

**ESTIMATING THE COST STRUCTURE OF THE
LOCAL TELEPHONE EXCHANGE NETWORK**

prepared for the

NATIONAL REGULATORY RESEARCH INSTITUTE

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Executive Summary

Effective regulation requires a thorough understanding of the cost structure of the industry. Costs serve as a basis for judging the reasonableness of rates, and provide an indication of the extent to which an industry is a natural monopoly.

Regulatory commissions have lacked an analytical tool that permitted them to independently quantify the cost of different services. Instead, information regarding the cost structure of the industry has largely come from telephone company-sponsored cost studies. While the companies' cost studies provided valuable insights into many issues, we felt that Commissions would benefit from having in-hand their own analytical tool that could provide an aid in analyzing such issues as the cost of exchange services, the economics of bypass and fiber optics in the local telecommunications network, and the extent to which the industry is a natural monopoly.

The attached report describes the operation of the cost model as well as our findings. We have concluded that the replacement of analog with digital technology has lowered the marginal cost of providing switched exchange and toll services and has raised the marginal cost of providing switched access and private line services. The reduction in the cost of providing switched services is largely due to the savings in interoffice transport costs. Switched access costs have increased in large part because many of the functions that were previously handled by the central processor unit of the switching machine, as well as other peripheral equipment, are now handled by customer specific equipment. Private line costs have increased, in part, because of the replacement of analog copper with digital trunks, and because these services no longer share the fixed cost of interoffice channel banks with switched services.

Based on our analysis of the stand-alone cost of constructing private line systems, we have found that in densely populated markets, it is possible for an entrant to provide private line services at a lower cost than the local exchange telephone companies. The entrant, unlike the incumbent telephone companies, chooses to provide all services through one central office. This provides an important cost saving on interoffice

trunking. Consequently, bypass can occur not because of the commonly alleged regulatory inefficiencies, but because an entrant can provide service at a lower cost than the local exchange telephone company.

In less densely populated markets, an entrant can not provide service at a lower cost than the local exchange company. Because of the cost of placing cables over a wide geographical area, society's costs are minimized when all services are provided by one firm.

In order for an industry to be a natural monopoly, it must be cheaper for one firm to provide all services than to have two or more firms provide the same products. We have found that while in general the industry may be a natural monopoly, in densely populated markets the telecommunications industry is not a natural monopoly. The provision of private line services by one firm, and switched services by a second firm, leads to a reduction in the total cost of production.

The finding that the industry is not always a natural monopoly has important regulatory implications. The history of the industry indicates that there is a strong need for regulatory oversight in order to ensure that services subject to competition are not subsidized by monopoly services.

The output from the cost model also indicates that fiber optics in the local loop is not the cost minimizing technology. On short loops, copper cable is still the cost minimizing technology. On longer loops, copper is more expensive than digitally derived loops using subscriber-line carrier. Subscriber-line carrier on copper is 8 to 16 percent cheaper than subscriber-line carrier on fiber. This comparison is based on the assumption that the telephone company deploys a small fiber cable (one that satisfies the level of demand). In practice local exchange companies often install fiber cables with a large amount of excess capacity (dark fiber). When this extra capacity is installed, the cost of fiber in the loop is increased and this makes subscriber-line carrier on fiber significantly more expensive than suggested by the data developed in this report. The cost difference between subscriber-line carrier on copper and fiber is not large, and because of the greater bandwidth available on fiber, telephone companies are willing to incur the additional cost associated with fiber. As with the other technologies that

improve the provision of data and enhanced services at the cost of raising access to the public switched network (for example, digital switching), we believe that these costs should not be borne exclusively by customers of plain-old-telephone-service.

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Foreword

From time to time the NRRI funds a study by an "outside" researcher on a topic likely to be of interest to our clientele as part of our Occasional Paper series. We view this series as something like a technical journal and as such a fairly specialized knowledge of the subject matter is usually helpful for a full understanding of the analysis.

In this Occasional Paper the faculty authors have devised and tested a costing tool for allowing commissions to analyze issues such as the real cost of exchange services, the economics of bypass, and the extent to which the industry is a natural monopoly. One copy of the software has been transmitted to the chair of each commission. Copies may also be obtained by contacting the authors.

We hope commission staff find this a useful contribution.

Douglas N. Jones
Director, NRRI
Columbus, Ohio
October 1, 1991

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CHAPTER ONE

AN OVERVIEW OF PREVIOUS COST STUDIES

Since 1960 the cost function of the telecommunications industry has been studied extensively, the initial work coinciding with the introduction of microwave facilities. This mode of long-distance transmission made it possible for firms to establish networks that could compete with American Telephone and Telegraph Company's (AT&T) long-distance lines.

Responding to this entry, AT&T offered large business customers significant price discounts for bulk private line service. Since then, state and federal regulatory commissions have sought a sound economic method to evaluate the reasonableness of rates.

Three costing methods have emerged over this time period each having various strengths and weaknesses. The methods are: 1) accounting, 2) engineering, and 3) statistical studies. This report offers an alternative modelling approach combining engineering process modelling, optimization techniques, and statistical estimation.

Accounting data have been used to determine the embedded cost of service in virtually every jurisdiction in the United States. The advantage of this type of analysis is that the same data are used to determine the firm's revenue requirement; therefore, it is readily available. Its primary drawback is that it is of limited value in indicating the future economic costs that the utility will incur. For economic efficiency, rates should reflect forward looking, or opportunity, cost of service.

Telephone companies have generally argued that setting rates should be based on prospective costs. Economic theory stresses that to maximize society's welfare, prices should reflect the forward looking marginal cost of production. To support tariff changes telephone companies often submit long-run incremental cost studies (LRIC).

Based upon engineering production rules, the LRIC studies identify the cost of increasing output on only one component of the network, such as a switch or a loop. The LRIC studies are not designed to quantify the total cost of service (that is, the total

cost, both variable and fixed, of providing multiple services), however, the total cost of service is important for decisions regarding entry into the industry. The restructuring of AT&T¹ as well as federal and state commission proposals to allow entry into the industry can be characterized as "beneficial" or "harmful" in part depending on the extent to which the industry is a natural monopoly. This, as well as the degree of economies of scale and scope, can only be measured by having information about the total cost curve.²

In recent years participants in regulatory and judicial proceedings have presented statistical estimates of the industry's total cost curve. While an important innovation, these studies had significant limitations due to the quality of the data.

Starting with historical data, econometricians encountered the problem of how to control for technological change. While proxies such as research and development expenditures or the number of access lines served by electronic switching machines have been used, they only roughly capture the impact of technological change.

Researchers also had trouble controlling for input prices and constructing output indexes for the various categories of service. Because of these and other data problems, Evans and Heckman have argued that before conclusive statements about the cost function can be made, new data would have to be located.³

This research attempts to address these data problems by combining engineering process models with optimization techniques to estimate the cost of local exchange facilities. The model, LECOM (local exchange cost optimization model) was created by first developing algorithms that incorporate the engineering standards and practices used

¹United States v. American Tel. & Tel. Co., 552 F. Supp. 131 (D.D.C. 1982) *aff'd sub nom.* Maryland v United States, 460 U.S. 1001 (1983).

²William W. Sharkey, *The Theory of Natural Monopoly* (Cambridge, MA: Cambridge University Press, 1982).

³See, for example, Leonard Waverman, "U.S. Interexchange Competition," in Robert Crandall and Kenneth Flamm, *Changing the Rules: Technological Change, International Competition, and Regulation in the Communications Industry* (Washington: Brookings Institute, 1988); and D.S. Evans and J.J. Heckman, "Rejoinder: Natural Monopoly and the Bell System: Response to Charnes, Cooper and Sueyoshi," *Management Science* 34 no. 27: 37 (1988).

by telephone company engineers for designing local exchange networks (that is, a process model). Second, the cost-output relationship is derived as a result of assumed optimization behavior. Here the minimum cost of production is identified for various output levels given input prices and the production function. LECOM was designed to search for the combination and location of switching machines that minimize the cost of production.⁴

Through repeated simulations of the cost-output relationship, we were able to develop a data base that helps us measure the cost impact of varying the level of output of various services. The cost data generated by LECOM is summarized through a statistical estimate of the cost function.⁵

For policy analysis, this method of generating data offers an important advantage compared to the data used by earlier econometricians. Much of the research interest in the industry's cost structure is tied to a concern about the efficiency of entry and competition. Most of the published work has been based on data from the Bell Operating Companies, each of which provides service in many cities. The level of observation is therefore the firm, not a market, such as for a city. Entry, on the other hand, often occurs at the city level. Entrepreneurial firms, such as Teleport, do not provide statewide operations, but instead offer just service in the most profitable markets.

⁴This is a departure from the methodology used by most telephone companies. By searching for the combination and location of switching machines, the model is implicitly unconstrained by prior investment decisions. Typically telephone company cost studies assume that the number and location of telephone switches is fixed.

⁵Summarizing the output from a process model through the use of a statistical cost function, has been used in other industry studies. See, for example, James M. Griffen, "The Process Analysis Alternative to Statistical Cost Functions," *American Economic Review* 62 (Mar. 1972): 46-56; Alan Manne, "A Linear Programming Model of the U.S. Petroleum Refining Industry," *Econometrica* 26 (Jan. 1958): 67-106; Hollis B. Chenery, "Engineering Production Functions," *Quarterly Journal of Economics* 43: 507-31; and James M. Griffen, "Long-run Production Modeling with Pseudo Data: Electric Power Generation," *Bell Journal of Economics* 8 (Spring 1977): 112-27.

To understand the economic rationale of entry a comparison between the operations of an incumbent and an entrant at the market level is of some value. Little insight is gained by comparing the statewide operations of a firm with the operations of an entrant which operates in only one market (for example, Teleport). Since most existing data sets are at the firm level, aggregation bias is a possibility. For example, assume that firm A serves 10,000 customers in ten different cities and that the service territory in each locality is seven square miles. Firm B serves an equal number of customers, 100,000, but in only one city covering twenty-five square miles. Because of the difference in customer density and the fixed cost of establishing service in each city, it is unlikely that A's costs equal B's. The firm-specific data used heretofore did not generally control for density or the number of exchanges, however. Consequently, the econometric cost functions estimated by Christensen, Evans, Charnes, et al. are not well suited to make a comparison at the market level.⁶

Modeling Advantages Associated with LECOM

As noted, LECOM incorporates engineering standards and practices used by telephone companies to plan and design capacity additions and changes to their network. These standards are incorporated into their incremental cost models. However, the model presented in this report extends and improves on these engineering models in five important ways:

1. Cost minimizing behavior is explicitly recognized rather than being implicitly assumed.
2. Alternative technologies are evaluated with the final selection of facilities based on the objective of minimizing costs.
3. Output mix can be varied.

⁶L. Christensen, D. Cummings, and P. Schoech, "Econometric Estimation of Scale Economies in Telecommunications," Social System Research Institute, Discussion Paper No. 8013, University of Wisconsin and the references at footnote 3.

4. Direct accounting for digital versus analog technologies is made available to the analyst.
5. Direct interaction between fixed and variable cost is explicitly recognized.

A. Minimizing the Cost of Service

The existing cost models include no explicit optimization objective. This is best illustrated by example. When telephone companies calculate the incremental cost of a local loop, they do not try to determine the cost-minimizing location of a central office. Instead, they assume that the current location is optimal. Their models *assume* that the current location is the long-run cost-minimizing solution.

Existing locations may or may not be optimal. A telephone company can determine this by comparing the present discounted cost of keeping the switch at its current location with the present discounted costs of alternative locations. Such an analysis would be consistent with the economic notion of the long run where all inputs are variable.

In our model we search for central office locations that minimize the cost of service. Due to the cost of collecting data on all existing cable routes and the lack of such publicly available data, however, we have chosen to solve a related problem. Instead of solving the dynamic optimization problem faced by the incumbent⁷, we solve

⁷With dynamic optimization, the firm forecasts how it can minimize the present value of its future stream of costs. Year-by-year changes in demand are considered, and how they affect the cost-of-production. Costs are incurred in the future due to capacity exhaustion of some, or all facilities.

In our static model, we minimize the cost of production for a given level of demand. In a given run of the model, we assume that the level of demand is constant, and then seek the combination of facilities that will minimize the production costs in the long-run.

The dynamic cost minimization methodology is rarely used by the telephone companies to identify the marginal cost of service (the companies also generally use the static approach). And where the dynamic methodology is used, the studies do not allow for such options as consolidating or moving the location of wire centers. See, for example, New England Telephone Company, work papers, book 1, tab 1, p.1-2,

the long-run, static problem of the optimal location of the telephone switches. The solution to the dynamic problem requires finding the network configuration that minimizes the sum of the net present value of loop, switching, and interoffice trunking costs. Since the telephone company cost models do not try to solve such a problem, or, in general, the dynamic optimization problem, their marginal-cost equations should not be viewed as first-order derivatives of the long-run cost function. This raises theoretical questions about their use in determining welfare maximizing prices.

B. Evaluation of Alternative Technologies

Our second extension is that our selection of facilities is based on the criteria that the configuration minimizes costs for a given level of demand. Often telephone cost studies assume that, whether or not it is most economical, a specific technology will be used. For example, telephone company cost studies often assume that only fiber is used for interoffice transport. The cost advantage or disadvantages of using carrier on copper versus carrier on fiber is not determined.⁸ Our choice of technology is based on the criteria established in the objective function--finding the combination of inputs that minimizes production costs for a given level of demand and input prices.

C. Output Mix

The local exchange companies have separate cost models for private line, enhanced, and switched services. This approach implicitly assumes that no cost complementarities or discomplementarities exist.⁹ The soundness of this assumption

attachment 1, in Massachusetts D.P.U. Docket 86-33.

⁸Bridger M. Mitchell, "Incremental Costs of Telephone Access and Local Use," Rand R-3909-ICTF, July 1990.

⁹"Cost complementarity is said to exist if an increase in the production of any one output lowers the incremental cost of producing other outputs." Sharkey, *Natural Monopoly*, 56-57. Sharkey shows that cost complementarity is a sufficient condition for subadditivity. Ibid., 69. Subadditivity of the cost function is a necessary and sufficient condition for natural monopoly.

merits investigation. For example, the integration of high-speed data and enhanced services with voice services affects the engineering standards used in the local loop and the local switch.¹⁰ In the local loop, the offering of high-speed circuit switched digital services becomes feasible after modifications have been made to the local loop (for example, unloading and compression multiplexing).¹¹ Often these changes to the facilities are not restricted to those used by nonbasic services, and consequently the cost of providing plain old telephone service is increased.

The design of the local switch is affected by the offering of enhanced services. Prior to the introduction of switched digital services, the local switch was typically engineered under the assumption that during the peak usage hour of the switch, a customer would place one call and be on the line for approximately three minutes. Due to the increased marketing of nonbasic services, these assumptions are no longer valid. Where a customer uses the switch for packet switching, many short calls will be placed (for example, automatic teller machine transactions). At the other extreme, a customer using the switch for large data transfers, telecommuting, or video services, may be connected to the switch for the full system busy-hour.¹² The digital switches being deployed and developed today must allow for this wide variation in customer needs, and this increases the cost of providing switched access to the network.

D. Technological Change

The fourth contribution is the model's ability to compare how different marketing and engineering objectives affect the industry's cost structure. The cost models developed by the telephone companies reflect the direction that the industry is heading.

¹⁰David Gabel, "An Application of Stand-Alone Costs to the Telecommunications Industry," *Telecommunications Policy*, February 1990 and references cited therein.

¹¹G.J. Handler and D. Sheinbein, "Improving the Local Loop to Provide New Network Capabilities," in *International Symposium on Subscriber Loops and Services* (New York: IEEE, 1982), 1-3.

¹²Kenneth F. Geisken, "ISDN Features Require New Capabilities in Digital Switching Systems," *Journal of Telecommunication Networks* 3 (Spring 1984): 19-28.

Digital switches, fiber optics, and subscriber-line-carrier are being deployed to facilitate the provision of video and high-speed data services. Existing cost models are based on these forward-looking technologies, and the models identify the incremental cost of usage on a state-of-the-art network. Usage, or output, is the sole cost-causing activity.

Optimal prices cannot be set merely by looking at the incremental cost of usage. Since redesigning the network is affected by concerns about quality, the marginal cost of service is also a function of quality.

