFERENT DEMAND VALUES

```
 ********************************************************************
 *                                                                  *
 *                                                                  *
 *  FORTRAN SOURCE LISTING OF THE PROGRAM PERCENT USED TO PROVIDE   *
 *  POLICIES OF EXPANSION FOR OPTIMAL AND SUBOPTIMAL NET PRESENT    *
 *  VALUF (NPV) FOR DIFFERENT DEMAND VALUES                         *
 *                                                                  *
 *                                                                  *
 ********************************************************************

      DIMENSION DA(25),PER(3),PERC(3),RESUL(25,16),RES(25)
      INTEGER TYPE(7),PAGE
      REAL INFLA,INTER,MANTE,LAMDA
C
C READ THE NAME OF THE CABLE
C
      READ(5,1)(TYPE(I),I=1,7)
    1 FORMAT(7A4)
C
C READ DATA ABOUT THE ECONOMY
C
      READ(5,2) INFLA,INTER,AUMAR
    2 FORMAT(3F10 2)
C
C READ DATA RELATED TO THE TYPE OF CABLE
C
      READ(5,3) LIFE,VALRE,MANTE,BETAO,BETA1
    3 FORMAT(I5,4F10 2)
C
C READ NEXT THREE PERCENTACE VALUES DESIRED TO CONSIDER OVER THE
C                MINIMUM COST
C
      READ(5,5)(PER(1),I=1,3)
    5 FORMAT(3F6 2)
C
C CALCULATION OF RHO, GAMA AND LAMDA FOR THIS TYPE OF CABLE
C
      RHO=(1 +INFLA)/(1 +INTER)
      GAMA=(1 +AUMAR)/(1.+INTER)
      X=((1 +MANTE)*RHO**LIFE)/(1 -RHO**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1.-GAMA**LIFE)
      LAMDA=1+X-Y
C
C INITIALIZATION OF PARAMETERS
C
      TA=100.
      A=1./ALOG(RHO)
      PAGE=0
      DELTAT = 0 02
      DELTR=0.4
      DELRI=DELTR
      DELTL=0 02
      DLEFT=DELTL
      TEST=500.
C
C READ THE NEXT 25 DIFFERENT VALUES OF DEMAND TO USE IN THIS RUN
C
   55 READ(5,4)(DA(I),I=1,25)
    4 FORMAT(13F6 1)
C
C CHECK IF NO MORE DATA REMAINS
C
      IF(DA(1) LE 0 ) GO TO 1000
C
C CALCULATION OF OPTIMAL VALUES FOR THE DEMANDS PROVIDED
C
      DO 50 L=1,25
      RESUL(L,1)=DA(L)
```

TABLE XX (Continued)

```
C
C CALCULATION OF LHS IN OPTIMAL EXPRESION
C
      FDA=BETA0/(BETA1 * DA(L))
C
C CALCULATION OF OPTIMAL VALUES (COLUMNS 2,3 AND 4 OF MATRIX RESUL)
C
      KK=0
   51 KK=KK+1
      TA=TA-DELTAT
      S=(RHO**TA)/(1 -RHO**TA)
      FTA=(-A/S)-TA
      IF(FTA-FDA)52,52,53
   53 IF(KK-9000)51,51,301
   52 RESUL(L,2)=TA
      RESUL(L,3)=DA(L)*TA
      FL=(BETA0/BETA1)/DA(L)
      RES(L)=LAMDA*(BETA0+BETA1*DA(L)*(TA+S*(FL+TA)))
      RESUL(L,4)=RES(L)/1000.
   50 CONTINUE
C
C CALCULATE COLUMNS 5 TO 16 OF MATRIX RESUL
C
      DO 59 L=1,25
      TAULE=RESUL(L,2)
      TAURI=RESUL(L,2)
      FL=(BETA0/BETA1)/DA(L)
      DO 60 I=1,3
      COSTI=(1 +PER(I))*RES(L)
C
C CALCULATION FOR BEFORE-OPTIMAL VALUES
C
   61 TAULE=TAULE-DELTL
      IF(TAULE LE 0 ) GO TO 998
      SLEFT=(RHO**TAULE)/(1 -RHO**TAULE)
      CLEFT=LAMDA*(BETA0+BETA1*DA(L)*(TAULE+SLEFT*(FL+TAULE)))
      IF(CLEFT-COSTI)61,62,62
   62 IF((CLEFT-COSTI) GT TEST) GO TO 101
      RESUL(L,1+4*I)=TAULE
      RESUL(L,2+4*I)=TAULE * DA(L)
      DELTL=DLEFT
C
C CALCULATION FOR AFTER-OPTIMAL VALUES
C
   65 TAURI=TAURI + DELRI
C
C TEST IF THE TIME IS GREATER THAN 150 YEARS
C
      IF(TAURI GT 999 ) GO TO 999
      SRIGH=(RHO**TAURI)/(1 -RHO**TAURI)
      CRIGH=LAMDA*(BETA0+BETA1*DA(L)*(TAURI+SRIGH*(FL+TAURI)))
      IF(CRIGH-COSTI)65,66,66
   66 IF((CRIGH-COSTI) GT TEST) GO TO 102
      RESUL(L,3+4*I)=TAURI
      RESUL(L,4+4*I)=TAURI*DA(L)
      DELRI=DELTR
   60 CONTINUE
   59 CONTINUE
C
C PRINT RESULTS FOR THIS SET OF PERCENTAGES AND DEMANDS
C
      PAGE=PAGE+1
      WRITE(6 10) PAGE
   10 FORMAT('1',123X,'PAGE ',I2)
      WRITE(6,11)
   11 FORMAT(' ',3X,'VALUES OF TAU (INFERIOR AND SUPERIOR) AND THEIR COR
     1RESPONDENT CAPACITY FOR A NPV')
      WRITE(6,12)(TYPE(I),I=1,7)
   12 FORMAT(' ',3X,'GREATER THAN THE OPTIMAL, IN DIFFERENT PERCENTAGES
     1, FOR THE GROUP OF CABLES      ',7A4//)
```