This can best be illustrated by considering the local switch and the loop. Analog switches are rather cumbersome in providing high-speed switched services. To enhance their market position for digital switched services, the local exchange companies are replacing these machines with digital switching machines.¹³

Simultaneously, the standards for the local loop are being changed. Loop resistance design standards have been modified to reflect the more stringent needs of high-speed digital services.¹⁴ These actions suggest that the marginal cost of service is a function of quality and quantity. The theoretical literature has stressed that to maximize welfare, both of these factors should be taken into account.¹⁵ LECOM allows us to identify the cost of service for either analog and digital facilities. This provides some insight to the issue of how quality affects the cost of providing different services.

As a related issue, there is a debate in the telecommunications pricing literature over whether existing marginal-cost studies of the loop reflect digital technology deployment.¹⁶ Some have suggested that new technology may shorten the distance

¹³Gabel, "Stand-Alone Costs": 75-84.

¹⁴Thomas P. Byrne, Ron Coburn, Henry C. Mazzoni, Gregg W. Aughenbaugh, and Jeffrey L. Duffany, "Positioning the Subscriber Loop Network for Digital Services," *IEEE Transactions on Communications* 30 (September 1982): 2009.

¹⁵Michael A. Spence, "Monopoly, Quality and Regulation," *Bell Journal of Economics* 6 (1975): 417-29.

¹⁶See, for example, Alfred Kahn and William Shew, "Current Issues in Telecommunications Regulation: Pricing", *Yale Journal on Regulation* 4 (1987): 200, 216. The future topology of the network also affects the need to maintain the line of business

between the customer's location and the point at which network concentration begins. If so, this could lower the cost of providing customer access, and changes should be reflected in the price of exchange service. By using the optimization methodology, we provide later on some quantitative insight to these debates. By building separate models to represent the analog and digital world, we can see how new technology affects the network's topology.

E. Fixed and Variable Costs of Production

Existing cost of service studies often use average unit costs as inputs. This approach fails to distinguish between the fixed and variable cost of facilities. By taking into account these separate cost components, we more accurately measure the cost of service.

For example, a few Bell Operating Companies calculate the fiber cost per pair-foot by taking the total fiber investment and dividing by the total footage of fiber pairs (the cost of all fiber installations is divided by the number of installed fiber pairs). This provides the average cost of a pair-foot of fiber. This may, for example, result in an estimate of \$.30 per pair-foot.

The actual cost of an installation varies widely, in part, because the number of installed pairs varies. One cable may only include eight fibers, while another may include as many as 144. As with many parts of the network, there is a clear fixed and variable cost of installing new facilities. The fixed and variable cost per pair-foot of underground fiber is approximately \$1.60 and \$.20, respectively. If the average cost per pair-foot of \$.30 is used to estimate the cost of deploying an eight fiber cable, an

restrictions imposed on the Bell Operating Companies in the 1982 AT&T antitrust case. See Peter Huber, "The Geodesic Network: 1987 Report on Competition in the Telephone Industry," United States Department of Justice (1987); and Flamm, "Technological Advance and Costs," in Robert Crandall and Kenneth Flamm, *Changing the Rules: Technological Change, International Competition, and Regulation in the Communications Industry*.

estimate of \$2.40 per foot would be obtained ($8 \times \$0.30$). If the more accurate fixed and variable costs are used, the cost estimate would be \$3.20 per foot ($1.60 + (8 \times \$0.20)$).

The use of the average cost per pair-foot (\$0.30) results in an understatement of the cost of deploying small fiber cables.¹⁷ When this type of unit cost information is used to determine where it is cost efficient to install fiber, an analyst may recommend to deploy fiber prematurely. By distinguishing between the fixed and variable cost of placing fiber, we hope to represent more accurately the cost of deploying different facilities.

Modeling Disadvantages Associated with LECOM

Two primary limitations associated with LECOM are addressed below: administrative costs and bounded rationality.

A. Administrative Costs

Engineering process models are designed to identify the cost-minimizing technical configuration that will satisfy a given level of demand. Typically, process models are not designed to quantify the less tangible costs of providing service. The models simulate the physical production process and spend little or no effort measuring marketing and administrative efforts.

For a number of years the telephone companies have been submitting long-run incremental studies to state and federal commissions. In response to the charge that their process models did not reflect these overhead costs, the telephone companies have developed cost ratios that take into account administrative and marketing expenses. These loadings have been included in our optimization model.¹⁸

¹⁷Conversely, it results in an overstatement of the cost of deploying large fiber cables. These large cables are likely to be installed on interoffice routes.

¹⁸Some telephone company studies include "direct" (for example accounting) and "overhead" (for example legal) administrative expenses, while others only include direct

B. Bounded Rationality

We have no a priori reason to believe that the cost function is globally concave. Therefore we do not know if the solution found by the optimization model is a local or global minimum. Ideally, we would like to locate the global solution. Since there is an infinite number of possible configurations to be considered, and since each proposed solution is costly to evaluate, our research is limited to a reasonable number of possibilities. For each combination of switches, we allow for more than 1,000 cost evaluations.

The larger the number of customers residing in a city, the more feasible combination of switches is evaluated, further increasing the number of solutions

expenses. We have included both direct and overhead expenses.

Administrative costs are treated as a linear function of the level of investment. Therefore, the administrative costs will exhibit the same economies or diseconomies that are present in the use of physical facilities.

Evans and Heckman raise the issue of whether managerial diseconomies can exceed engineering economies. Because of this concern, they conclude that "Although engineering studies may be useful to businessmen choosing between alternative technologies, they are of little use for determining whether an industry is a natural monopoly." David S. Evans and James J. Heckman, "Natural Monopoly," in *Breaking Up Bell: Essays on Industrial Organization and Regulation*, ed. David S. Evans (New York: North-Holland, 1983), p. 141.

We have controlled for these managerial economies by building models for the analog and digital environment. Whatever may be the extent of managerial economies of scale, we believe that they are independent of the type of technology deployed. By providing results for both types of technology, we are able to indicate the extent to which the degree of economies of scale is changing due to the introduction of new technology.

Evans and Heckman express their preference for "hard data" rather than engineering constructs. As their own research indicates, the "hard data" provide little or no indication of the industry's future cost trends. In order to identify prospective, marginal costs, in a dynamic, capital intensive industry, we believe LECOM provides more insights than the use of "hard," but historical data.

The cost data used in LECOM is based on the observed cost of such things as placing cables in the ground or installing a switching machine. Furthermore, we believe that the model provides some valuable insights regarding the extent to which the industry is a natural monopoly. As show in chapter four, the model indicates why, under certain conditions, the industry is not a natural monopoly.

evaluated. Therefore, while this search process is not exhaustive, we consider a wide-range of feasible solutions.

Existing cost models make no effort to search for the combination of switches and outside plant that minimize the total cost of service. Therefore while our results *may* not be a global solution, they are likely *closer* to that optimum than those offered by existing models.¹⁹

A Preview of Remaining Chapters

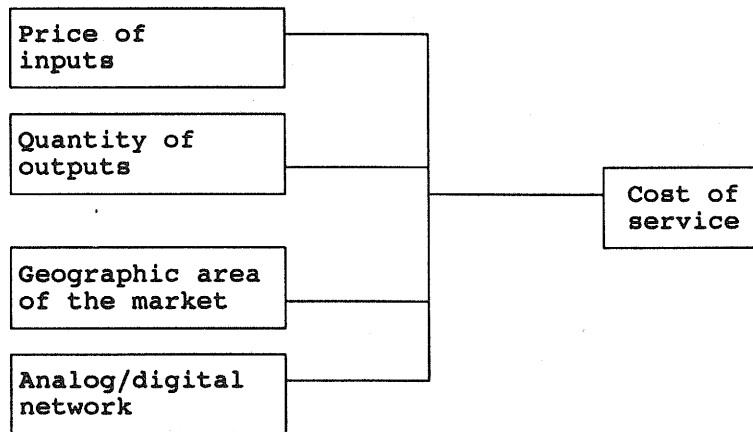
The remainder of this Occasional Paper is organized into four chapters and two appendixes. In chapter two we review the procedures and standards used to design a telecommunications network. These practices, along with the current cost of technologies, serve as the basis for establishing the mathematical relationships used to estimate the cost of service. These practices and costs have been incorporated into LECOM.

In constructing LECOM, we assume that a supplier of new telecommunication services is choosing the optimal location of facilities, and its decision is not affected by the current location of equipment. This assumption is consistent with the economic notion of a long-run cost study, for in the long run, all inputs are variable. As discussed later, by assuming that all inputs are variable, we are more closely modeling the cost function of an entrant, rather than existing firms. Nevertheless, this serves a useful purpose because the results establish a competitive standard for evaluating the reasonableness of rates. Furthermore, since the engineering standards used to construct the model are based on the current practices of telephone companies, almost all of our findings apply equally to an incumbent and an entrant.

¹⁹We do not know if our solution is a global minimum because of the lumpy nature of the cost function. Since the cost function is not smooth, we are unable to take derivatives in order to verify that the located solution is in fact a global minimum.

As described in chapter three, after LECOM was constructed we ran the model over a thousand times in order to determine how the cost of service was affected by changes in the level of output, input prices, digital versus analog technology, and the size of the city (see figure 1 below). This data set was then used to calculate the marginal cost of different services, as well as to analyze the extent to which the industry is a natural monopoly. Our findings are reported in chapters four and five. Appendix one provides a technical description of our findings.

FIGURE 1
LECOM FLOW DIAGRAM



The final chapter of the paper provides a summary of our findings. We emphasize there that the model can be used to evaluate many important issues being confronted by the industry (for example, fiber optics in the local loop, the cost impact of digital technology). The mechanics of the model are described in the LECOM User Manual, Appendix Two.

CHAPTER TWO

TELEPHONE NETWORK FACILITIES

I. Introduction

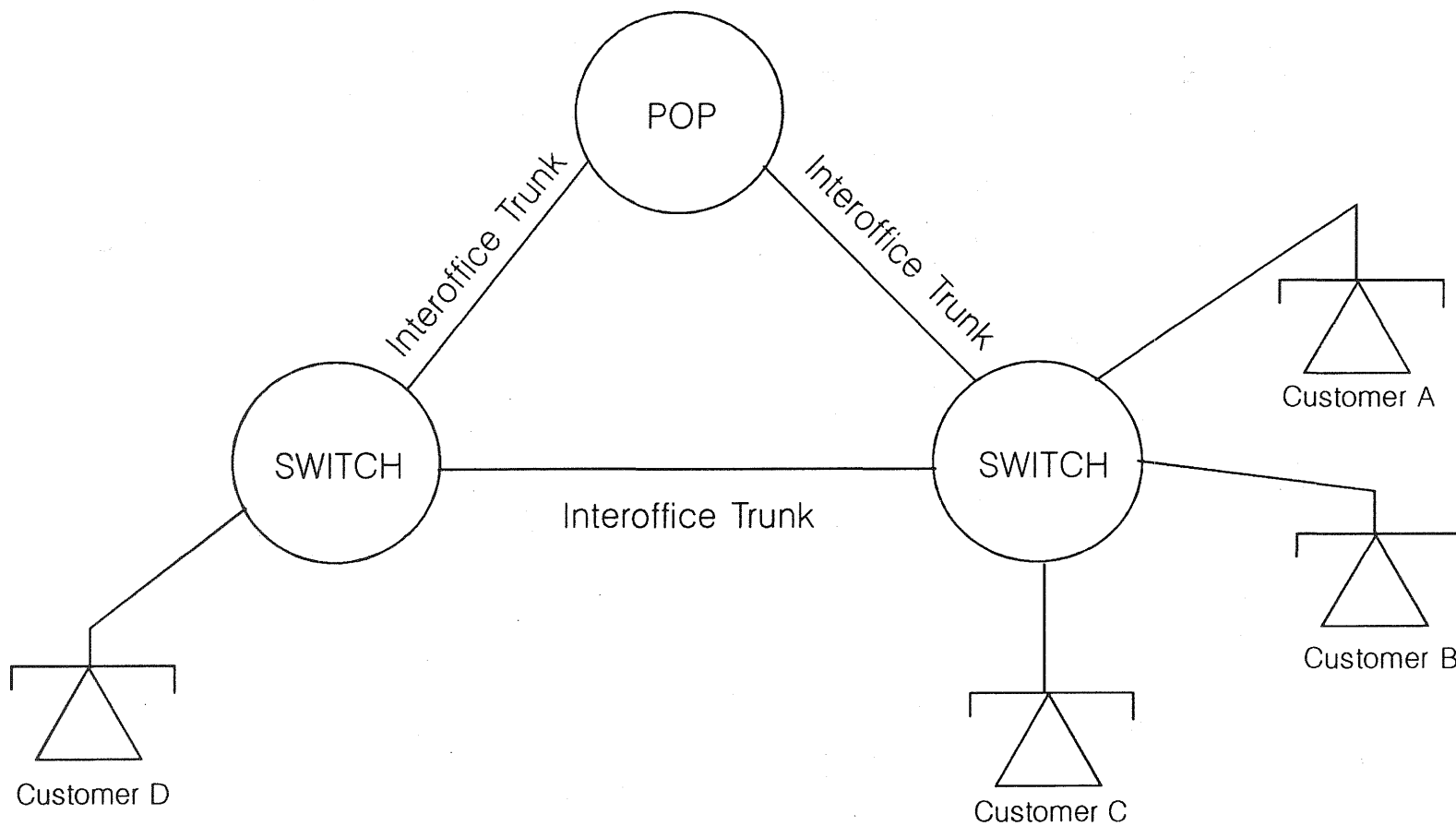
This chapter describes the network's technology and topology, providing information about the technology that was dominant around 1980--analog--and the equipment that is most prevalent today--digital. Constructing separate models for analog and digital technology allows us to identify the cost impact of new technologies, holding all other factors constant. As described in this chapter and in appendix two, the user of LECOM (Local Exchange Cost Optimization Model) can evaluate how the cost of service is affected by modifying the standard engineering practices incorporated in the model. For example, the user could see how the cost of service is affected by varying the utilization rate in the local loop, interoffice trunking, or the switching machines.

In section three of this chapter we outline our principal assumptions, and the mechanics of LECOM. Later we discuss the cost of the different types of facilities and the algorithms used in LECOM.

II. Network Topology

Three primary types of facilities can be found in the local exchange carrier's network: the local loop, end-office (class five) and tandem switches, and interoffice transport or trunking. The local loop is composed of facilities that provide a signalling, voice, video, and data transmission path between a central office and the customer's station. The central office (or wire center) houses the switching machine that connects a customer's line either to another customer served by the same switch or to an interoffice trunk. Calls between central offices are carried on trunks (see figure 2).

FIGURE 2
NETWORK ARCHITECTURE



Local Loop Topology

Telephone engineers break the service territory of a central office into discrete regions, called serving areas. Since the early 1970s, serving areas have been the basic building block used to determine the most economical choice of facilities.¹ A serving area typically includes 350 to 600 subscribers. Feeder plant connects the service area to the central office. In turn, distribution plant connects the feeder plant to the subscriber, and is often referred to as the distribution plant.

Figure 3 depicts a typical serving area. A backbone cable runs from the serving area interface and street cables--or legs--branch off the backbone at equal intervals. Each time street cables branch off, the backbone cable tapers down.²

The same design principle is used with feeder plant (Figure 4). Feeder cable runs from the central office and is connected to a number of branch feeder cables. This design, known as the "pine tree geometry," minimizes the cost of outside plant facilities.³

¹Bell Telephone Laboratories, *Telecommunications Transmission Engineering: Networks and Services* (2nd edition), 40-44; and John Freidenfelds, *Capacity Expansion: Analysis of Simple Models with Applications* (New York, North Holland, 1981) 238.

The facilities that compose the serving area are commonly referred to as the distribution plant.

²J.A. Stiles, "Economic Design of Distribution Cable Networks," *Bell System Technical Journal* 57 (April 1978): 945.

³Bell Laboratories, *Telecommunications Transmission Engineering*, 62. The use of the pine-tree topology provides an approximately 5 to 30 percent saving over a bush architecture.