TABLE XX (Continued)

```
      WRITE(6,13)
   13 FORMAT(' ',33X,'+------------------------------------------------------
     1--------- -------------------------------------+')
      WRITE(6,15)
   15 FORMAT(' ',5X,'*** COST IN THOUSANDS ***',3X,'+',10X,'CORRESPONDEN
     1T VALUES FOR A DEVIATION FROM THE OPTIMAL COST, OF
     2      +')
      WRITE(6,16)
   16 FORMAT(' ',' +--------+------------------------+---------------------
     1----------+---------------------------------+----------------------
     2---------+')
      DO 30 I=1,3
   30 PERC(I)=PER(I) * 100
      WRITE(6,17)(PERC(I),I=1,3)
   17 FORMAT(' ',' +         +    O P T I M A L     +',3(6X,F5 1,' PERCE
     1NTAGE        +'))
      WRITE(6,18)
   18 FORMAT(' ',' + ANNUAL +------------------------+-----------------+----
     1----------+---------------+-----------------+---------------+------
     2---------+')
      WRITE(6,19)
   19 FORMAT(' ',' + DEMAND +  TAU     CAP.   COST + TLEFT    CAP  + TRI
     1GHT   CAP  + TLEFT    CAP  + TRIGHT   CAP  + TLEFT    CAP  + TRIGH
     2T   CAP. +')
      WRITE(6,20)
   20 FORMAT(' ',' +--------+- ----------------------+-----------------+----
     1----------+---------------+-----------------+---------------+------
     2---------+')
C
      DO 26 K=1,25
      WRITE(6,21)
   21 FORMAT(' ',' +         ¦                        ¦                 ¦
     1          ¦               ¦                 ¦               ¦
     2         +')
      WRITE(6,22)(RESUL(K,J),J=1,16)
   22 FORMAT(' ',' + ',F5 1,' ¦ ',F5 2,F8 1,F7.1,' ¦',6(F6.2,F8 1,' ¦')
     1)
   26 CONTINUE
      WRITE(6,20)
C
C GO BACK TO READ NEXT SET OF DEMANDS
C
      GO TO 55
C
  C REDUCE DELTL TO GET BETTER APPROXIMATION FOR THE DIFFERENCE CLEFT-COST
C
  101 TAULE=TAULE+DELTL
      DELTL=DELTL*0 5
      GO TO 61
  102 TAURI=TAURI-DELRI
      DELRI=DELRI*0 5
      GO TO 65
  301 WRITE(6,23)
   23 FORMAT('1',3X,'IT IS REQUIRED TO INCREASE THE NUMBER OF ITERATIONS
     1 ( KK VALUE ) FOR SEARCHING WHEN FDA = FIA  (STATEMENT #      ) ')
      GO TO 1000
  998 WRITE(6,24)
   24 FORMAT('1',3X,'IT IS REQUIRED TO MAKE DELTL SMALLER (STATEMENT #
     1    )')
      GO TO 1000
  999 WRITE(6,25)
   25 FORMAT('1',3X,'IT IS REQUIRED TO MAKE LARGER THE LIMIT TO THE RIGH
     1T SIDE')
 1000 STOP
      END
```

TABLE XXI

FORTRAN SOURCE LISTING OF THE PROGRAM CABLES USED TO CALCULATE THE NET PRESENT VALUE OF EXPANDING THE NETWORK WITH A SPECIFIC CABLE AND THE EXTENT OF EXTENSION

```
********************************************************************
*                                                                  *
*                                                                  *
*   FORTRAN SOURCE LISTING OF THE PROGRAM CABLES USED TO CALCULATE *
*   THE NET PRESENT VALUE OF EXPANDING THE NETWORK WITH A SPECIFIC *
*   CABLE FOR DIFFERENT VALUES OF EXTENT OF EXTENSION              *
*                                                                  *
*                                                                  *
********************************************************************

      DIMENSION RESUL(25,14)
      REAL INFLA,INTER,MANTE,LAMDA,MATR(1/5,2)
      INTEGER PAGE,P,TYPE(7),CAP(30)
C
C READ THE NAME OF THE CABLE
C
      READ(5,1)(TYPE(I),I=1,7)
    1 FORMAT (7A4)
C
C READ DATA ABOUT THE ECONOMY
C
      READ(5,2) INFLA,INTER,AUMAR
    2 FORMAT(3F10 2)
C
C CALCULATION OF PHO AND GAMA FOR THIS TYPE OF CABLE
C
      RHO=(1 +INFLA)/(1 +INTER)
      GAMA=(1 +AUMAR)/(1 +INTER)
C
C READ DATA RELATED TO THE TYPE OF CABLE
C
   50 READ(5,4) LIFE,VALRE,MANTE,BETAO,BETA1
    4 FORMAT(I5,4F10 2)
      IF(LIFF)1000,1000,40
   40 PAGE=0
C
C CALCULATION OF LAMDA FOR THIS TYPE OF CABLE
C
      X=((1 +MANTE)*RHO**LIFE)/(1 -RHO**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1 -GAMA**LIFE)
      LAMDA=1 +X-Y
C
C READ NUMBER OF CAPACITIES TO BE WORKED.
C
C
      READ(5,5) NC
    5 FORMAT(I2)
C
C READ CAPACITY OF CABLES TO BE CONSIDERED
C
      READ(5,6)(CAP(I),I=1,NC)
    6 FORMAT(16I5)
C
C CALCULATION OF NPV FOR EACH CABLE
C
C
C
      DO 500 L=1,NC
      DO 110 K=1,30
      TA=K
      TA=TA/10
      MATR (K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      DA=CAP(L )/TA
      F=(BETAO/BETA1)/DA
      COST=LAMDA*(BETAO+BETA1*DA*(TA+S*(F+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  110 CONTINUE
```

TABLE XXI (Continued)

```
      N=30
      DO 111 K=31,120
      N=N+2
      TA=N
      TA=TA/10
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      DA=CAP(L)/TA
      F=(BETA0/BETA1)/DA
      COST=LAMDA*(BETA0+BETA1*DA*(TA+S*(F+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  111 CONTINUE
      N=210
      DO 112 K=121,160
      N=N+5
      TA=N
      TA=TA/10
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      DA=CAP(L)/TA
      F=(BETA0/BETA1)/DA
      COST=LAMDA*(BETA0+BETA1*DA*(TA+S*(F+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  112 CONTINUE
      N=41
      DO 113 K=161,165
      N=N+1
      TA=N
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      DA=CAP(L)/TA
      F=(BETA0/BETA1)/DA
      COST=LAMDA*(BETA0+BETA1*DA*(TA+S*(F+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  113 CONTINUE
      N=46
      DO 114 K=166,170
      N=N+2
      TA=N
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      DA=CAP(L)/TA
      F=(BETA0/BETA1)/DA
      COST=LAMDA*(BETA0+BETA1*DA*(TA+S*(F+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  114 CONTINUE
      N=50
      DO 115 K=171,175
      N=N+10
      TA=N
      MATR(K,1)=TA
      S=(RHO**TA)/(1 -RHO**TA)
      DA=CAP(L)/TA
      F=(BETA0/BETA1)/DA
      COST=LAMDA*(BETA0+BETA1*DA*(TA+S*(F+TA)))
      COST=COST/1000
      MATR(K,2)=COST
  115 CONTINUE
```

TABLE XXI (Continued)

```
C
C FORMATION OF MATRIX OF RESULTS
C
      DO 220 I=1,25
      RESUL(I,1)=MATR(I,1)
      RESUL(I,2)=MATR(I,2)
      RESUL(I,3)=MATR((I+25),1)
      RESUL(I,4)=MATR((I+25),2)
      RESUL(I,5)=MATR((I+50),1)
      RESUL(1,6)=MATR((I+50),2)
      RESUL(1,7)=MATR((I+75),1)
      RESUL(1,8)=MATR((I+75),2)
      RESUL(1,9)=MATR((I+100),1)
      RESUL(1,10)=MATR((I+100),2)
      RESUL(1,11)=MATR((I+12 ),1)
      RESUL(I,1 )=MATR((I+125),2)
      RESUL(I,13)=MATR((I+150),1)
      RESUL(I,14)=MATR((I+150),2)
  220 CONTINUE
C
C PRINT RESULTS FOR THE DEMAND ANALYZED
C
      PAGE=PAGE+1
      WRITE(6,20)
      WRITE(6,21) PAGE
      WRITE(6,22)
      WRITE(6,23)(TYPE(I),I=1,7)
      WRITE(6,24) CAP(L)
      WRITE(6,25) INTER,MANTF,BETAO
      WRITE(6,26) INFLA,AUMAR,BETA1
      WRITE(6,27)
      DO 325 P=1,25
      WRITE(6,28)(RESUL(P,I),I=1,14)
  325 CONTINUE
  500 CONTINJE
C
C GO BACK TO READ AND PROCESS ANOTHER TYPE OF CABLE
C
      GO TO 50
  20  FORMAT('1',' ',/)
  21  FORMAT(' ',115X,'PAGE ',I2)
  22  FORMAT(4X,'NET PRESENT VALUE OF THE SERIE OF COSTS ASSOCIATED WITH
     1 EXPANDING THE CAPACITY OF THE TELEPHONE CABLES NETWORK')
  23  FORMAT(4X,'WITH CABLES OF THE TYPE   ',7A4,', AT DIFFERENT TAU INT
     1ERVALS OF TIME '/)
  24  FORMAT(4X,'*** NPV IS IN THOUSANDS, MONEY IS IN 1981 VALUE ***
     1     CALCULATIONS MADE FOR A CABLE OF CAPACITY OF   ',I4,' PAIRS.'
     2//)
  25  FORMAT(4X,'VALUE OF THE PARAMETERS CONSIDERED FOR THIS RUN   COST
     1OF CAPITAL   ',F6 2,' ,  MAINTENANCE   ',F6 2,' , BETAO = ,F10 0)
  26  FORMAT(60X,'INFLATION   ',F6.2,' ,    DEFLATION   ',F6.2,' , BETA1
     1 =',F10 0//)
  27  FORMAT(5X,7('TAU    NPV      ')/)
  28  FORMAT(3X,7(F5 1,1X,F7 1,3X)/)
 1000 STOP
      END
```

TABLE XXII

FORTRAN SOURCE LISTING OF THE PROGRAM BOUND USED TO CALCULATE THE RANGE OF DEMAND VALUES TO PRODUCE A NET PRESENT VALUE WHICH IS AT MOST A PRE-SPECIFIED PERCENT OVER THE MINIMUM

```
  ********************************************************************
  *                                                                  *
  *                                                                  *
  *   FORTRAN SOURCE LISTING OF THE PROGRAM BOUND USED TO CALCULATE  *
  *   THE RANGE OF DEMAND VALUES TO PRODUCE A NET PRESENT VALUE      *
  *   WHICH IS AT MOST A PRE-SPECIFIED PERCENT OVER THE MINIMUM COST *
  *                                                                  *
  *                                                                  *
  ********************************************************************

      DIMENSION RES(50,1,),PER(7),CAB(50),P(7)
      INTEGER PAGE,TITLE(24)
      REAL INFLA,INTER,MANTE,LAMDA,LHS,LIFE
      COMMON TDUMM,LAMDA,BETAO,BETA1,RHO
C
C READ DATA ON ECONOMIC SITUATION
C
      READ(5,1) INFLA,INTER,AUMAR
    1 FORMAT(3F10 4)
C
C READ TYPE OF CABLE
C
      READ(5,3)(TITLE(I),I=1,6)
    3 FORMAT(6A4)
C
C READ PARAMETERS FOR THIS GROUP OF CABLES
C
      READ(5,2) BETAO,BETA1,LIFE,VALRE,MANTE
    2 FORMAT(5F10 2)
C
C READ PERCENTAGES TO CONSIDER OVER THE MINIMUM COST
C
      READ(5,4) (PER(I),I=1,7)
    4 FORMAT(7F10 2)
C
C READ NUMBER OF CABLES TO CONSIDER IN THIS RUN
C
      READ(5,5) N
    5 FORMAT(I2)
C
C READ CABLES TO CONSIDER IN THIS RUN
C
      READ(5,6)(CAB(I),I=1,N)
    6 FORMAT(20F4 0)
C
C CALCULATION AND INITIALIZATION OF CONSTANTS TO USE IN THIS RUN.
C
      GAMA=(1 +AUMAR)/(1 +INTER)
      RHO=(1 +INFLA)/(1 +INTER)
      A=1 /ALOG(RHO)
      DELTAT = 0.1
      PAGE = 0
      LINES = 0
      X=((1 +MANTE)*RHO**LIFE)/(1 -RHO**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1 -GAMA**LIFE)
      LAMDA=1 +X-Y
C
C CALCULATION OF VALUES FOR EACH PROVIDED CABLE
C
      DO 50 I=1,N
      RES(I,1)=CAB(I)
```