Consistent with engineering practices, we have assumed that the main feeder cables leave the wire center in four directions. Bridger M. Mitchell, "Incremental Costs of Telephone Access and Local Use," Rand R-3909-ICTF (July 1990), 17. The figure depicts one of the four quadrants.

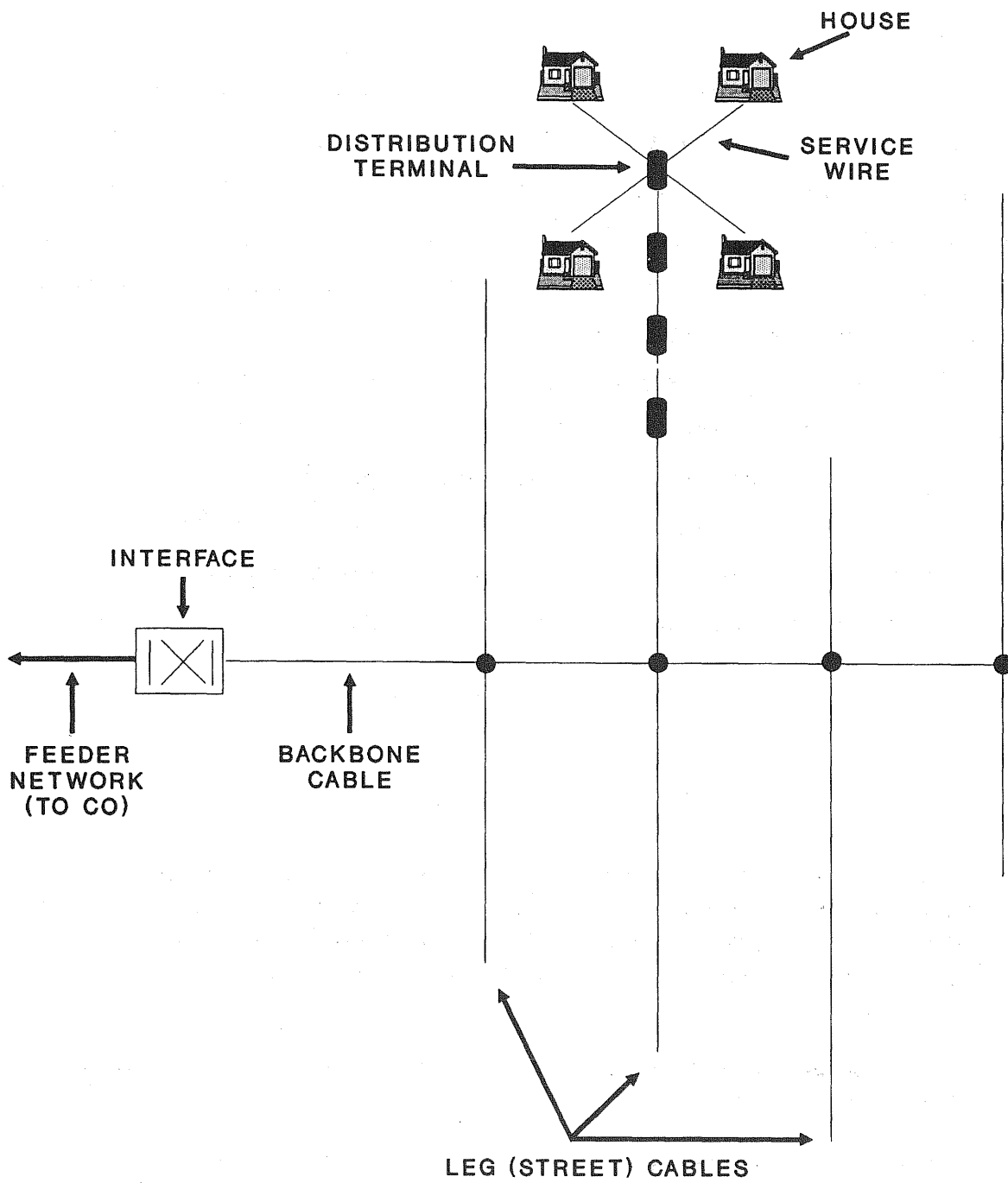


Figure 3

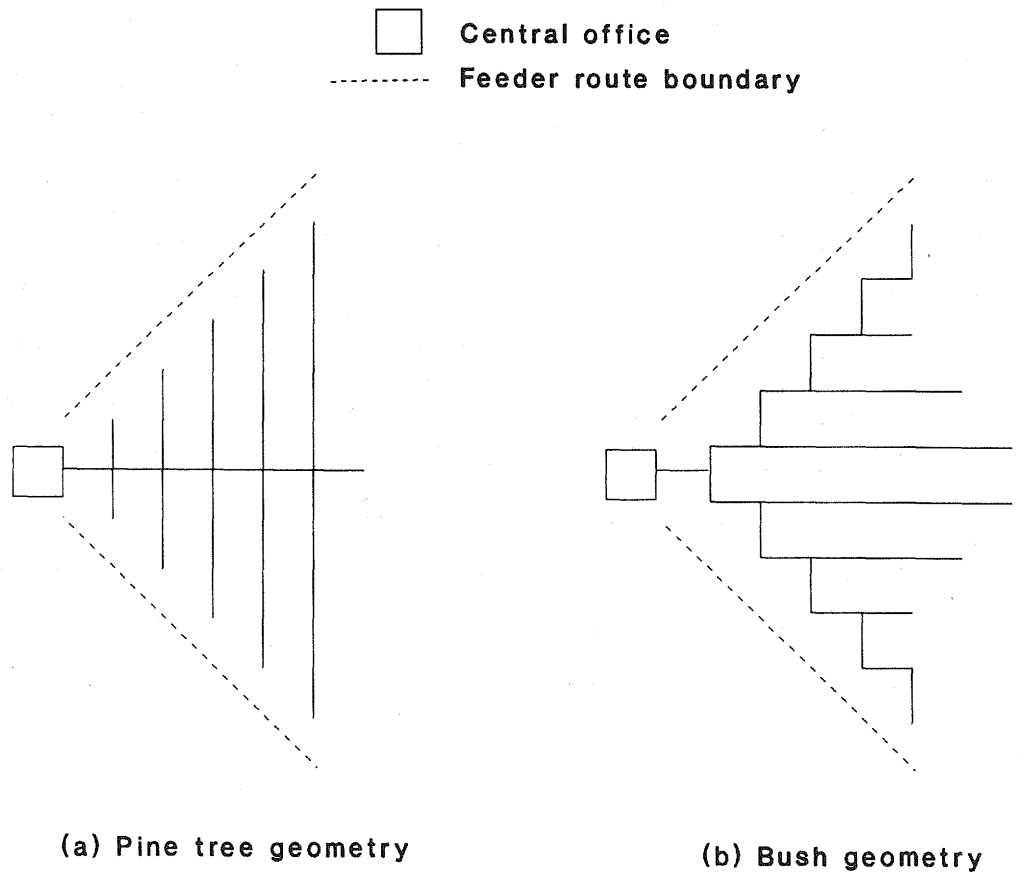


Figure 4

The Local Loop: Copper Wires in the Analog Network

Prior to the deployment of digital switches, loop facilities were essentially all copper wires. Copper cables come in four different sizes: 26, 24, 22 and 19-gauge wire. The installed size (gauge) of copper wire depends on the distance between the subscriber and the serving central office. For loops that were located close to the central office, small diameter, relatively inexpensive copper wire could be used. The drawback to these small wires was that they had more resistance than large wires, which could hinder communications. For this reason, customers more than about 18,000 feet from the central office were served by larger wire (24, 22 or 19-gauge). Furthermore, on customer lines more than 15,000 feet from the central office, the resistance design standards required that load coils be installed to counteract the capacitance of the cables.

During the past ten years, local exchange companies have started to eliminate load coils from the exchange plant. While these coils served as an effective amplification device for voice communications, they interfered with high-speed data transmission.⁴ As the public switched network is increasingly used for transmitting data at high bit rates, these coils will be replaced by equipment more suited to digital transmission. Our cost estimates assume that load coils are still deployed in the local loop.⁵

⁴See, for example, Haru Ogiwara and Yasukazu Terada, "Design Philosophy and Hardware Implementation for Digital Subscriber Loops," *IEEE Transactions on Communications* 30 (September 1982): 2057; and Thomas P. Byrne, Ron Coburn, Henry C. Mazzoni, Gregg W. Aughenbaugh, and Jeffrey L. Duffany, "Positioning the Subscriber Loop Network for Digital Services," *IEEE Transactions on Communications* 30 (September 1982): 2006-7.

⁵When using LECOM, the user of the model can study the impact of removing the load coils and replacing them with subscriber-line-carrier. This is done by changing the crossover point of copper to t-carrier in the program data file DXOVER.DAT to 15 kilofeet (see "Fiber Optics in the Local Loop," 82 *infra*).

The reader of the report might want to take special note of this and other footnotes where we indicate how the model can be used.

Installed Capacity in the Local Loop

The number of cable pairs installed in the feeder and distribution plant is based on the forecasted number of installed lines. In the 1970s AT&T established a standard of 1.5 cable pairs per household in the feeder plant, and two pairs per household in the distribution plant.⁶ The number of lines installed for businesses follows similar engineering rules.

One motivation for allowing two pairs per customer was to have available capacity to serve, on demand, customers desiring a second line, which might be needed because of heavy use by teenagers or for computer communications. Partly out of anticipating high levels of usage, AT&T decided to provide spare capacity in the feeder and distribution. We have used these standards for cities where the level of usage falls in the range of one and 4.2 ccs (ccs = one hundred calling seconds) per main station (see Table I).⁷ These standards would not be sustained where a customer's usage falls outside this range.

If usage is "low," less spare capacity would be built into the outside plant facilities. While busy-hour usage is almost always greater than one ccs, an entrant's deployment of cable pairs per customer would be a function of usage. If usage is "high," additional spare would be built into the outside plant because this would raise the probability that customers would order a second line.

The model can be used to calculate the cost of stand-alone toll systems, whose usage typically would be below one ccs per customer. By allowing for the different

⁶J.A. Stiles, "Economic Design of Distribution Cable Networks," *Bell System Technical Journal* 57 (April 1978): 943.

Post-divestiture, some of the Bell Operating Companies may have adopted different standards.

⁷The data shown under the column "one to 4.2" are based on standard engineering practices. The data reported in the other two columns were selected by us to reflect how network design changed under different demand scenarios.

design criteria, it was our intention to more fully reflect the design principles that would be followed by an entrant.

Table I Feeder and Distribution Pairs Per Customer			
	Busy-Hour CCS Usage Per Customer		
	Less than one	One to 4.2	Greater than 4.2
Feeder pairs per customer (copper)	1.10	1.50	1.65
Feeder pairs per customer (SLC-96 [®])	1.04	1.05	1.08
Distribution pairs per customer	1.50	2.00	2.20

These assumptions imply that within certain ranges of usage the cost of outside plant facilities will be traffic sensitive in the long run. For example, if usage increased from .8 to 2.5 busy-hour ccs (bhccs⁸) per line, the number of distribution pairs per customer would increase. This, in turn, would raise the cost of the local loop.

For other levels of usage, the number of distribution pairs per customer would be independent of the level of usage. If usage increased from 2.5 to 3.0 bhccs, there would be no change in the number of pairs per subscriber.⁹

⁸Traffic-sensitive equipment is designed to satisfy peak-hour calling requirements. The level of demand is measured at the busiest hour (bh) of the busiest season of the year. Usage is measured in terms of hundred calling seconds (ccs).

⁹This does not imply that the cost of the loop is nontraffic sensitive. Additional usage may affect the optimal number and location of switches, which, in turn, would make the loop cost traffic sensitive.

Placing the Cable Underground

Aerial cable is obviously more exposed to the elements than cables placed underground. In recent years, to minimize repair problems that may arise from storms, exchange companies have almost exclusively placed new loop installations underground.¹⁰

Buried cable is placed in the dirt by a tractor and is installed mostly in suburban and rural areas where such operations are possible. In urban areas, a utility's right of way is almost exclusively under paved streets. Consequently, cable must be pulled through underground conduit. The cost of installing conduit is high--ranging from approximately \$4 to \$50 a foot.¹¹

New Technology in the Local Loop

Digital network topology is significantly different than analog. With analog switches, the central office served as the exclusive means for concentrating lines into the switched network. In the digital world, concentration can occur closer to the customer. As described below, customers may begin sharing facilities at either the serving area interface or at a remote switching center. When concentration first occurs away from

¹⁰Local exchange companies (LECs) continue to make capital expenditures for aerial cable. These expenditures are typically related to expansion of existing routes or maintenance, rather than the provision of service to new communities.

While our use of LECOM reflects the practice of installing only underground or buried cable, the user of the model can choose to study the cost of using aerial cable by dropping the deployment of underground or buried cable.

¹¹In our model, we have assumed that only underground and buried cable are used in the local exchange network. The user of LECOM declares in the input file what ratio of buried and underground facilities should be deployed.

the central office, the topology is called a double-star architecture, the second star being the central office.¹²

We have constructed LECOM under the assumption that in the analog world of telephony no subscriber carrier is deployed. In the digital version of the model subscriber line carrier is used where it provides a cost saving. Below we briefly summarize the engineering procedures for subscriber line carrier.

A. Subscriber Line Carrier

The introduction of digital switching has affected local loop economics. When a customer is served by a digital switch, voice signals must be converted from an analog to a digital format at either the central office or at the serving area interface. If the analog-digital conversion is done in the field, some cost savings can be achieved. Once the communication signals are converted to a digital format, concentrating a number of channels on a reduced number of pairs of copper wires or a fiber optic cable becomes economical.¹³ The Bell Operating Companies typically deploy SLC-96® (subscriber-line-carrier) for subscriber line concentration.

SLC-96® in an unconcentrated mode¹⁴ (Mode-1), the type normally used by the Bell Operating Companies, provides ninety-six subscriber channels over five copper T-1 digital lines (four working and one protection).¹⁵ The T-1 lines extend from the central

¹²L. Coathup, J.P. Poirier, D. Poirier, and D. Kahn, "Fiber to the Home -- Technology and Architecture Drives," *1988 International Symposium Subscriber Lines Services* (New York: IEEE, 1988), 14.2.1 - 14.2.5.

¹³Since we found that subscriber-line-carrier on copper was less expensive than subscriber-line-carrier on a fiber optic cable, our discussion here will focus on the former mode of transport.

¹⁴The unconcentrated model provides a dedicated voice path to the central office for each customer.

¹⁵Because of one-way transmission, ten copper pairs are used.

office terminal to the serving area interface.¹⁶ Although rarely deployed by the Bell Operating Companies, SLC-96® can be configured so that ninety-six voice channels are concentrated into forty-eight voice paths (Mode-2). By using SLC-96® in a concentrated mode, only three copper T-1 digital lines (two working and one protection) are needed to serve ninety-six subscribers.¹⁷

With Mode-2 SLC-96®, forty-eight voice channels are available between the serving area interface and the central office. Because of this two-to-one concentration ratio, the deployment of Mode 2 SLC-96® raises the likelihood that a subscriber will receive a busy signal. However, the likelihood is small.¹⁸

In the unconcentrated mode, ninety-six voice channels are provided through ten pairs of copper wire (Mode 1 SLC-96®). Since each customer is provided with a dedicated voice channel, use of this configuration does not affect the likelihood that a customer will receive a busy signal.

The Bell Operating Companies have not widely deployed concentrated SLC-96® despite significant potential cost savings (an approximate 38 percent first-cost savings¹⁹), and a low probability of blockage.²⁰ The Independent Telephone Companies have

¹⁶T.A. Abele and A.J. Schepis, "The SLC-96 Subscriber Loop Carrier System: Overview," *AT&T Bell Laboratories Technical Journal* 63 (December 1984): 2273-2281.

¹⁷R.J. Canniff, "A Digital Concentrator for the SLC-96 System," *Bell System Technical Journal* 60: 121-158.

¹⁸In the concentrated format, SLC-96 mode-2 could carry a load of 12.02 ccs/line and the probability of blockage would be 0.5%. Y-S. Cho, J.W. Olson, and D.H. Williamson, "D4 Digital Channel Bank Family: The SLC-96 System," *Bell System Technical Journal* 61 (November 1982): 2677, 2691. Actual customer usage is approximately one-fourth this level and, consequently, the likelihood of blockage is lower than 0.5%.