TABLE XXII (Continued)

```
C
C CALCULATION OF OPTIMAL VALUES OF TAU AND DEMAND FOR THIS CAFLE
C
      DELTA=0 1
      TAK=0.0
      DK=0 0
      TA = 0 0
 51   TA-TA + DELTA
      IF(TA GT 100 ) GC TO 1001
      TAP=TAK
      TAK=TA
C
C   CALCULATE LHS AND RHS
C
      LHS=TA*BETA0*1 /(BETA1*CAB(I))
      RHS=(-A*(1 -RHO**TA)/RHO**TA) - TA
      DP=DK
      DK=RHS-LHS
C
C    OPTIMAL VALUES HAVE BEEN REACHED ?
C
      IF(RHS-LHS) 51,55,55
C
C    LINEAR INTERPOLATION TO APPROXIMATE TX
C
  55  DT=TAK-TAP
      DMINU = DP
      DPLUS=DK
      TX=TAP - DT * DMINU/(DPLUS-DMINU)
      DEMX=CAB(1)/TX
      RES(I,2)=DEMX
      RES(I,3)=TX
C
C    CALCULATION OF MINIMUM COST
C
      S=(RHO**TX)/(1 -RHO**TX)
      F=(BETA0/BETA1)/DEMX
      CMIN=LAMDA*(BETA0+BETA1*DEMX*(TX+S*(F+TX)))
      TDUMM=TX
C
C CALCULATION OF COLUMNS 4 TO 17 OF MATRIX OF RESULTS 'RES'
C
      DO 50 J=1,7
      PERC=PER(J)
      CABLE=CAB(I)
      CALL BOUND(PERC,CABLE,CMIN,DENEW,TNEW)
      IF(TNEW EQ 0 0) GO TO 1002
      RES(I,(2*J+2)) = DENEW
      RES(I,(2*J+3)) = TNEW
50    CONTINUE
C
C PRINT RESULTS
C
      K=0
      DO 800 I=1,7
800   P(I)=PER(I) * 100
600   WRITE(6,500)
      PAGE = PAGE + 1
      WRITE(6,700) PAGE
700   FORMAT(122X,'PAGE ',I2,/)
      WRITE(6,701)
701   FORMAT(4X,'CALCULATION  OF  DEMANDS  AND  CORRESPONDENT  STAGE  OF
     1 EXTENSION  (TAU)  TO  PRODUCE  A  NET  PRESENT  VALUE  WHICH  IS
     2'/)
```

TABLE XXII (Continued)

```
      WRITE(6,702) (TITLE(I),I=1,6)
702   FORMAT(4X,'GREATER  THAN  THE  MINIMUM  COST  BY  THE  INDICATED
     1PERCENTAGES,  FOR  THE  GROUP  OF  CABLES   ',6A4,2(/))
      WRITE(6,703)
703   FORMAT(13X,'VALUES THAT')
      WRITE(6,704)
704   FORMAT(12X,'GIVE  OPTIMAL    VALUE  OF  DEMAND  (UPPER BOUND)  AND
     1  CORRESPONDENT  TAU  THAT  INCREASE THE MINIMUM  COST  BY')
      WRITE(6,705)
705   FORMAT(13X,'POLICY  FOR')
      WRITE(6,706)(P(I),I=1,7)
706   FORMAT(2X,'           THIS  CABLE       ',F4 0,'%',6(10X,F4 0,'%'))
      WRITE(6,707)
707   FORMAT( ,2X, CABLE OF  ',8('------ ------  '))   '
      WRITE(6,708)
708   FORMAT(/,3X,'(PAIRS)',8('  DEMAND   TAU '),2(/))
      LINES=13
710   K=K+1
      WRITE(6,709)(RES(K,L),L=1,17)
709   FORMAT(/,4X,F4 0,2X,8(2X,F6 2,2X,F5 2))
      IF(K GE N) GO TO 999
      LINES=LINES+2
      IF(LINES GE 52) GO TO 600
      GO TO 710
1001  WRITE(6,500)
      WRITE(6,499)
 499  FORMAT(10X,'RUN WAS ABORTED BECAUSE IN SEARCHING FOR THE OPTIMAL V
     1ALUES, TA BECOMED GREATER THAN 100 YEARS')
      GO TO 1000
1002  WRITE(6,500)
 500  FORMAT('1',' ',//)
      WRITE(6,501)
 501  FORMAT(10X,'RUN WAS ABORTED BECAUSE TDUMM WAS ALMOST ZERO')
999   WRITE(6,500)
1000  STOP
      END
      SUBROUTINE BOUND(PER,CABLE,CMIN,DENEW,TNEW)
      COMMON TDUMM,LAMDA,BETA0,BETA1,RHO
      REAL LAMDA
      TDELT=0 05
      CTEST=CMIN
      CPER=CMIN*(1 +PER)
10    TPREV=TDUMM
      TDUMM=TDUMM-TDELT
      IF(TDUMM LT 0 05) GO TO 100
      DENEW=CABLE/TDUMM
      F=(BETA0/BETA1)/DENEW
      S=(RHO**TDUMM)/(1 -RHO**TDUMM)
      CPREV=CTEST
      CTEST=LAMDA*(BETA0+BETA1*DENEW*(TDUMM+S*(F+TDUMM)))
C
C CPER HAS BEEN REACHED ?
C
      IF(CTEST GE CPER) GO TO 20
      GO TO 10
100   TNEW=0 0
      DENEW=0 0
      RETURN
20    TNEW=TPREV+(CPER-CPREV)*(TDUMM-TPREV)/(CTEST-CPREV)
C
C UP DATE TDUMM FOR NEXT PERCENT
C
      TDUMM=TDUMM+TDELT
      RETURN
      END
```