¹⁹AT&T System Letter IL 83-06-103, June 13, 1983.

²⁰The BOCs reluctance to adopt this cost minimizing technology may be explained, in part, by the poor performance of the concentrators installed in the late 1950s. J.H. Miller and J.G. Schatz, "Loop Concentrators, Present and Future," *National Telecommunications Conference: 1977* (New York: IEEE, 1977), 39:1-1 - 1-5. The concentrator technology of thirty years ago was far inferior to the equipment available

deployed concentrators more widely in the local loop than the Bell Operating Companies.²¹

Wide-scale deployment of SLC-96® by the BOCs was delayed until they began to install digital switches. When analog switches were the workhorses of the network, SLC-96® was not economical because the analog-digital conversion had to be done both at the serving area interface and at the central office. The digital signal could not be processed by the analog switches, so the customer's signal had to be in an analog format before it entered the switch.

The Bell Operating Companies increased their commitment to digital switching technology about 1984. Since digital switches were designed to process digital signals, the SLC-96® lines could be terminated directly on the switch. This provided significant savings enticing local exchange companies to increase their use of SLC-96® beginning about the same year.

A more recent development in the local loop has been the replacement of copper wires with fiber optic cables. When used in conjunction with t-carrier systems, fiber optic cables are capable of providing connections to thousands of customers through one cable.

The LECOM user determines in the input file if either Mode-1 or Mode-2 subscriber-line-carrier should be deployed.²² The model determines the distance at

today.

²¹The Independents have deployed equipment that is engineered with a greater degree of pair-gain, that is a higher ratio of customers to physical lines. See, for example, Raymond D. Hayden, Jr., "General Principles of Feeder - Distribution Cable Engineering," 1987 Rural Electrical Administration Engineering and Management Seminar; and Harold T. Mason, "Application of a New Subscriber Multiplex With Either Analog or Digital End Offices," *National Telecommunications Conference: 1981* (New York: IEEE, 1981).

²²This is done through variable SLC_MODE. See page 147 for the format of the input file. If SLC_MODE is set to one, SLC-96 Mode one is deployed. If the value is two, SLC-96 Mode two is deployed.

which point it becomes economical to use the subscriber-line-carrier on either copper or fiber.

B. Remotes

In the digital environment, the local loop cost is also affected by deployment of remote switches. Remote switches are connected to a large host switch (DMS-100®) and can terminate approximately 5,700 lines. The remote either can pass all traffic to the host switch or handle on a stand-alone basis calls that originate and terminate on the remote.

We assume that a serving area will be attached to a remote if the loop cost of connecting a customer to the remote is less than the cost of terminating customers on the host switch. We allow for up to nine remotes to be attached to each host switch.²³

Switch Deployment

During the analog era of telephony, Bell Operating Companies primarily installed two types of switching machines: the #2BESS and #1AESS. The smaller of the two, #2BESS, had a capacity of 20,000 lines and 38,000 busy-hour calls. The #1AESS switch could handle 128,000 lines and 240,000 busy-hour calls.²⁴

Despite its large capacity, it was not economical to serve all customers with the #1AESS machine. It was costly to use long loops to connect suburban neighborhoods with the machine, which often were located in the center of a city. In such a situation

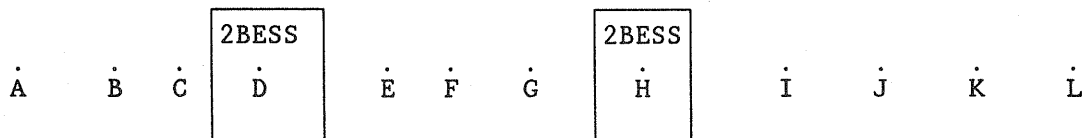
²³In a recent cost study conducted by David Gebhardt, Jr., Illinois Bell assumed that five remotes were attached to host switches in low density regions. Illinois Commerce Commission, 89-0033, ex. 18.24, 27. Apparently, Illinois Bell concluded that remotes were not economical in high-density regions. This is likely due to the short length of the loops in high-density areas. Remotes are only included in our cost-minimizing solution if they lower the total cost of service.

²⁴David Talley, *Basic Electronic Switching for Telephone Systems* (Rochelle Park, NJ: Hayden Book Co., 1982), 228-29.

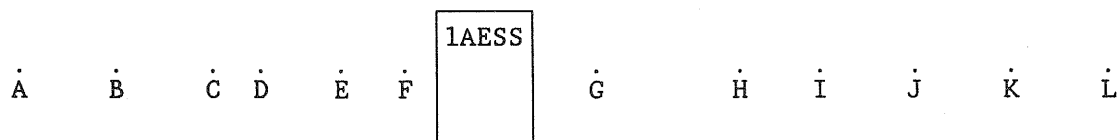
the cost of service may be minimized by substituting switching for loops. The #2BESS machine was used in less densely populated neighborhoods because the fixed cost was about one-fourth that of the #1AESS.

Installing an additional switch is economical if the incremental loop savings equal or exceed the additional trunking and switching costs.²⁵ To illustrate this condition, assume that the cost of usage is independent of the number of switches. Because of this assumption, we need only be concerned about the fixed cost of the switch versus the cost of loops.

Consider the following diagram.



Assume that each letter represents an area with a few thousand subscribers served by two #2BESS switches. The switches are located at points D and H. Alternatively, a large #1AESS switch located between F and G could serve the entire area.



It is economical to use only one switch if the avoided cost of a second switch is greater than the incremental cost of longer loops.

When only one switch is used, the cost of the loops increases because the distance between customers at points A, B, C, D, E, H, I, J, K and L and the nearest switching machine has increased. On the other hand, the length of the loops for customers located at points F and G has declined. The number of switches deployed should not be

²⁵Rural Electrification Administration, "Telephone System Design," *Telecommunications Engineering and Construction Manual* Section 204, April 1971, 7.

reduced if the incremental cost of longer loops is greater than the switching and trunking savings that could be achieved by not deploying these switches.

The tradeoff between switching, loops, and trunking is illustrated in Table II where we report the results from LECOM when 112,872 switched customers and 1,140 private line customers are served by three alternative configurations of analog switches. In each case, the total switched busy-hour ccs equals 270,891 and the town is 63.3 square miles in area.

<p style="text-align: center;">Table II Cost Trade Off: Large v. Small Switches Type of Switch Configuration</p>			
<u>Cost Categories</u>	<u>2 1AESS</u>	<u>1 1AESS & 3 2BESS</u>	<u>11 2BESS</u>
Feeder	\$8,219,808	\$6,985,588	\$4,076,173
Distribution	7,586,989	7,463,126	7,322,102
Switching	5,362,758	5,264,277	6,001,853
Interoffice	1,218,890	1,179,149	1,551,406

Total annual cost	22,388,444	20,892,140	18,951,534
Average loop length (miles)	2.61	2.32	1.60
Source: LECOM (date generated by the cost model).			

As additional switches are added the length of the loop declines, and the reduction is reflected in a decline in feeder costs. The distribution savings are small. Since the serving area dimensions are fixed by population density, the length of the distribution cable is unaffected by the deploying of additional switches. The savings in the distribution plant result from using higher-gauge wire when the distance to the central office is reduced.

Switching costs decline because the fixed cost of three 2BESS switches is less than the fixed cost of the discarded 1AESS machine. The traffic-sensitive costs of the larger machine are lower, but these savings are smaller than the incremental cost of getting started.

Interoffice trunking costs increase relative to the option of two 1AESS switches because the three 2BESS machines terminate fewer lines than the discarded 1AESS switch. This raises the percentage of intraoffice traffic on the remaining 1AESS machine.²⁶

In the digital model, we assume that the supplier deploys either DMS-100® or DMS-10® switches. The DMS-100® is capable of processing approximately 300,000 busy-hour busy-season calls. Remote switches, with a capacity of about 5,700 lines, can be attached to this type of switch. The DMS-10® is capable of handling traffic for about 10,000 lines, or 20,000 busy-hour calls.

Toll Office

We have assumed that a city is served by one toll tandem office handling the traffic going in and out of the city.²⁷ Further, we assume that a #4ESS switch is used for the toll traffic and that the switch is located in the city's central business district, an assumption made not only to expedite the search process, but because the location is consistent with telecommunications engineering practices. If only one switch is used, the standard engineering rule of thumb is to place the switch in the center of traffic.²⁸

²⁶Intraoffice traffic are calls that originate and terminate on the same switching machine.

²⁷Smaller cities would often be served by a combined toll-local office. Our assumption that each city is served by a toll office does not cause any significant cost distortions since we assume that the cost of toll tandem traffic is linear, with no fixed costs.

²⁸H. Stromberg, "Local Exchange Areas," in *International Telecommunication Union Swedish Telecommunications Administration: Planning and Projecting of National Switching*

Interoffice Traffic

Exchange traffic either may originate and terminate on the same switch (intraoffice traffic), or go between central offices (interoffice traffic). As shown in Table III, the proportion of calls that originate and terminate on the same switch varies between communities. In rural areas, all customers in an exchange typically are served by one switch. Consequently, interoffice exchange calls from small towns occur only where extended area service has been established.

Table III
Intraoffice Calls: Proportion of Total Calls

<u>Community</u>	<u>Percent</u>
Rural	66
Suburban	54
Urban	31

Source: R.F. Rey, ed., Engineering Operations in the Bell System (Murray Hill, N.J.: Bell Laboratories, 1983, second edition), 125.

In larger cities, the local exchange company typically deploys more than one switch. Suburban customers are less likely than urban customers to place an interoffice call because their primary community of interest is in nearby stores and among neighbors, locations often served by the same switch. Urban customers, on the other hand, are more likely to need to call customers served by a different switch.

Networks (Stockholm, 1967), 5-22.

The cost minimizing location of the toll tandem is a function of the location of other toll nodes that connect with the office. The optimal location of all toll nodes is beyond the scope of this model.

Traffic studies show that when an interoffice call is placed, there is a greater likelihood that it will be placed to a customer served by a nearby switch rather than a distant machine. For example, a subscriber placing an interoffice call from downtown is more likely to call another downtown customer than a suburban subscriber.

We have constructed LECOM to take into account business customers being more likely to place interoffice calls that mostly go to nearby switches. The percent of intraoffice calls is an increasing function of the number of customers terminated on the customer's host switch divided by the number of switched customers in the city.²⁹

Customer Density

The cost of telephone service is also a function of customer density. An increase in customer density may lower the average cost of service because as density increases, the network's fixed cost can be shared by more customers.

²⁹For example, for business customers, we use the following algorithm:
percent of *exchange* calls that are intraoffice calls =

$$0.1735358 + 0.826 * \text{pct}$$

where $\text{pct} = x/y$

x = number of customers on the same switch as the business customer

y = total number of switched customers in the city

For example, assume that pct is equal to 45%. The following percentage of *exchange* calls would be intraoffice calls: $0.1735358 + 0.826 * .45 = .5452$. The remaining 45.48% of exchange calls would be interoffice exchange calls.

The formula, $0.1735358 + 0.826 * \text{pct}$ was derived by looking at subscriber line usage studies, and observing that as the size of the market increased, the percent of interoffice calls increased (or conversely, the percent of intraoffice calls declined). Larger local markets are typically served by multiple central offices. Based on our reading of the studies, we fitted curves to represent this relationship.

Similar relationships were estimated for the residential and mixed districts, as well as private line customers.

Note that the equation provided in this footnote is the percentage of *exchange* traffic that is intraoffice. Table III reports the percentage of *total* traffic that is intraoffice.

The model was run for various levels of customer density. To give a sense of the variation in density in different cities, Table IV provides some customer density data developed by AT&T in the 1970s.

Subscriber Densities in Selected Cities, in Subscribers Per Square Mile Table IV			
City	Density in highest density exchange	Average density citywide	Density in lowest density exchange
Philadelphia	33,609	10,276	1,930
New York	277,495	17,032	612
District of Columbia	12,367	1,023	19
Boston	33,971	9,955	1,814
Bangor	157	97	38
Portland	1,005	319	35
Jacksonville	2,075	314	2
Miami	3,584	1,140	51
Hartford	2,651	344	3
Atlanta	3,974	1,439	191
Source: George P. Mandanis, "An Empirical Analysis of Economies of Scale and Specialization in Communications," in <u>New Dimensions in Public Utility Pricing</u> , ed. Harry M. Trebing (East Lansing: Michigan State University Public Utilities Studies, 1976), 363.			

A local exchange company provided data from a recently completed study of customer density in different types of neighborhoods. As with the previous table, the information in Table V will help the user of LECOM determine what values of customer density should be evaluated.

Table V
Customer Density per Square Mile

Type of Neighborhood	Density per Square Mile
Single-family	2,560 - 3,840
High Density Residential (high rise apartments)	20,480 - 49,960
Office Park	7,680 - 10,240
Industrial Park	1,280 - 11,536
Medium Density Business	5,120 - 7,680
High Density Business	153,600 - 179,200
Commercial Strip (Linear Mile)	614

Source: Proprietary.

III. Assumptions (A) and Definitions (D) in the Model

In this section we outline some additional assumptions made in constructing LECOM. As previously discussed, the model is largely based on standard telecommunication engineering practices. In order to keep the program tractable, some important assumptions had to be made. They are outlined in this section of the paper.

A(1). The city being served by the telephone system can be characterized geographically by three nested rectangles. This assumption enables a simple space allocation rule for serving areas, discussed below. It is not in itself unduly restrictive, since the dimensions of the rectangles are user-declared values (see figure 5).

CITY TOPOLOGY

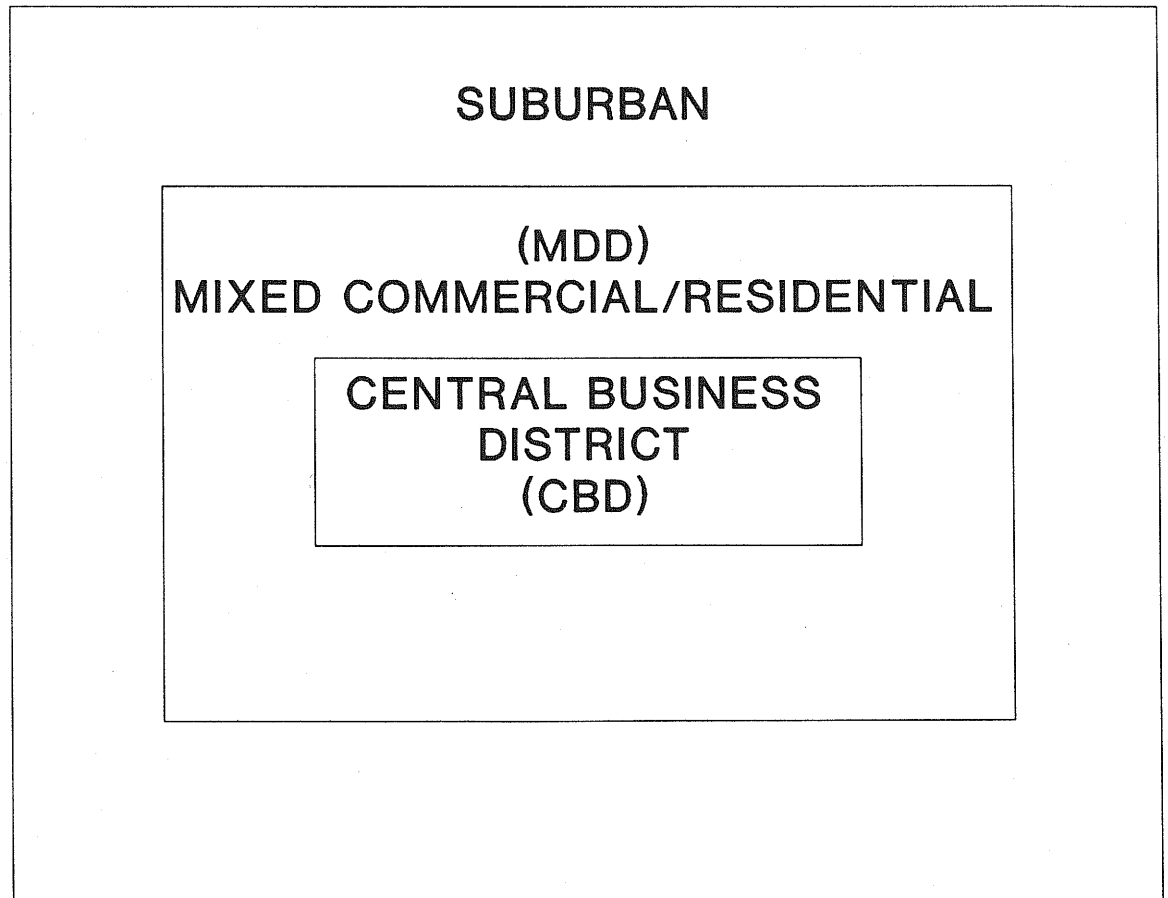


Figure 5

D(1). The innermost rectangle is known as the central business district (CBD), the region between the CBD and the rectangle surrounding it is known as the medium density district (MDD), and the area outside the MDD but within the city limits is known as the suburbs.