TABLE XXIII

FORTRAN SOURCE LISTING OF THE PROGRAM UNCERT USED TO CALCULATE THE COST ASSOCIATED WITH A POLICY OF EXPANSION TO PROVIDE PROTECTION FOR A DESIRED LEVEL OF UNCERTAINTY ON THE REAL DEMAND

```
*********************************************************************
*                                                                   *
*                                                                   *
*   FORTRAN SOURCE LISTING OF THE PROGRAM UNCERT  USED TO CALCULATE *
*   THE COST ASSOCIATED WITH A POLICY OF EXPANSION TO PROVIDE       *
*   PROTECTION FOR A DESIRED LEVEL OF UNCERTAINTY ON THE REAL       *
*   DEMAND.                                                         *
*                                                                   *
*                                                                   *
*********************************************************************

      DIMENSION RES(12,4),TDEM(50),STDEV(50)
      INTEGER PAGE,TITLE(24)
      REAL INFLA,INTER,MANTE,LAMDA,LHS,LIFE,MEAND(50),MEAN
      COMMON BETA0,BETA1,LAMDA,RHO,A
C
C READ DATA ON ECONOMIC SITUATION
C
      READ(5,1) INFLA,INTER,AUMAR
    1 FORMAT(3F10 4)
C
C READ TYPE OF CABLE
C
      READ(5,2)(TITLE(I),I=1,6)
    2 FORMAT(6A4)
C
C READ PARAMETERS FOR THIS GROUP OF CABLES
C
      READ(5,3) BETA0,BETA1,LIFE,VALRE,MANTE
    3 FORMAT(5F10 2)
C
C READ THE NUMBER OF THRESHOLD DEMAND VALUES TO CONSIDER IN THIS RUN
C
      READ(5,4) N
    4 FORMAT(I2)
C
C READ THE THRESHOLD VALUES OF DEMAND TO CONSIDER IN THIS RUN.
C
      READ(5,5)(TDEM(K),K=1,N)
    5 FORMAT(16F5 0)
C
C CALCULATION AND INITIALIZATION OF CONSTANTS TO USE IN THIS RUN
C
      GAMA=(1 +AUMAR)/(1 +INTER)
      RHO=(1 +INFLA)/(1 +INTER)
      A=1 /ALOG(RHO)
      X=((1 +MANTE)*RHO**LIFE)/(1 -RHO**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1 -GAMA**LIFE)
      LAMDA=1 +X-Y
C
C READ PARAMETERS OF THE NORMAL PROBABILITY DISTRIBUTIONS
C OF THE REAL DEMANDS, TO CONSIDER IN THIS RUN
C
      DO 8 K=1,N
    8 READ(5,6) MEAND(K),STDEV(K)
    6 FORMAT(2F15 4)
C
C ****** PROCESS BEGINS ******
C
      DO 20 K=1,N
      PAGE=0
C
C CALCULATE THE MINIMUM COST FOR THIS THRESHOLD DEMAND
C
      DEM=TDEM(K)
      CTMIN=CMIN(DEM)
      IF(CTMIN.LT 0.) GO TO 1001
C
C BEGINS CALCULATION OF CORRESPONDENT UNCERTANITY FOR EACH REAL DEMAND
C BETWEEN 1 AND 50 PAIRS PER YEAR
C (REAL = REAL DEMAND (IN OPPOSITION TO THE ESTIMATED THRESHOLD DEMAND)
```

TABLE XXIII (Continued)

```
C
        DO 30 I=1,72
        RES(I,1)=FLOAT(I)
        DREAL=RES(I,1)
C
C CALCULATION OF THE LEVEL OF UNCERTANITY CORRESPONDENT TO THIS DEMAND
C
       MEAN=MEAND(K)
       STD=STDEV(K)
       PROB=GINT(DREAL,MEAN,STD)
       RES(I,2)=PROB*100.
C
C CALCULATION OF THE MINIMUM COST FOR THIS REAL DEMAND
C
       CRMIN=CMIN(DREAL)
       IF(CRMIN LT 0 ) GO TO 1001
       RES(1,3)=CRMIN/1000
C
C CALCULATION OF CTMIN/CRMIN
C
       RELAC=CRMIN/CTMIN
       RELAC=(RELAC - 1 )*100
       RES(I,4)=RELAC
30     CONTINUE
C
C PRINT RESULTS
C
       LL=0
2000   PAGE=PAGE+1
       WRITE(6,600) PAGE
600    FORMAT('1',122X,'PAGE ',I2)
       WRITE(6,601)(TITLE(L),L=1,6)
601    FORMAT(8X,'RELATION BETWEEN THE COST OF AN EXPANSION POLICY FOR A
      1NETWORK WITH CABLES OF THE TYPE . ',6A4,/)
       WRITE(6,602) TDEM(K)
602    FORMAT(13X,'TO  SECURE  THE  UNCERTANITY  LEVELS  SHOWN,  FOR  A
      1THRESHOLD  ESTIMATED  DEMAND  OF    ',F4.1,'  PAIRS ',/)
       WRITE(6,603)
603    FORMAT(83X,'% (RCMIN) IS OVER THE')
       WRITE(6,604)
604    FORMAT(59X,'OPTIMAL COST (RCMIN)',6X,'MINIMUM  COST')
       WRITE(6,605)
605    FORMAT(67X,'FOR',15X,'CORRESPONDENT  TO')
       WRITE(6,606)
606    FORMAT(42X,'CORRESPONDENT',6X,'THIS REAL DEMAND',8X,'AN OPTIMAL PO
      1LICY')
       WRITE(6,607)
607    FORMAT(34X,'REA'        LEVEL  OF',9X,'( THOUSANDS  OF',13X,'FOR THI
      1S')
       WRITE(6,608)
608    FORMAT(3 X,'DEMAND     UNCERTANITY     1980S MEXICAN PESOS  )      TH
      1RESHOLD DEMAND',/)
       LINES=5
800    LL=LL+1
       IF(LL GT 72) GO TO 20
       WRITE(6,609)(RES(LL,LLL),LLL=1,4)
609    FORMAT(34X,F4 1,/X,F7 3,9X,F11 2,17X,F8 2,/)
       LINES=LINES+2
       IF(LINES GE 53) GO TO 2000
       GO TO 800
1001   WRITE(6,700) TDEM(K)
700    FORMAT('1',15X,'JOB ABORTED BECAUSE WHEN SEARCHING FOR CMIN FOR ',
      1F10 2,' THE VALUE OF TA BECAME GREATER THAN 100 YEARS ')
       WRITE(6,500)
500    FORMAT('1',' ')
       GO TO 1000
20     CONTINUE
       WRITE(6,500)
1000   STOP
       END
       FUNCTION CMIN(DEM)
       COMMON BETA0,BETA1,LAMDA,RHO,A
       REAL LHS,LAMDA
       DELTA=0 1
       TAK=0.0
       DK=0 0
       TA=0 0
21     TA=TA+DELTA
       IF(TA GT 100 ) GO TO 1001
       TAM=TAK
       TAK=TA
```