A(2). Within each area population density is uniform. This assumption is somewhat restrictive, but not wholly unrealistic especially given that we allow differing densities for the three districts.

D(2). A serving area (SA) is a rectangular geographic area within a district containing a fixed number of customers. The number of customers in each serving area is approximately the same throughout the city. A typical serving area includes 600 customers, although this value can be changed by our software users.

A(3). The dimensions of serving areas are determined by the shape of the district and the percentage of the city's area that lies within that district. Ideally, the dimensions of serving areas would be computed endogenously as part of the optimization process we describe later. However, such an optimization would raise the computational burden considerably and would most likely require the use of a super computer for its solution (especially in the context of the repeated optimizations we perform here). Instead, we employ a simple rule: Divide each district into rectangles of equal size such that the required number of customers per serving area resides in each rectangle.

A(4). There are two types of analog switches, 1AESS and 2BESS, and three types of digital switches, remotes, DMS10® and DMS100®, each with a unique capacity. In the digital environment, subscriber line concentrators, also with unique capacities, will be deployed where they lower the cost of service. This assumption simply reflects the available technologies. As we will discuss later, part of the optimization problem solved in this model is a combinatorial optimization over the various feasible mixtures of these technologies.

General Program Description

The programs, which have been written in Pascal (one program is dedicated to the analog environment, one for the digital) take the annual costs of land, labor, materials, and capital, as well as the size of the city and customer demand patterns as inputs. With these input data, the minimum possible number of central offices (given the capacity of the largest feasible switch) is computed. At this point, the main routine conducts a search of feasible combinations of central office types for the cost minimizing arrangement. For each combination of switches, starting locations are estimated by spacing the switches of each type in intervals between the city boundaries. The program then searches for other switch locations that will lower the cost of service. For each location, the cost of an exchange network is computed using the input data, and the switching, distribution, trunking, and feeder cable algorithms compiled from engineering studies. The locations of the switches are optimized by a nonlinear, derivative-free, downhill-simplex routine proposed by Nelder and Mead (1965) and described in Press in other words.³⁰

³⁰William H. Press, Brian P. Flannery, Saul A. Teukolsky, and William T. Vetterling, *Numerical Recipes: The Art of Scientific Computing*, Cambridge, MA (Cambridge University Press, 1986).

The simplex is constructed by augmenting a vector of starting values with a matrix formed by adding the starting value vector to each column of an identity matrix of order equal to the order of the vector in which the diagonal elements have been replaced with appropriate scalars. These scalars are chosen heuristically in the program to be the value halfway between the current cell in the starting value vector and a value on the boundary of the feasible solution set. The algorithm works by taking a series of steps, most of which consist of finding the vertex on the simplex with the highest function value and reflecting it through the opposite face. The same operation is performed on the new simplex, and the process is continually repeated. If a reflection seems to bring about no improvement, the simplex shrinks itself and the algorithm restarts. If the algorithm reaches a point where no further improvements seem possible, it will continue to shrink the simplex until all vertices are within the user-defined tolerance of each other, and convergence is achieved. The user can also specify a maximum number of iterations to allow the algorithm, in which case the routine passes back its best effort for the given number of iterations.

Whereas the switch location may be a local rather than a global cost-minimizing location, we restart the program by randomly adjusting the starting values. The number of random restarts is determined through the user interface.

The cost computation depends on a crucial simplifying assumption: serving areas are added sequentially to each switch until a central office's capacity is exhausted.³¹ A serving area is attached to the switch located the shortest distance from its serving area interface. Distance serves as a monotonic approximation of the cost-minimizing solution. This procedure relieves the potentially massive computational burden of performing a high-dimensional integer optimization in allocating serving areas to switches.

While it is not computationally feasible to test every possible combination of serving areas and switches, we allow the model to consider "gains from trading." After attaching each serving area to a central office, we look to see if the cost of production could be reduced by having one switch trade serving areas with another.³² The serving

Press et al. recommend that the algorithm be restarted using any claimed minimum as a new starting vector. The program incorporates this recommendation, allowing the user to specify how many restarts s/he wishes to implement.

³¹The user declares the percent of the switches' theoretical capacity that may actually be used. For the results reported herein, we assume that up to 90 percent of the theoretical capacity is in use.

³²Consider the following example. Assume that there are two switches, A and B, and six serving areas. The assumed cost of attaching each of the serving areas to the two switches is shown below:

Serving Area	Cost of Attaching to A	Cost of Attaching to B
1	10	15
2	12	14
3	14	8
4	11	7
5	35	17
6	36	22

In the first pass through the program, the following sequence would occur.

A attaches to serving area 1

areas must be exchanged, rather than just changing the assignment of one serving area, because of the switching machines' capacity constraint. Also, we do not attach a serving area to a remote switching machine if it would be less expensive to attach it directly to the host switch. Since the capacity of the host switch is determined in part by the number of lines attached to the remote, one-way trading may occur.

Once it has been determined which serving areas are served by a switch, "feeder" routes are determined for the region served by the switch according to the industry-standard pinetree topology. The pinetree approach minimizes the cost of feeder plant; the physical plant that distributes telephone signals from the switching office to the serving area interfaces.

LECOM also takes into account the higher costs of longer loops resulting from the thicker gauge wire and load coils required to ensure good quality signal transmission. These computations are stored in a matrix of feeder lengths and gauge distributions. This matrix is also employed in computing distribution plant costs (within serving areas). In the digital program, subscriber-line carrier is deployed on the longer loops.

Analog switching costs for the 1AESS and 2BESS switches depend on user declared busy-hour usage by each type of customer class, the presence of other switches in the local network, and the number of customers served by the switch. Usage patterns can affect the capacity of switches, especially 2BESS. The program enables recomputation of 2BESS capacity internally to handle this problem.

The program, then, essentially nests an inner location optimization (that is, finding the best location of the switches) in an outer combinatorial optimization (that is,

B attaches to serving area 4
A attaches to serving area 2
B attaches to serving area 3
A attaches to serving area 5
B attaches to serving area 6

The program would then search for gains from trade. The cost of the outside plant can be reduced by offices A and B trading serving areas 4 and 5 respectively. The savings associated with attaching serving area 4 to switch A ($14 = 35 - 11$) exceeds the additional cost of attaching serving area 5 to switch B ($10 = 17 - 7$).

experimenting with different combinations of switches). After the combinatorial search of switches the program reports the cost minimizing arrangement and location of switches as well as summarizes relevant input data.

Cost minimization is defined in terms of minimizing the annual production costs, equivalent to minimizing the present worth of capital, maintenance, and tax expenditures.³³

Whose Costs Are Being Modeled?

LECOM is designed to determine the network configuration that minimizes the cost of production. In seeking the optimal combination and location of switches, the model is not constrained by existing locations. The LECs, by contrast, are not in this situation--their investment decisions are affected by the current location of facilities. In this section of the paper we address the extent to which LECOM's cost estimates provide insight into the process of determining the reasonableness of the rates of the LECs.³⁴

Microeconomic theory emphasizes that pricing decisions should be based on an analysis of the costs and benefits associated with changes made at the margin. Economists disagree whether long-run or short-run marginal costs should be used in the analysis.³⁵

³³J. Freidenfelds, "A Simple Model for Studying Feeder Capacity Expansion," *Bell System Technical Journal* 57 (April 1978): 821.

³⁴LECOM can also be used to determine the cost-of-production when the facility locations are known. By removing the optimization routine from the program, we have also provided the user of the model with a tool that allows the analyst to determine the cost of production for given switch locations. As described at page 140, if the user indicates the type and location of switches, the model will estimate the cost of service for the indicated network configuration.

³⁵See, for example, Alfred Kahn, *The Economics of Regulation*, v.1, chs. 3 and 4. The short-run is that time period during which the facilities of the telephone company are fixed and cannot be varied except at so substantial a cost that it is never profitable. In the long-run, the firm can alter its equipment.

It has become the accepted convention in the industry to quantify long-run marginal costs. When these studies have been conducted, most notably the Bell LRIC studies, analysts have assumed that the existing location of the central office is that which minimizes the cost of production.³⁶ Because of these assumptions, only some of the inputs are variable. Typically, what is assumed to be variable is the type of technology. Measured costs are characterized as long run because the analyst allows for replacing existing technology with newer types of equipment.

In our study we have assumed that all inputs are variable. By assuming this, our model is consistent with the economic notion that in the long run no inputs are fixed.³⁷ While this approach is consistent with economic theory, it raises the question: "Whose costs are being modeled?" The incumbent firm's investment decisions are affected by its existing investment. The incumbent solves a dynamic problem: it wants to minimize the present discounted value of its costs of production given the current state of its network, which involves considering different expansion paths. Strong assumptions must be made about the cost and capabilities of new technology, price trends for inputs such as labor, the discount rate, and future demand patterns. Typically, such studies involve projections made over a fifteen to twenty year period.

Both approaches, minimizing the present discounted value of a supplier's costs over fifteen years as well as our static analysis, are consistent with the economic notion of long-run cost analysis. Our approach is more tractable because it requires less speculation about future cost and demand levels, and the information requirements are

³⁶The assumption is never tested.

³⁷"In strict economic terms, the concept of long-run marginal costs relates to a hypothetical situation in which all inputs are variable, and a supplier confronts the possibility of installing entirely new facilities, in effect from the ground up. And the 'marginal' relates to the incremental cost of a single unit of output." Affidavit of Alfred E. Kahn, In the Matter of Expanded Interconnection with Local Telephone Company Facilities, FCC CC Docket No. 91-141, page 22, note 26, August 5, 1991.

less severe.³⁸ The dynamic optimization approach requires that the analyst collect data on the utilization rates of individual network components, and the relevant forecasted growth rates for various services.

Our approach provides an estimate of the long-run cost of production, holding technology constant. Furthermore, the model provides a method for quantifying the cost effect of introducing new technologies. Because of the assumption of no sunk or fixed investments, the model provides an estimate of the production costs that a rival would incur. An entrant's planning decisions would not be affected by existing facilities because, by definition, it does not currently have a presence in the market. Therefore, the model provides a competitive benchmark--it suggests the level of production costs that would be incurred if an entrant were to provide local telecommunication services.

The model of competitive markets is a reference framework used by economists and regulators to assess the propriety of regulatory economic policy decisions.³⁹ This paradigm is used because under certain conditions competitive markets provide the most efficient use of society's scarce resources and maximize welfare.

Furthermore, the Bell Operating Companies and AT&T have previously based some of their rates for competitive services on their rival's cost structure. For example, when the Bell System faced rivalry for bulk private-line services, Bell requested permission to lower its rates. The proposed rates "were based on the cost structure of AT&T's competitors, not those of AT&T itself."⁴⁰

³⁸For example, it is likely that optical switches will be deployed within the next ten years. An analyst who selects the dynamic optimization methodology would need to make assumptions about the cost and capabilities of these switches. But little information is available about this undeveloped technology.

³⁹See, for example, Charles P. Phillips Jr., *The Economics of Regulation: Theory and Practice in the Transportation and Public Utilities Industries* (Homewood, Illinois: Richard D. Irwin, Inc. 1965), 69.

⁴⁰Peter Temin, "Cross-Subsidies in the Telephone Network after Divestiture," *Journal of Regulatory Economics* 2 (December 1990): 353.

In the past there has been an asymmetry in the manner in which cost studies have been done. While great effort has been placed in identifying the cost of providing competitive services, there have been comparatively few studies of the cost of providing monopoly services. The rates for monopoly services have typically been set on a residual basis. First a commission determines the firm's revenue requirement, and second, the amount of revenue generated by nonbasic services. The remaining revenue requirement was recovered from basic telephone service.

Since the divestiture of AT&T there has been an increased interest in determining the cost of different services. We believe that LECOM can be used to indicate the costs an entrant would incur. These costs can serve as a competitive benchmark to judge the reasonableness of the rates for monopoly services.⁴¹

IV. Cost of the Technologies

In this section of the paper we discuss the price of the inputs used to provide telecommunication services.

The results reported in chapters four and five are based on 1990 input prices. Where we had available only prices of inputs purchased in earlier years, we adjusted the input prices by using telephone price indexes. This adjustment process is widely used due to the cost of collecting and updating input prices.

Cost Structure of the Local Loop

The cost of providing customer access to the network is largely determined by the cost of the associated outside-plant facilities. The greater the distance between the central office and a customer's location, the longer the line; if copper wire is used, the

⁴¹The use of unobserved but cost based estimates to judge the reasonableness of rates is used in other regulated industries. See, for example, Interstate Commerce Commission, "Coal Rate Guidelines, Nationwide," Ex. parte No. 347 (Sub-No. 1), decided August 8, 1985, 1 ICC Reports 2d, 520.

diameter of the wire may be larger. Therefore, because of both the length of the connection and the diameter of the wire, the cost of a local loop is distance-sensitive.⁴²

Outside-plant facilities have a fixed and variable cost component. The fixed cost per foot is associated with the engineering and placement of the wires underground. This fixed cost is independent of the number of wire pairs inside the cable sheath while the variable cost is positively correlated.

Table VI provides the fixed and marginal cost per foot for the various gauges of copper wire used in the loop. We have followed the convention of estimating a linear cost function from broad-gauge cost data.⁴³ The cost of different size cables was the dependent variable, and the size of the cables, along with the intercept term, were the explanatory variables. The estimated coefficient of the intercept measures the per-foot, fixed-cost of installing a cable.

⁴²The Bell Operating Companies have traditionally taken the position that even though the cost of the loop is dependent on the distance between the customer and the wire center, the marginal cost of serving each customer is independent of distance. AT&T explained this paradox by noting that a wire center is placed at a location where it minimizes the cost-of-service for all customers. AT&T, "Network Service Costs Methods Manual," volume 8, part 3, section 1.1, April 28, 1978. See, also, Testimony of David H. Gebhardt, Jr. on Behalf of Illinois Bell Telephone, Ex. 18.24, p.3, ICC 89-0033.

⁴³See, for example, Rural Electrical Administration, "Design Techniques of Feeder-Distribution Cable Engineering," Telecommunications Engineering and Construction Manual, section 231, February 1986, p.B-41; and New England Telephone, Massachusetts Department of Public Utility, Docket 86-33, work papers, book 1, tab 1, p.20 of attachment 4.

While not shown here, these investments must be loaded for miscellaneous investments, such as conduit and load coils.

Table VI
Fixed and Marginal Investment per Foot of Copper Cable
Data Year: 1987

Gauge of Wire	Fixed Investment per Foot	Marginal Invest- ment per Pair Foot	Cable Capacity
26			
Underground	\$1.68	\$.0075	3600
Buried	2.17	0099	3600
24			
Underground	1.91	.0097	2400
Buried	2.41	.012	2400
22			
Underground	1.74	.013	1800
Buried	2.23	.016	1800
19			
Underground	2.58	.013	400
Buried	3.06	.015	400

Source: New England Telephone, work papers, book 1, tab 1, p. 1-2, attachment 1, in Massachusetts D.P.U. Docket 86-33.

Viewed at this micro level, Table VI suggest that due to the fixed cost per pair-foot of cable, the marginal cost of adding a customer to the network is less than the average cost.⁴⁴

As indicated in Table VI, a cable's capacity is a function of the gauge of wire. The model starts with the serving area farthest from the central office, and determines the gauge(s) of wire needed to serve those customers. If the cable capacity is not

⁴⁴The fixed cost per foot of 22-gauge cable (\$1.74) is lower than the fixed cost per foot of 24-gauge cable (\$1.91). We have looked at data from two other Bell Operating Companies, and in each case we see no clear relationship between the fixed cost per foot and the gauge of the wire. The fixed cost reflects the cost of placing the cable in the ground, and because of variations in local obstructions, the costs are a function of more than gauge size.

With each data set we see that the marginal investment per pair-foot of wire, in general, increases positively with the diameter of the wire. This positive correlation is consistent with our expectations.

exhausted, and if customers located closer to the central office use the same gauge(s) of wire, the excess capacity is used by the second serving area. When the capacity is exhausted, an additional cable is installed.

For example, assume that the 600 customers in the serving area the farthest distance from the central office must be served by 19-gauge wire. Using the standard of 1.5 feeder pairs per customer, the serving area would need 900 pairs of wire requiring that three cables extend from the central office to the serving area.⁴⁵ The three cables have a capacity of 1,200 pairs, but since only 900 pairs are required, 300 pairs are "free" to be used by a serving area closer to the central office.

Customers are connected to the distribution cable by a drop wire, which goes from the customer's location to the closest leg in the distribution plant. This investment varies by the type of customer and the number of customers in the city. The more densely populated the area, the shorter the drop wire. For a given city, business customers are generally closer to the distribution leg than residential customers, reducing the level of investment.

Table VII provides the investment per subscriber drop wire in exchanges of varying sizes.

For the digital model, we have assumed that SLC-96® equipment may be deployed on long loops. Esty estimated that the cost of the t-carrier terminal equipment was approximately \$5,000 for twenty-four channels,⁴⁶ which is in line with data obtained from other, proprietary sources.

We assume that SLC-96® on fiber, or SLC-96® on copper, is installed where the annual cost of these technologies is less than providing service via copper cable.

⁴⁵Round($900/400 + .5$). In this example we assume that the full capacity of the cable may be used. But because of the ratio of 1.5 cable pairs per customer, this is an effective fill rate of 66%.

⁴⁶Scott A. Esty, "Fiber Beats Copper in the Feeder Plant," *Telephony*, November 16, 1987, 42-46.

Table VII
1987 Investment Per Drop Line: Business v. Residential

Primary Calling Area (number of customers)	Business	Residential
Less than 15,000	\$42.00	\$81.60
15,000-37,500	36.60	76.80
37,501-75,000	36.00	73.20
75,001-120,000	23.40	70.20
120,001-175,000	23.40	69.60
175,001-325,000	29.40	69.00
Greater than 325,000	6.00	31.20

Source: New England Telephone. work papers, book one, tab 1, p. 19, in
Massachusetts D.P.U. 86-33.

Fiber Optics

In the digital environment we evaluate the economics of using fiber optics in both the local loop and in interoffice trunking. The terminal fiber optics costs are a function of the number of T1 systems. As shown in Table VIII, we allow for a large range of multiplexers.

Table VIII
Fiber Multiplexers

Mb/s	T systems	equivalent voice channels	investment per end*
45	28	672	8,000
90	56	1344	12,000
135	84	2016	15,000
405	252	6048	22,000
565	336	8064	38,500

*Data obtained from Information Gatekeepers, the Rural Electrical Administration, and Esty, "Fiber Beats Copper in the Feeder Plant, 42-46. At the rate of 135 MB/s or faster, an additional \$10,000 investment per end is needed for each 28 t-carrier systems.

We believe that our cost modelling approach provides richer insights than the methodology often followed by telephone companies. Frequently the telephone companies calculate transport costs by multiplying unit average costs by the appropriate quantity. As a result, fixed and variable costs are lumped together. By allowing for different sizes of multiplexers, we are able to distinguish between large lumpy investments (for example, the multiplexers), and the smaller incremental costs associated with increased usage (for example, T1 interface cards and digital cross-connects).

The Cost of Interoffice Calls

The cost of an interoffice trunk is a function of the fixed cost of terminating the trunk and the distance between the central offices. In the analog mode local exchange companies essentially choose between two technologies: copper wire and t-carrier on copper wire. The deployment of t-carrier reduces the number of copper pairs between offices, but, due to the channel banks, raises the fixed cost of service. For short distances, copper wire technology minimizes annual costs. For longer distances, t-carrier is more efficient because the savings in copper wire exceed the higher fixed cost of terminating the t-carrier.

Our model is designed to determine at what distance the technology of choice changes from copper wire to t-carrier. For all interoffice trunks shorter than this crossover point we calculated the cost of interoffice transport based on copper technology. For longer distances, trunking costs are based on the assumed deployment of t-carrier.

In the digital regime the choices are different. Analog copper interoffice trunks are not cost effective because of the expense of analog-digital conversion. Here we assume instead that the engineer is choosing between t-carrier on copper wire and t-carrier on fiber optics. T-carrier on copper is the technology of choice for low-volume, short-distances routes.

Private-Line Costs

Private-line loops are more expensive to provide than ordinary telephone service because of more stringent technical requirements of data and video services. Prior to the advent of digital technology in the loop, private-line loops often had to be engineered individually, an expensive process.⁴⁷ We have assumed that the cost of a private-line loop for a given length and customer density is approximately 50 percent higher than a loop used for analog switched services.⁴⁸ The data that we have seen suggests that this difference persists in the digital world. For the digital model, we assume a mark-up factor of 45 percent.

This additional cost, attributable to the more stringent technical requirements of private-line services, introduces into our model the possibility of diseconomies of scope. The cost of the private-line loops is reduced when customers are located close to the central office. By placing the central office close to the private-line customers (who are primarily located in the center of a city), the distance may increase between the POTS

⁴⁷Byrne, et al., 2006; G.J. Handler and D. Sheinbein, "Improving the Loop to Provide New Network Capabilities," in *Proceedings 1982 International Symposium on Subscriber Loops and Services* (New York: IEEE, 1982), 1-1; Arvina Karia and Salvatore Rodi, "A Digital Subscriber Carrier System for the Evolving Subscriber Loop Network," *The Institute of Electrical and Electronics Engineers, Inc. Transactions on Communications* 30 (September 1982), 2013; and Testimony of Leon J. Titman on Behalf of New York Telephone, New York Public Service Commission Proceeding on Telephone Services that Bypass Local Exchange or Toll Networks (28710), December 11, 1984, 2657.

⁴⁸Based on the data presented in the articles cited in the prior footnote, this factor may be too low. Furthermore, many private line customers are served by two-pairs of cable, rather than the single pair used for plain-old-telephone service. These higher costs are partly offset by the relatively lower cost of providing alarm and burglary service. Balancing these two affects, we arbitrarily assume that private line loops cost about fifty percent more than ordinary loops. In the analog regime, we have assumed that the cost of an interoffice private line trunk is no more expensive than the cost of a POTS trunk. In the digital world, the cost of a private line trunk is greater due to the need to deploy channel banks.

(Plain Old Telephone Service) customers and the closest central office. The additional distance would cause an increase in the cost of the loop for POTS customers.⁴⁹

On the other hand, the addition of private-line customers spreads the fixed cost per foot of cable over a larger number of customers, causing the long-run average cost of providing POTS access to fall.

Switching Costs

The cost of the analog #2BESS and #1AESS machines (estimated based on switching-cost-information-system (SCIS) algorithms originally developed by AT&T and currently supported by Bellcore and SCIS) is used by the Bell Operating Companies to estimate the cost of switched services.

For the digital switches, we relied on the SCIS algorithms to estimate the level of remote switching investment. For DMS10® and DMS100®, some information was obtained from SCIS, while the majority of the algorithms are based on our analysis of how equipment engineers determine the required facilities.

Input Prices

The cost of production is a function of the available technology, the level of output, and the price of inputs. The sources for the "baseline" material prices have been described above.

We have used the model to explore how the cost of production is affected by changes in the cost of capital, materials, and labor. The annual cost of facilities is obtained by multiplying the level of investment by plant-specific carrying charges. There are separate carrying charges for land, buildings, circuit equipment, switching, conduit,

⁴⁹Diseconomies of scope also may arise when the number of private line customers is held fixed, and the number of switches increases. The additional switches will raise the cost of private-line interoffice trunking.

underground copper cable, buried copper cable, underground fiber cable, and buried fiber cable.

The annual charge factors per dollar of investment are derived from the following expense categories: maintenance, depreciation, administrative expenses, and taxes. We define the price of labor as the sum of the maintenance and administrative portions of the annual charge factors. The price of capital is equal to the sum of the cost of money and taxes. Finally, we define the price of materials as equaling the rate of depreciation on the equipment. Reflecting current practices, the rates of depreciation varies by the type of equipment (for example, approximately 2 percent for conduit, 6 percent for switching machines).⁵⁰

User Inputs

Table IX provides a list of the some of the user inputs that affect the total cost of service. A complete list of the user inputs is found on page 145.

⁵⁰The user of LECOM may modify the level of the annual charge factors by changing the price of labor, material, or capital. For example, if the price of labor is increased by ten percent, the administrative and maintenance portion of each carrying charge is increased by ten percent. If the user wants to evaluate the impact of a five percent decrease in the price of capital, this may be done by changing the input variable PRICECAP from 1.00 to 0.95.

Table IX: LECOM User Inputs

Investment costs*
 Annual charge factors
 Geographical dimensions of city
 Area of business district
 Area of residential district
 Area of mixed commercial/residential district
 Number of residential, business and private line customers
 Busy-hour usage by customer classes
 Call mix (toll, exchange)
 Holding time by type of call
 Switch utilization
 Ccs per interoffice trunk
 Private line cost markup
 Customers per serving area
 Underground/buried cable mix
 Block width
 Private lines
 Switched lines
 T-carrier utilization rate
 Loop utilization rate

*Most of our investment cost data came from Bell Operating Companies, the Rural Electrical Administration, and public sources. The only major departure that we make from conventional data sources is our assumption regarding analog switch pricing trends since 1984. Prior to divestiture, AT&T was the sole supplier of analog switches to the Bell Operating Companies. As part of its incentive to get BOCs to migrate to digital switches, AT&T has priced analog switches at prices that depart radically from price trends with similar (PBXs) and like products (for example 8088 microcomputers). The pricing pattern has also departed from the life-cycle pricing history of competitive electronic products (for example VCRs). We assume that after 1984, that the price of analog switches increases (decreases) at the same rate as digital switches.

We evaluated the impact of substituting our telephone plant index for analog switching, for the higher index used by the telephone companies (the telephone company index for analog electronic switching machines was approximately 89% higher).

We found that this change raised the total cost of service on an analog network by six to seventeen percent. The seventeen percent increase occurred in smaller cities, where under both scenarios, LECOM said that it was optimal to deploy only one switch.

The lower range, six percent, was observed where there were a large number of customers, and LECOM said that multiple switches should be deployed. When the cost of switching increased by 89%, LECOM said that fewer switches should be deployed, and this in turn, increased the length of the local loop.

CHAPTER THREE

METHODOLOGY FOR GENERATING DATA

Optimization

In the previous chapter we outlined some of the primary engineering steps that are used to design a telecommunications network. An important step in constructing LECOM was to reduce these procedures into mathematical relationships. This reduction is the essence of an engineering process model--expressing engineering functions in a series of equations.

For example, when operating at full capacity, a t-carrier system is designed to simultaneously carry twenty-four voice conversations. The number of t-carrier systems required between two points is determined by dividing the number of voice channels by twenty-four, and rounding up to the next integer. The following equation illustrates this process:

$$\text{t-carrier} = \text{round}(x/24 + .5),$$

where x = the number of voice channels.

If twenty-six voice channels needed to be installed between points a and b, the equation tells us that two t-carrier systems should be deployed [$2 = \text{t-carrier} = \text{round}(26/24 + .5)$].

After determining the facility requirements, LECOM multiplies the applicable physical quantities by their respective prices. If one end of a t-carrier system costs \$5,000, the model would report that the cost of terminating the two t-carrier systems as being \$10,000 ($\$5,000 \times 2$ t-carrier systems).

We have undertaken similar process representations for all components of the network (that is, the local loop, switching and other components of interoffice trunking).

Using these cost algorithms, LECOM searches out for the combination of facilities that minimizes the cost of production. This is achieved by evaluating both different combinations of large and small switches, as well as different node locations.

Because of the search for the cost minimization location of switches, we are able to characterize LECOM as an optimization model.

Generating Data

After we completed the construction of LECOM we ran the model a few hundred times in order to evaluate how changes in the level of demand, as well as input prices, affected the cost of service. It is through these repeated simulations of our cost model that we obtained the data discussed in chapters four and five, and appendix one.

The data generated by the model reflects the current costs incurred by telephone companies in providing telecommunication services. The input price data used to generate our results are based on actual cost data (for example, cost per pair-foot of cable; the cost of a remote switching machine). But unlike telephone cost models, our estimated cost of service is based on an assumption of optimization behavior; that is, minimizing the long-run cost of production.

In generating the data, we have tried to take into consideration the need to evaluate changes in output over a wide-range of outputs (summary statistics are provided on page 107), as well as an in-depth view of how the marginal cost of production of service A is affected by an increase in the output of service B. This second objective was achieved by starting with varying "base cases," and then looking at different, but not all, increments of the studied services. Table X provides a summary of the different increments studied for each base case. The list reported in Table X provides twenty-six observations for regression analysis (the base case and twenty-five increments to the base case). These same observations can be used to directly calculate the marginal cost of service (see "Using the Model to Calculate the Marginal Cost of Service, page 106).

Table X
Combinations Ran in Generating Data

Base case

Incrementing the demand of one service

1 2 3 4 5

Incrementing the demand for two services

1,2 3,4 3,5 1,3 1,4 1,5 2,3 2,4 2,5
4,5

Incrementing the demand for three services

5,2,3 5,1,4 5,1,3 5,1,2 5,2,4

Incrementing the demand for four services

5,1,3,4 5,2,3,4 5,1,2,3 5,1,2,4

Incrementing the demand for five services

1,2,3,4,5

Definitions:

1 = Exchange switched service

2 = Toll switched service

3 = Local private line service

4 = Toll private line service.

5 = Switched access

Because of the orthogonal nature of the twenty-six observations referenced in Table X, the validity of the data is easily evaluated. The twenty-six observations permit the calculation of the marginal cost of each of the five services in many different ways.¹

Sometimes the model will select switch locations that do not minimize the cost of production. When this occurs, the calculated incremental costs are likely to appear to be unreasonably low or large. These out-of-range values were corrected using the methodology described at page 140.

¹The formulas are provided on LOTUS spreadsheets VRESLARG.WK1 and DRESLARG.WK1. The spreadsheets are found on the enclosed disk.

CHAPTER FOUR

COST ESTIMATES

In this and the following chapter we provide an analysis of the data generated by LECOM. As mentioned in the last chapter, we ran LECOM a few hundred times in order to generate a data base that could be used to analyze the cost structure of the industry. The more technical results are reported in appendix one. Here we briefly summarize the econometric results from the model, provide estimates of the marginal cost of different services, and discuss the extent to which the data indicate that the industry is a natural monopoly.

In chapter five we use the output from LECOM to analyze the economics of fiber optics in the local exchange plant and the pricing implications of our study.

Discussion of Econometric Results

Traditionally, the telephone industry has been considered an increasing-cost industry.¹ The marginal cost of serving a subscriber was believed to be an increasing function of usage because as the number of customers on the local network increased, the number of theoretical connections increased exponentially. In order to be able to make all of these theoretical possible connections, the switching equipment became increasingly sophisticated and expensive.²

¹See, for example, John Lee, *The Economics of Telegraphs and Telephones* (London: Sir Isaac Pitman and Sons, 1913), 74.

²Microeconomic theory suggests that where an industry is characterized by increasing average costs, production costs will be minimized if the product is produced by many small firms. If all firms have a small share of the industry output, they will be operating with a lower average cost than if one firm produced the total output.

Because of customers' desire for universal service, this market structure is not practical for switch telecommunication services. Customers want universal access to all subscribers. Since the various suppliers of switched telecommunication services must interconnect, the atomistic market structure would not provide any cost savings. Because

In the early 1980s the view of the industry as being characterized by increasing average costs was challenged by the econometric work of Christensen et al.³ who concluded there were strong economies-of-scale in the Bell System. We have used LECOM, and traditional statistical tools to further study this issue (see appendix one, page 93).