TABLE XXIII (Continued)

```
C
C CALCULATE LHS AND RHS
C
      LHS=BETAO / (BETA1*DEM)
      RHS=(-A*(1 -RHO**TA)/RHO**TA) - TA
      DP=DK
      DK=RHS-LHS
C
C OPTIMAL VALUES HAVE BEEN REACHED ?
C
      IF(RHS-LHS) 21,25,25
C
C LINEAR INTERPOLATION TO APPROXIMATE TX
C
  25  DT=TAK TAP
      DMINU = DP
      DPLUS = DK
      TX = TAP - DT * DMINU / (DPLUS-DMINU)
C
C CALCULATION OF MINIMUM COST ASSOCIATED WITH THIS THRESHOLD DEMAND
C
      S=(RHO**TX)/(1 -RHO**TX)
      F=(BETAO/BETA1)/DEM
      CMIN=LAMDA*(BETAO+BETA1*DEM*(TY+S*(F+TX)))
      RETURN
1001  CMIN=-1.
      RETURN
      END
      FUNCTION GINT(Y,XMEAN,SIGMA)
C
C  GINT IS THE INTEGRAL FROM MINUS INFINITY TO X OF THE GAUSSIAN
C  (NORMAL) CURVE WITH MEAN AT XMEAN, STANDARD DEVIATION SIGMA, AND
C  HAVING UNIT AREA
C
      GINT              = 5*ERFC((XMEAN-X)/(ABS(SIGMA)*1 414214))
      RETURN
      END
      FUNCTION ERFC(X)
C
C  ERFC(X) IS THE COMPLEMENTARY ERROR FUNCTION, ERFC(X)=1.-ERF(X) .
C
      ERFC   =SIGN (ERFCP(X),X)+(1 -SIGN (1.,X))
      RETURN
      END
      FUNCTION ERFCP(X)
C
C  ERFCP(X) IS THE COMPLEMENTARY ERROR FUNCTION OF ABS(X), X REAL
C  HANDBOOK OF MATHEMATICAL FUNCTIONS, P 299
C
      TT(X)=1./(1 + 3275911*ABS(X))
C
      ERFCP=EXP(-Y*X)*TT(X)*(.254829592+TT(X)*(- 284496736+
     *  TT(X)*(1 421413741+TT(X)*(-1 453152027+TT(X)*1 061405429))))
      RETURN
      END
```

TABLE XXIV

FORTRAN SOURCE LISTING OF THE PROGRAM INFLA TO CALCULATE THE EFFECT OF INFLATION ON THE OPTIMAL COST

```
***********************************************************************
*                                                                     *
*                                                                     *
*   FORTRAN SOURCE LISTING OF THE PROGRAM INFLA USED TO CALCULATE     *
*   THE EFFECT OF INFLATION ON THE OPTIMAL COST                       *
*                                                                     *
*                                                                     *
***********************************************************************

      DIMENSION RES(100,3),VRHO(100)
      INTEGER PAGE,TITLE(24)
      REAL INFLA,INTER,MANTE,LAMDA,LIFE
      COMMON MANTE,LIFE,Y,TAU,DEM,F,CMIN,BETA0,BETA1
C
C  READ DATA ON ECONOMIC SITUATION
C
      READ(5,1) INFLA,INTER,AUMAR
    1 FORMAT(3F10 4)
C
C  READ TYPE OF CABLE
C
      READ(5,2) (TITLE(I),I=1,6)
    2 FORMAT(6A4)
C
C  READ PARAMETERS FOR THIS GROUP OF CABLES
C
      READ(5,3) BETA0,BETA1,LIFE,VALRE,MANTE
    3 FORMAT(5F10 2)
C
C  READ THE NUMBER OF RHO VALUES TO CONSIDER IN THIS RUN.
C
      READ(5,4) N
    4 FORMAT(I2)
C
C  READ THE VALUES OF RHO TO CONSIDER IN THIS RUN
C
      READ(5,5)(VRHO(I),I=1,N)
    5 FORMAT(10F8 4)
C
C  READ THE NEXT VALUES OF DEMAND AND TAU OPTIMAL TO CONSIDER
C  AS CONSTANTS IN THIS RUN.
C
    7 READ(5,6) DEM,TAU
    6 FORMAT(2F10 2)
C
      IF(DEM EQ 0 ) GO TO 999
      DO 8 K=1,100
      DO 8 KK=1,3
    8 RES(K,KK)=0
C
C  CALCULATION OF MINIMUM COST FOR THIS DEMAND AND TAU
C
      GAMA=(1 +AUMAR) / (1.+INTER)
      RHOOP=(1 +INFLA) / (1 +INTER)
      X=((1 +MANTE)*RHOOP**LIFE) / (1 -RHOOP**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1 -GAMA**LIFE)
      LAMDA=1 +X-Y
      S=(RHOOP**TAU)/(1 -RHOOP**TAU)
      F=(BETA0/BETA1)/DEM
      CMIN=LAMDA*(BETA0+BETA1*DEM*(TAU+S*(F+TAU)))
C
C  CALCULATION OF MATRIX OF RESULTS   RES
C
      DO 20 I=1,N
      RES(I,1)=VRHO(I)
      RHO=VRHO(I)
      X=((1 +MANTE)*RHO**LIFE) / (1 -RHO**LIFE)
      LAMDA=1 +X-Y
      S=(RHO**TAU)/(1 -RHO**TAU)
      RES(I,2)=LAMDA*(BETA0+BETA1*DEM*(TAU+S*(F+TAU)))
```

TABLE XXIV (Continued)

```
C
C  CALCULATION OF CINF/CMIN
C
      RELAC=RES(I,2) / CMIN
      RELAC=(RELAC - 1 ) * 100
      RES(I,3)=RELAC
   20 CONTINUE
C
C  PRINT RESULTS
C
      LL=0
      PAGE=0
 2000 PAGE=PAGE+1
      IF (LL EQ N) GO TO 7
      WRITE(6,600) PAGE
  600 FORMAT('1',122X,'PAGE ',I2,/)
      WRITE(6,601) (TITLE(L),L=1,6)
  601 FORMAT(10X,'RELATION  BETWEEN  THE  COST  OF  AN  EXPANSION  POLIC
     1Y  FOR  A  NETWORK  OF  THE  TYPE      ',6A4)
      WRITE(6,602)
  602 FORMAT(31X,'AND  DIFFERENT  VALUES  OF  THE  RATIO  RHO  =  (1. +
     1INFLA) / (1  + INTER)')
      WRITE(6,603) RHOOP,CMIN
  603 FORMAT(10X,'IN  THIS  RUN,  THE  VALUE  OF  RHO  TAKEN  AS  BASIS,
     1  WAS  ',F6 4,'  ,  WITH  A  MINIMUM  COST(CMIN)  OF  ',F10.1)
      WRITE(6,604) DEM,TAU
  604 FORMAT(28X,'OTHER  CONSTANTS  CONSIDERED  ARE     DEMAND  =  ',F5.
     11,'  TAU  OPTIMAL  =  ',F5 1,/)
      WRITE(6,605)
  605 FORMAT(63X,'COST(CINF)')
      WRITE(6,606)
  606 FORMAT(61X,'FOR THIS VALUE')
      WRITE(6,607)
  607 FORMAT(50X,'RHO',11X,'OF   RHO',11X,'% CINF IS OVER CMIN',/)
      LINES=0
  800 LL=LL+1
      IF(LL GT N) GO TO 7
      WRITE(6,608)(RES(LL,LLL),LLL=1,3)
  608 FORMAT(48X,F6 4,6X,F12.0,16X,F9 1,/)
      LINES=LINES+1
      IF(LINES GE 25) GO TO 2000
      GO TO 800
  999 WRITE(6,500)
  500 FORMAT('1',' ')
      STOP
      END
```

TABLE XXV

FORTRAN SOURCE LISTING OF THE PROGRAM <u>OCCUPA</u> USED TO CALCULATE THE PERCENT THAT THE COST IS INCREASED BY GOING FROM AN OCCUPATION POLICY OF (A)% TO AN OCCUPATION POLICY OF (B)%

```
*****************************************************************************
*                                                                           *
*                                                                           *
*   FORTRAN SOURCE LISTING OF THE PROGRAM OCCU     USED TO CALCULATE       *
*   THE PERCENT THAT THE COST IS INCREASED BY GOING FROM AN                 *
*   OCCUPATION POLICY OF (A)% TO AN OCCUPATION POLICY OF (B)%.              *
*                                                                           *
*                                                                           *
*****************************************************************************

      DIMENSION GAPER(10,20),RES(10,10),GAIN(10)
      DIMENSION H(10),V(10) CV(10),CH(10)
      INTEGER PAGE,TITLE(24)
      REAL INFLA,INTER,MANTE,LAMDA,LHS,LIFE
      COMMON BETAO,BETA1,LAMDA,RHO,A
C
C READ DATA ON ECONOMIC SITUATION
C
      READ(5,1) INFLA,INTER,AUMAR
    1 FORMAT(3F10 4)
C
C READ TYPE OF CABLE
C
      READ(5,2)(TITLE(I),I=1,6)
    2 FORMAT(6A4)
C
C READ PARAMETERS FOR THIS GROUP OF CABLES
C
      READ(5,3) BETAO,BETA1,LIFE,VALRE,MANTE
    3 FORMAT(5F10 2)
C
C READ GAINS TO CONSIDER IN THIS RUN
C
      READ(5,4)(GAIN(I),I=1,10)
    4 FORMAT(10F5 1)
C
C READ A% OF OCCUPATION TO CONSIDER IN THIS RUN.
C
      READ(5,5)(H(I),I=1,10)
    5 FORMAT(10F5 3)
C
C READ B% OF OCCUPATION TO CONSIDER IN THIS RUN
C
      READ(5,6)(V(I),I=1,10)
    6 FORMAT(10F5 3)
C
C
C CALCULATION AND INITIALIZATION OF CONSTANTS TO USE IN THIS RUN
C
      GAMA=(1 +AUMAR)/(1 +INTER)
      RHO=(1 +INFLA)/(1 +INTER)
      A=1 /ALOG(RHO)
      X=((1 +MANTE)*RHO**LIFE)/(1.-RHO**LIFE)
      Y=(VALRE*GAMA**LIFE)/(1 -GAMA**LIFE)
      LAMDA=1 +X-Y
C
C ***** PROCESS BEGINS FOR CALCULATION OF MATRIX GAPER
C
C CALCULATION OF THE NUMBER OF PAIRS NEEDED FOR A% OF OCCUPATION.
C
      DO 20 I=1,10
      DO 20 J=1 10
      DEM=GAIN(I)/H(I)
      CMID=CMIN(DEM)
      IF(CMID LT 0 ) GO TO 1001
      GAPER(I,J)=CMID
   20 CONTINUE
```