The results reported in table E-1, page 96, are in line with the earlier perception of diseconomies of scale. The estimated coefficient of the squared value of the outputs is positive. This suggests that the marginal cost of service is an increasing function of usage.

For exchange service, the increasing marginal cost is likely the result of the capacity constraint of a switch. Because a given switch can only process a limited number of calls, at some point additional switches need to be added. Since an interoffice call is more expensive than an intraoffice call, the cost of an exchange ccs should increase as the volume of traffic increases.

When only one switch is deployed in a city, it is likely to be located in the center of town near the toll tandem office. When additional switches are deployed, some will be located away from the center of town. Because of the additional transport cost, toll ccs should be an increasing function of usage.⁴

It is less obvious why the second-order term for access lines should be positive. A switch can terminate only a limited number of access lines. When that capacity is exceeded, an additional switch must be added. The deployment of a second switch

of the cost penalty of interoffice trunking, as well as the substantial fixed cost of a switching machine, costs may still be minimized through one supplier, even though that one firm incurs increasing average costs. See, David Gabel, "Deregulation: Should the Local Telephone Market Be Next?" *New England Law Review*, 24 (1989): 39-61; and the discussion *infra* at page 69.

³L. Christensen, D. Cummings, and P. Schoech, "Econometric Estimation of Scale Economies in Telecommunications," Social System Research Institute, Discussion Paper No. 8013, University of Wisconsin.

⁴The cost of toll ccs is also a function of the switch capacity constraint discussed in the prior paragraph.

lowers the length of a loop, and this should lead to a reduction in the marginal cost of a loop. Conceivably, the second-order term for access lines is positive because it is picking up the quasi fixed cost of deploying additional switches.

It is perhaps because of the lumpy nature of interoffice trunks, as well as the outside plant cables used in the local loop, that the second-order terms for local and toll private lines are positive. When the capacity of a cable or an interoffice channel bank is exceeded, additional, quasifixed costs must be incurred. These costs may be the force that is causing the second-order terms to be positive.

The cross-product terms indicate that increased usage of one product has a statistically significant effect on the marginal cost of other services. The cost tools used by the local exchange carriers are not designed to capture these effects and therefore do not capture the total cost impact of increased usage.

Two product interaction terms are of special interest because of the recent debate regarding optimal recovery of access line costs. In the analog model, the interaction term between access lines and toll ccs is not statistically significant. This suggests that the cost of an access line is independent of toll usage. In the digital model when homogeneity is imposed,⁵ the coefficient may be considered statistically significant, depending on the chosen level of significance and the alternative hypothesis. On the other hand, the cross term between access lines and exchange ccs is statistically significant in the analog and digital model. This suggests that exchange usage has a statistically significant affect on the cost of customer access.

Directly Estimating the Incremental Cost of Service

In studying the cost function, we have analyzed the impact of increasing the demand for one service while holding all other variables constant. In doing so, we have constructed what are known as orthogonal data, which allows us to calculate the average incremental cost of a service without doing any regression analysis (the incremental cost

⁵See discussion, page 94.

is divided by the incremental usage of the one service whose demand has not been held constant).

We have used this approach to estimate the marginal cost of private line and switched services, as well as access. The results based on 1990 input prices, from LECOM, are reported on pages 61 through 67. For each cell the datum is the average of eleven estimates of the incremental cost of service. The standard deviation for each estimate is reported in parenthesis.

The data on page 61, Table XI indicates that for a city covering 31.69 square miles, if a telephone company was to serve 70,508 customers with digital technology, the total annual cost would be \$12,426,213. The same city could be served with analog technology for \$11,398,767. Despite the higher total cost, the marginal cost of switched exchange and toll ccs is lower with digital technology. The costs are \$6.72 and \$14.29 respectively per bhccs, versus \$8.29 and \$29.64 with analog technology. The cost of local private line service is also lower, \$135.26 versus \$157.76 on the analog network. On the other hand, the annual marginal cost of private line services and switched access are higher on the digital network. The annual cost of switched access is \$87.81 on the digital network, and \$71.84 with analog technology. While the annual marginal cost of toll private line service would be \$243.92 with analog technology, on a digital network it would be \$340.69.

Marginal Cost of Service
Per Year

Table XI

	(1) DIGITAL	(2) ANALOG	RATIO: Digital/ Analog = (1)/(2)
TOTAL COST	\$12,426,213	\$11,398,767	1.09
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS*	6.72 (2.96)	8.29 (3.67)	0.81
INCREMENTAL COST TOLL BUSY-HOUR CCS	14.29 (4.66)	29.64 (6.35)	0.48
INCREMENTAL COST LOCAL PRIVATE LINE	135.26 (31.97)	157.76 (54.30)	0.86
INCREMENTAL COST TOLL PRIVATE LINE	340.69 (85.87)	243.92 (56.45)	1.40
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	87.81 (8.17)	71.84 (9.97)	1.22
NUMBER OF CUSTOMERS	70,508	70,508	1
LOOP LENGTH (MILES)	1.14	1.51	.75
NUMBER OF SWITCHES	8	4	2
SQUARE MILES	31.69	31.69	1

n=11 for each cell

standard deviation in parenthesis

*Onc ccs = one hundred calling seconds.

Table XII

	DIGITAL	ANALOG	RATIO
TOTAL COST	9,472,592	8,315,164	1.14
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS	\$1.53 (0.69)	3.57 (1.24)	.43
INCREMENTAL COST TOLL BUSY-HOUR CCS	13.28 (0.64)	22.85 (5.75)	.58
INCREMENTAL COST LOCAL PRIVATE LINE	137.22 (28.90)	116.07 (33.21)	1.18
INCREMENTAL COST TOLL PRIVATE LINE	402.60 (145.12)	163.09 (77.29)	2.47
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	136 (1.79)	99.75 (3.12)	1.36
NUMBER OF CUSTOMERS	56,420	56,420	1
LOOP LENGTH (MILES)	1.034	1.74	.59
NUMBER OF SWITCHES	6	1	6
SQUARE MILES	23.08	23.08	1

Table XIII

	DIGITAL	ANALOG	RATIO
TOTAL COST	43,487,947	36,348,995	1.20
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS	8.68 (2.13)	7.28 (3.46)	1.19
INCREMENTAL COST TOLL BUSY-HOUR CCS	17.73 (6.91)	20.05 (6.77)	.88
INCREMENTAL COST LOCAL PRIVATE LINE	220.88 (74.19)	195.76 (52.68)	1.13
INCREMENTAL COST TOLL PRIVATE LINE	291.00 (149.93)	234.92 (61.43)	1.24
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	177.97 (8.28)	107.08 (9.24)	1.66
NUMBER OF CUSTOMERS	212,040	212,040	1
LOOP LENGTH (MILES)	1.56	1.36	1.15
NUMBER OF SWITCHES	15	9	1.67
SQUARE MILES	62.02	62.02	1

Table XIV

	DIGITAL	ANALOG	RATIO
TOTAL COST	25,549,965	20,200,009	1.26
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS	\$3.53 (1.00)	11.25 (2.78)	.31
INCREMENTAL COST TOLL BUSY-HOUR CCS	20.21 (7.74)	28.59 (8.96)	.71
INCREMENTAL COST LOCAL PRIVATE LINE	151.51 (23.63)	129.74 (29.89)	1.17
INCREMENTAL COST TOLL PRIVATE LINE	360.86 (86.04)	193.67 (63.57)	1.86
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	112.69 (2.78)	51.12 (2.18)	2.20
NUMBER OF CUSTOMERS	179,000	179,000	1.0
LOOP LENGTH (MILES)	0.89	0.78	1.14
NUMBER OF SWITCHES	4	4	1.0
SQUARE MILES	8.12	8.12	1.0

Table XV

	DIGITAL	ANALOG	RATIO
TOTAL COST	32,408,560	26,778,053	1.21
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS	\$4.74 (1.11)	9.15 (3.46)	.52
INCREMENTAL COST TOLL BUSY-HOUR CCS	20.77 (3.69)	23.97 (5.13)	.87
INCREMENTAL COST LOCAL PRIVATE LINE	210.89 (12.40)	172.59 (26.50)	1.22
INCREMENTAL COST TOLL PRIVATE LINE	354.47 (32.94)	217.04 (40.90)	1.63
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	83.75 (3.34)	74.12 (10.15)	1.13
NUMBER OF CUSTOMERS	178,032	178,032	1.0
LOOP LENGTH (MILES)	1.48	1.26	1.17
NUMBER OF SWITCHES	5	5	1.00
SQUARE MILES	43.94	43.94	1.0

Table XVI

	DIGITAL	ANALOG	RATIO
TOTAL COST	8,897,422	6,700,767	1.33
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS	\$3.78 (3.28)	2.31 (.01)	1.64
INCREMENTAL COST TOLL BUSY-HOUR CCS	13.75 (4.43)	19.46 (.07)	.71
INCREMENTAL COST LOCAL PRIVATE LINE	67.48 (27.71)	49.17 (6.98)	1.37
INCREMENTAL COST TOLL PRIVATE LINE	328.75 (89.09)	197.61 (28.13)	1.66
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	70.33 (9.71)	42.60 (.19)	1.65
NUMBER OF CUSTOMERS	70,508	70,508	1.0
LOOP LENGTH (MILES)	1.48	1.26	1.17
NUMBER OF SWITCHES	5	5	1
SQUARE MILES	3.59	3.59	1.0

Table XVII

	DIGITAL	ANALOG	RATIO
TOTAL COST	25,758,970	21,801,521	1.18
INCREMENTAL COST EXCHANGE BUSY- HOUR CCS	\$9.22 (4.61)	12.48 (.78)	.74
INCREMENTAL COST TOLL BUSY-HOUR CCS	20.34 (4.32)	25.51 (3.27)	.80
INCREMENTAL COST LOCAL PRIVATE LINE	141.11 (43.60)	159.75 (28.51)	.89
INCREMENTAL COST TOLL PRIVATE LINE	314.11 (85.64)	225.28 (44.71)	1.39
INCREMENTAL COST SWITCH ACCESS LINE (LOOP)	127.44 (13.21)	74.46 (2.26)	1.71
NUMBER OF CUSTOMERS	154,972	154,972	1.0
LOOP LENGTH (MILES)	1.23	1.23	1.0
NUMBER OF SWITCHES	12	5	2.41
SQUARE MILES	31.69	31.69	1.0

The data reported in the tables suggest that the introduction of digital technology raises the cost of access and private line services and lowers the cost of switched usage. Costs are lower on the digital network if the ratio appearing in column four (digital divided by analog cost) is less than one.

The cost of private line services increases because on interoffice routes these services no longer share terminating equipment with switched services. Consequently the

lumpy investments are no longer shared by as many customers. Furthermore, in today's digital environment carriers are only installing digital interoffice trunks, even though analog copper trunks may be the cost-minimizing technology for many private line interoffice trunks.

The cost of terminating an access line increases because the line termination equipment on a digital switching machine handles many functions that were previously the function of interoffice trunking equipment and the central processor unit of the switching machine.⁶ Because the access line termination equipment handles these functions, ccs related costs decline.

Why Might the Loop Length Increase When the Number of Switches Deployed Increases?

The data in table XIII shows that in the digital environment cost is minimized by deploying fifteen switches, six more switches than in the analog environment. Despite the larger number, the loop length is longer (1.56 miles for digital, 1.36 for analog). This anomaly is the result of the unique capacity of the switches. As we reported earlier the analog 2BESS switch has a capacity of 20,000 lines. The DMS10® switch has a capacity of 10,000 lines, and a remote switch attached to a host can terminate 5,720 lines. Of the fifteen switches referenced in table XIII, seven were remotes and seven were DMS10® switches. These fourteen switches have a theoretical capacity of 109,000 lines. Those

⁶A multiproduct firm, such as a telephone company, is often able to provide a number of services at a lower cost than if each product was produced by different companies. A major source of these economies of scope is cost complementarities, that is, "that the marginal cost of producing any one product decreases... with increases in the quantities of other products." Baumol, Panzar, and Willig, *Contestable Markets*, 74-75.

"Access service" does not exhibit this property. The marketing of digital services on the same network used for exchange voice service raises the marginal cost of access. If there were a product such as access service, there would be an economic incentive for access to be provided on a stand-alone basis unless none of the additional cost of access was included in the price of access.

customers not attached to one of these switches are attached to the host switch (a DMS100®).

In the analog environment, eight of the nine switches were 2BESS machines with a combined theoretical capacity of 160,000 lines. Those customers not attached to one of these 2BESS machines must be attached to the 1AESS switch.

Since the eight 2BESS machines have more capacity than the seven remotes and seven DMS100® machines, the loop length is longer in the digital environment. Those customers not attached to a nearby switch will be attached to the large switch (either the DMS100® or 1AESS). To reach the large switch, the average length of connection is longer in the digital environment.

Is the Local Exchange Market a Natural Monopoly?

An industry is considered a natural monopoly if and only if a single firm can produce the desired output at lower cost than any combination of two or more firms. This property, known as subadditivity of the cost function, holds if for any set of goods $N = 1, \dots, n$, and for any m output vectors $Q_1 \dots Q_M$ of the goods in N ⁷:

$$C(Q_1) + C(Q_2) + \dots + C(Q_M) > C(Q_1 + Q_2 + \dots + Q_M).$$

This equation merely states it is cheaper for one firm to produce all output than two or more firms.

This condition has little to do with the popular notion of a natural monopoly, declining average costs. For a multiproduct industry, scale economies are neither necessary nor sufficient for a natural monopoly.⁸

⁷William J. Baumol, "On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry," *American Economic Review* 67 (December 1977): 810.

⁸Ibid., 817. Neither is it necessary for a single product industry. Consider the following cost function.

$$\begin{aligned} \text{if } q \leq 8, c(q) &= 6 + 2q \\ \text{if } q > 8, c(q) &= 10 + 2q \end{aligned}$$

A necessary, but not sufficient condition for a natural monopoly is economies of scope. This property is illustrated by the following equation:

$$C(Q_1, 0) + C(0, Q_2) > C(Q_1, Q_2)$$

where Q_1 = the output of product one

Q_2 = the output of product two.

The equation merely states it is cheaper to have product one and two produced by a single firm [$C(Q_1, Q_2)$], than by having separate firms produce product one and two [$C(Q_1, 0) + C(0, Q_2)$].⁹

In this section of the paper we provide some data regarding the extent to which economies of scope are present in the telecommunications industry. A finding that economies of scope are not present indicates that the industry is not a natural monopoly. If economies of scope are present, the industry may be a natural monopoly.¹⁰

where q = the level of output.

When the level of output exceeds 8, the initial capacity is exhausted, and plant must be expanded. The additional capacity causes the quasi-fixed cost of production to increase by four dollars ($10 - 6$).

When the level of output is eight, the average cost is 2.75 [$c(8)/8 = (6 + 2 \cdot 8)/8 = 2.75$]. If output increases to nine units, the average cost is 3.11 [$c(9)/9 = (10 + 2 \cdot 9)/9 = 3.11$]. Despite this increasing average cost, it is cheaper for one firm to produce 9 units [$c(9) = 28$], then to have two firms produce the same output [$28 < c(1) + c(8) = 8 + 22 = 30$]

⁹Necessary and sufficient conditions for a natural monopoly are economies of scope and declining average incremental costs. David S. Evans and James J. Heckman, "A Test for Subadditivity of the Cost Function with an Application to the Bell System," *American Economic Review* 74 (September 1984): 615-16. The results from the translog equation (page 94) suggest that this condition is not satisfied (due to the increasing marginal costs).

Other sufficient conditions for a natural monopoly are discussed by William Sharkey, *The Theory of Natural Monopoly* (New York: Cambridge University Press, 1982), 67-73.

¹⁰In this paper we do not test to see if the sufficient conditions for natural monopoly are satisfied. As discussed below, the necessary condition is not always satisfied, and therefore we did not test the sufficiency condition.

The results from our optimization model suggest that the *local exchange telecommunications market is not a natural monopoly* under all feasible situations. As illustrated on pages 72 and 74, the cost function does not exhibit economies of scope. Production costs would be minimized if more than one firm produced local exchange services.