TABLE XXV (Continued)

```
C
      DO 21 I=1,10
      DO 21 J=11,20
      DEM=GAIN(I)/V(J-10)
      CMID=CMIN(DEM)
      IF(CMID LT.0 ) GO TO 1001
      GAPER(I,J)=CMID
  21  CONTINUE
C ***** PROCESS BEGINS FOR CALCULATION OF MATRIX RES
C
C
C COPY A% AND B% COST
C
      DO 31 I=1,10
      DO 32 J=1,10
      CH(J)=GAPER(I,J)
      CV(J)=GAPER(I,J+10)
  32  CONTINUE
C
C
C CALCULATION C  MATRIX RES FOR THIS GAIN
C
      DO 34 K=1,10
      DO 34 L=1,10
      RELAC-CV(I )/CH(K)
      RELAC=(RELAC - 1 ) * 100
      RES(K,L)=RELAC
  34  CONTINUE
C
C PRINT RESULTS FOR THIS GAIN
C
      WRITE(6,600)
 600  FORMAT('1',' ',//)
      WRITE(6,601)
 601  FORMAT(20X,'TABULATION OF THE % THAT THE COST IS INCREASED BY GOIN
     1G FROM AN OCCUPATION POLICY OF (A)%,')
      WRITE(6,602)
 602  FORMAT(20X,'TO AN OCCUPATION POLICY OF (B)% '/)
      WRITE(6,603)(TITLE(II),II=1,6)
 603  FORMAT(24X,'CALCULATIONS MADE IN THIS RUN WERE FOR THE GROUP OF CA
     1BLES   ',6A4,/)
      WRITE(6,604) GAIN(I)
 604  FORMAT(79X,'AND A GAIN OF ',F4.1,' SUBSCRIBERS.',//)
      WRITE(6,599)
 599  FORMAT(67X,'B(%)',/)
      WRITE(6,605)
 605  FORMAT(7X,'+-------+',10('----------+'))
      WRITE(6,606)
 606  FORMAT(7X,'+       +',10(10X,'+'))
      WRITE(6,607)(V(KK),KK=1,10)
 607  FORMAT(7X,'+       +',10(3X,F4.2,'   +'))
      WRITE(6,606)
      WRITE(6,605)
      DO 700 M=1,10
      WRITE(6,606)
      IF(M EQ 5) CALL AUX(H,RES,M)
      IF(M EQ 5) GO TO 800
      WRITE(6,608) H(M),(RES(M,MM),MM=1,10)
 608  FORMAT(7X,'+',F5 2,' +',10(F9 2,' +'))
 800  WRITE(6,606)
      WRITE(6,605)
 700  CONTINUE
  31  CONTINUE
      GO TO 1000
1001  WRITE(6,609) GAIN(I)
 609  FORMAT('1',15X,'JOB ABORTED BECAUSE WHEN SEARCHING FOR CMIN FOR A
     1GAIN OF ',F6 1,',',/)
      WRITE(6,610) H(I)
 610  FORMAT(15X,'AND AN OCCUPATION OF ',F6.1,' THE VALUE OF TA BECAME G
     1REATER THAN 100 YEARS ')
1000  STOP
      END
```

TABLE XXV (Continued)

```
      FUNCTION CMIN(DEM)
      DIMENSION RES(10,10),CV(10),CH(10)
      COMMON BETAO,BETA1,LAMDA,RHO,A
      REAL LHS,LAMDA
      DELTA=0 1
      TAK=0 0
      DK=0 0
      TA=0 0
   21 TA=TA+DELTA
      IF(TA GT 100 ) GO TO 1001
      TAP=TAK
      TAK=TA
C
C CALCULATE LHS AND RHS
C
      LHS=BETAO/(BETA1*DEM)
      RHS=(-A*(1 -RHO**TA)/RHO**TA) - TA
      DP=DK
      DK=RHS-LHS
C
C OPTIMAL TIME HAS BEEN REACHED ?
C
      IF(RHS-LHS) 21,25,25
C
C LINEAR INTERPOLATION TO APPROXIMATE TX
C
   25 DT=TAK-TAP
      DMINU = DP
      DPLUS = DK
      TX = TAP - DT * DMINU / (DPLUS-DMINU)
C
C CALCULATION OF MINIMUM COST
C
      S=(RHO**TX)/(1 -RHO**TX)
      F=(BETAO/BETA1)/DEM
      CMIN=LAMDA*(BETAO + BETA1*DEM*(TX+S*(F+TX)))
      RETURN
 1001 CMIN=-1.
      RETURN
      END
      SUBROUTINE AUX(N,RES,M)
      DIMENSION N(10),RES(10,10)
      WRITE(6,1) N(M),(RES(M,MM),MM=1,10)
    1 FORMAT(2X,'(A)% +',F5 2,' +',10(F9 2,' +'))
      RETURN
      END
```

VITA

Lorenzo Flores-Hernandez

Candidate for the Degree of

Doctor of Philosophy

Thesis: ECONOMIC CAPACITY EXPANSION PLANNING: AN APPLICATION TO THE TELEPHONE INDUSTRY

Major Field: Industrial Engineering and Management

Biographical:

Personal Data: Born in Mexico City, D. F., August 10, 1939, the son of Teofilo Flores Vasquez and Maura Hernandez de Flores.

Education: Graduated from the Escuela Vocacional No. 2, Mexico City, D. F., in December, 1962; received Ingeniero en Communicaciones y Electronica degree from the Instituto Politecnico Nacional, Mexico, in 1970; received Master of Science degree in Industrial Engineering from New Mexico State University in 1975; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in July, 1982.

Professional Experience: About 20 years in the Mexican Telephone Company, holding various positions, all related to the development of the expansion of the telephone network. Positions have ranged from investigator of the telephone demand to draftsman, network designer, engineer, head of section, head of department, and sub-manager of planning; teaching and research assistant, New Mexico State University; teacher Instituto Politecnico Nacional, Mexico; teaching and research assistant, Oklahoma State University; member, American Institute of Industrial Engineers, AMICCE (Mexican Association of Electronics and Communication Engineers), Operation Research Society of America; Honorary Society, Alpha Phi Mu.