We have assumed that the firm produces four outputs:¹¹ switched toll and exchange services, and toll and exchange private line services. Let

X(1) = exchange switched service

X(2) = toll switched service

X(3) = local private line service

X(4) = toll private line service.

We have estimated the cost of producing these services in common (that is, are all four services provided through one network), as well as on a stand-alone basis. For example, we used LECOM to estimate the cost of serving a city with 179,000 customers spread over 8.12 square miles. We report the results in Table XVIII and Table XIX.

¹¹Whenever toll or exchange switched service is provided, the customer is connected to the switch via an access line. While this cost is included in the tables below, we do not list it as a product because we do not believe that access is a service that would be provided on a stand-alone basis.

Diseconomies of Scope: Analog Network
Table XVIII

(a)	Stand- alone network	Common network	d= b/c
c(1) + c(2,3,4)	31359799	20200009	1.552465
c(2)+ c(1,3,4)	31779586	20200009	1.573246
c(3)+ c(1,2,4)	19956785	20200009	.9879592
c(4)+ c(1,2,3)	20631543	20200009	1.021363
c(1) + c(2) + c(3) + c(4)	32054497	20200009	1.586856
c(1,2) + c(3,4)	19957180	20200009	.9879788
c(1,3) + c(2,4)	31242080	20200009	1.546637
c(1,4) + c(2,3)	31216133	20200009	1.545352
c(1,2) + c(3) + c(4)	20473713	20200009	1.013550
c(1,3) + c(2) + c(4)	32086534	20200009	1.588442
c(1,4) + c(2) + C(3)	31350385	20200009	1.551999
C(2,3) + C(1) + C(4)	31920245	20200009	1.580209
C(2,4) + C(1) + C(3)	31210043	20200009	1.545051
C(3,4) + C(1) + C(2)	31305741	20200009	1.549788
VOLUME			
Exchange ccs	402544		
Toll ccs	55934		
Local private lines	17308		
Toll private lines	4684		
Access lines	157007		

The data in Table XVIII was calculated by determining the cost of constructing a network that provides one of the following combination of services:

1,2,3,4
1
2
3
4
1,2
3,4
1,3
1,4
2,3
2,4
1,3,4
1,2,4
1,2,3
2,3,4

The results for each of these combinations appear below:

1,2,3,4	20200009
1	15460054
2	12773019
3	2197461.
4	1623963.
1,2	16921844
3,4	3072668.
1,3	17689553
1,4	16379905
2,3	14836228
2,4	13552528
1,3,4	19006567
1,2,4	17854168
1,2,3	19182291
2,3,4	15899745

In order to determine the extent to which there are economies of scope, we compared the cost of providing all four services on one network (1,2,3, and 4), with the cost of providing the same four services on two or more networks. For example, the first row of Table XVIII shows that the cost of providing exchange service (1) on one network, and switched toll and private line services (2,3,4) on a second network is $31,359,799 = (15,460,054 + 15,899,745)$. The cost of providing the four services on one network was 20,200,009 (1,2,3,4). The ratio appearing in column d is greater than one. This indicates that it is more expensive to construct two networks, then to provide the four services on one network. When this ratio is less than one, diseconomies of scope are present and the industry is not a natural monopoly.

Diseconomies of Scope: Digital Network
Table XIX

(a)	Stand- alone network (b)	Common network (c)	d= b/c
c(1) + c(2,3,4)	42385760	25549965	1.658936
c(2)+ c(1,3,4)	42946616	25549965	1.680887
c(3)+ c(1,2,4)	25342285	25549965	.9918716
c(4)+ c(c1,2,3)	26237616	25549965	1.026914
c(1) + c(2) + c(3) + c(4)	43357093	25549965	1.696953
c(1,2) + c(3,4)	25097995	25549965	.9823103
c(1,3) + c(2,4)	42622810	25549965	1.668214
c(1,4) + c(2,3)	42165522	25549965	1.650316
c(1,2) + c(3) + c(4)	25749839	25549965	1.007823
c(1,3) + c(2) + c(4)	43370601	25549965	1.697482
c(1,4) + c(2) + C(3)	42575029	25549965	1.666344
C(2,3) + C(1) + C(4)	42947586	25549965	1.680925
C(2,4) + C(1) + C(3)	42609303	25549965	1.667685
C(3,4) + C(1) + C(2)	42705249	25549965	1.671441
VOLUME			
Exchange ccs	402544		
Toll ccs	55934		
Local private lines	17308		
Toll private lines	4684		
Access lines	157007		

The absence of economies of scope is tied to the essence of network design--the tradeoff between longer loops and interoffice trunking. When switched exchange or toll service is offered, costs are minimized by the deployment of more than two switches. While this increases the cost of interoffice trunking, it provides significant savings in loop costs (this tradeoff is illustrated in Table II, page 29. While Table II is for a different size city, it does illustrate the tradeoff of shorter loops (eleven 2bess switches) for additional trunking and switching costs).

For Table XVIII and Table XIX, the optimization model determined that if all services were offered on one network (column c), cost would be minimized by providing service through four switches. For a stand-alone private line system, the model determined that cost would be minimized by having all loops terminate at one wire

center.¹² For the stand-alone private line systems the additional trunking costs made it inefficient to establish more than one wire center.

When private line services are offered on a common network with switched services, extra trunking costs are incurred (because of the need to connect local private line customers who are served by more than one central office). This additional cost exceeded the loop savings and is one of the primary sources of diseconomies of scope.

Additional economies from a private line stand-alone system are also achieved because of the assumed number of pairs per customer (see Table I, page 22). In designing a network for multiple services, in many areas of the plant it is cost efficient to apply the same design to all services. When switched services are provided in common with private line customers, and switched usage is greater than one busy-hour ccs, LECOM assumes that the network is designed to provide 1.5 feeder pairs per customer. This value was established by the Bell System to reflect the increased busy-hour usage observed over time.

With a stand-alone private-line system, busy-hour usage is not at issue. Each customer has a dedicated line. LECOM assumes that if a stand-alone private-line system was constructed, there would be fewer pairs per customer in the feeder and distribution plant (again refer to table 1). This leads to a cost saving in the cost of serving private line customers.

A network designed to provide both switched and private line services does not achieve these savings in the loop plant because it would be expensive and cumbersome to design the loop plant on an individual customer basis. Furthermore, given the churn in customer demands, a firm may observe customers switching back and forth from private line and switched services. When a customer changes from private line to

¹²Private-line stand-alone costs are more expensive in the digital environment because of the more expensive main-distribution frame used in the digital environment, and because on interoffice routes, these services no longer share t-carrier terminating equipment with switched services. Consequently the lumpy investments are no longer shared by as many customers. Furthermore, in today's digital environment, carriers are only installing digital interoffice trunks, even though analog, copper trunks may be the cost minimizing technology for many private line interoffice trunks.

switched services, the utility would want to have adequate plant available. Hence it would choose to provide the higher value of feeder and distribution pairs to all customers.

Two obvious interpretations can be made regarding our assumption that a stand-alone private line system would have fewer pairs per customer. First, it could be argued that we are "fixing" the results. This assumption reduces the cost of private line stand-alone systems, and thereby increases the likelihood that we will conclude that the cost function is not subadditive.

Our preferred interpretation is that an entrant will not always adopt the same operating procedures as the incumbent, and LECOM merely reflects this possibility.¹³

These data suggest that to some extent bypass is the result of customers choosing the cost minimizing service, rather than a local exchange carrier being unable to compete due to regulatory barriers. Unless the local exchange carrier prices private line services below its own marginal costs, the incumbent will be unable to price its service at a rate below that of the entrants.

For the data reported on Table XVIII and Table XIX there were 22,044 customers per square mile. As indicated on Table V, page 34, this is in the range of

¹³We have assumed that an entrant's annual carrying charge factors are equal to those of the incumbent. Teleport Communications has suggested that their operating costs for fiber optics are lower than those of the local exchange companies. "Comments of Teleport Communications Group," Federal Communications Commission Common Carrier Docket Number 91-141, August 6, 1991, pp.24-25. If Teleport's and other entrants costs are lower, LECOM's estimates of the cost of an alternative network may be overstated.

Teleport's position is supported by the position of Ameritech. In a study of the economics of bypass, Ameritech suggested that non-local exchange carriers production costs were approximately fifty percent lower than those of the Bell Operating Companies:

For all [bypass] systems, engineering and installation costs are based on...Bell broad gauge costs for underground [cable]...However, these costs were reduced roughly 50% to account for lower competitive labor rates, engineering requirements, and loadings.

Ameritech submission to the Federal Communications Commission, October 2, 1984, "Effects of Access Pricing Policies on Customers of the Ameritech Companies," p.II-2.

customer density found in high density residential neighborhoods, and is considerably lower than the number of customers per square mile found in high density business district.

*For less densely populated markets (customers per square mile), the industry may be a natural monopoly.*¹⁴ In the following tables, the density was only 4,051 per square mile (slightly higher than the high end of the density found in districts dominated by single family homes). With the lower density, economies of scope were present, and therefore, with this scenario, the necessary condition for a natural monopoly is satisfied. This is so because customers are spread over a wider territory, cost savings are achieved by having everyone on one network.

¹⁴The qualifier "may" is used because we have only tested for the necessary condition for a natural monopoly.

Economies of Scope: Analog Network
Table XX

	Stand- alone network	Common network	
(a)	(b)	(c)	(d)
c(1) + c(2,3,4)	40918797	26778053	1.528072
c(2)+ c(1,3,4)	41366189	26778053	1.544780
c(3)+ c(1,2,4)	28721087	26778053	1.072561
c(4)+ c(c1,2,3)	29599307	26778053	1.105357
c(1) + c(2) + c(3) + c(4)	46308878	26778053	1.729359
c(1,2) + c(3,4)	29062391	26778053	1.085306
c(1,3) + c(2,4)	41014819	26778053	1.531658
c(1,4) + c(2,3)	40934163	26778053	1.528646
c(1,2) + c(3) + c(4)	31719585	26778053	1.184537
c(1,3) + c(2) + c(4)	44158386	26778053	1.649051
c(1,4) + c(2) + C(3)	43318232	26778053	1.617677
C(2,3) + C(1) + C(4)	43924809	26778053	1.640329
C(2,4) + C(1) + C(3)	43165311	26778053	1.611966
C(3,4) + C(1) + C(2)	43651684	26778053	1.630129

VOLUME

Exchange ccs	411,722
Toll ccs	68,821
Local private lines	15,395
Toll private lines	8,289
Access lines	154,348

Economies of Scope: Digital Network
Table XXI

	Stand- alone network	Common network	
(a)	(b)	(c)	(d)
c(1) + c(2,3,4)	53702766	32408560	1.657055
c(2)+ c(1,3,4)	53661205	32408560	1.655773
c(3)+ c(1,2,4)	34051102	32408560	1.050682
c(4)+ c(c1,2,3)	34443464	32408560	1.062789
c(1) + c(2) + c(3) + c(4)	58255836	32408560	1.797545
c(1,2) + c(3,4)	34768326	32408560	1.072813
c(1,3) + c(2,4)	53106496	32408560	1.638656
c(1,4) + c(2,3)	53349818	32408560	1.646164
c(1,2) + c(3) + c(4)	37198886	32408560	1.147811
c(1,3) + c(2) + c(4)	55624677	32408560	1.716358
c(1,4) + c(2) + C(3)	55522443	32408560	1.713203
C(2,3) + C(1) + C(4)	56083211	32408560	1.730506
C(2,4) + C(1) + C(3)	55737655	32408560	1.719844
C(3,4) + C(1) + C(2)	55825277	32408560	1.722547
VOLUME			
Exchange ccs	411,722		
Toll ccs	68,821		
Local private lines	15,395		
Toll private lines	8,289		
Access lines	154,348		

The data reported on Table XX and Table XXI show that in a less densely populated market there are economies of scope. For both the digital and analog model we find it is less expensive to construct one network that serves all customers [column (c)], than construct multiple networks [column (b)].

In summary, the data reported in this section suggest that the coalition of telecommunications users will minimize their production costs using only one network when the customer density is low (for representative data on customer density, see page 33). In high customer density areas, the coalition is not stable and there is an economic savings from constructing multiple networks.

If the Industry is Not a Natural Monopoly, What Does This Imply
About the Need to Regulate the Industry?

We have argued in this chapter that in densely populated areas, the cost structure exhibits diseconomies of scope. While this suggests that competition is feasible, these results should not be used to argue that there is no longer a need to regulate the industry. First, there are barriers to entry that limit the opportunity for entry into the industry.¹⁵ Because of these barriers, it may be difficult for new firms to enter the industry and provide service at a lower cost than the incumbent firms. State regulatory commissions can increase the extent to which the local market is contestable by reviewing and modifying the rules that govern the different services.

More importantly, at times when faced with entry, the Bell Operating Companies have adopted rates that were based on the cost structure of their competitors.¹⁶ The private line rates adopted in the 1960s (for example, Telpak) did not reflect the incumbent's cost structure, and therefore may have been below their own cost of service. In the future, the regulatory commissions need to determine the local exchange carriers costs of providing private line services. If the local exchange carriers are allowed to set rates below their marginal cost of service, inefficient production will result and entry will be discouraged.

¹⁵David Gabel, "Deregulation: Should the Local Telephone Market Be Next?," *New England Law Review* 24 (1989): 39-61.

¹⁶Peter Temin, "Cross-Subsidies in the Telephone Network after Divestiture," *Journal of Regulatory Economics* 2 (December 1990): 353.

CHAPTER FIVE

ADDITIONAL ANALYSIS OF THE COST OF SERVICE

The Economics of Fiber Optics

LECOM can also be used to evaluate the economics of fiber optics in the local loop and for interoffice trunking. The mechanics for this type of analysis, as well as our results, are discussed in the following two sections.

Fiber Optics on Interoffice Trunks

In order to explore the extent to which fiber optics is the cost minimizing technology for interoffice transport, we constructed the model to compare the cost of t-carrier on fiber and t-carrier on copper. In general the output from LECOM indicated that t-carrier on copper was less expensive than t-carrier on fiber. This is consistent with the wide-spread belief that the greatest economies from fiber are achieved on long-haul routes (due in part to savings in repeater costs). On short-haul routes, these savings are out-weighed by the additional cost of the multiplexer.

In order to study this issue the user of the model should select level 3 output (see page 123). Data will be written to the file DIGITAL.OUT which shows for each central office the cost of using either t-carrier on copper or t-carrier on fiber. The model calculates both costs and selects the technology that minimizes the annual cost of production.

Fiber Optics in the Local Loop

The model determines which technology--copper, slc-96 on copper, or slc-96 on fiber--is the cheapest for connecting loops between the central office and serving area interface. The calculations are made when the program "dxinit.exe" is executed (see page 125). The program can evaluate the sensitivity of the results by changing the values of the variables that appear in "dvariabl.dat," as well as the number of customers per serving area (the first variable in "populatn.dat").

When LECOM is used to evaluate the economics of fiber optics in the local loop,¹ the program writes the results to two data files. The first file, "DXOVER.DAT" contains just two numbers, for example, 23 100. These numbers indicate that up to twenty-three kilofeet, copper is the cost-minimizing technology for the feeder plant. Between twenty-three and 100 kilofeet, slc-96 on copper is the cost-minimizing technology.

The second file, "CRSSOUT.DAT" provides the cost data, by technology, for lengths ranging from one to 100 kilofeet. The data appears as follows:

(a)	(b)	(c)	(d)	(e)	(f)
1	5418	99859	108073	62467	68270
2	8619	100805	109661	63301	69858
3	11820	101752	111248	64135	71446
.					
.					
.					
100	584622	242206	265257	183893	225455

Where column

- (a) = kilofeet
- (b) = annual cost of copper per serving area
- (c) = annual cost of slc-96 mode 1 on copper per serving area
- (d) = annual cost of slc-96 mode 1 on fiber per serving area
- (e) = annual cost of slc-96 mode 2 on copper per serving area
- (f) = annual cost of slc-96 mode 2 on fiber per serving area.

¹By executing program "dxinit.exe."

The data from "crssout.dat" can be imported to lotus and graphed. The following two figures illustrate the crossover point for different technologies when either mode 1 or mode 2 subscriber line carrier is deployed.

The graph indicates that at approximately thirty-four kilofeet, subscriber-line-carrier on copper is the technology of choice. For shorter length feeder pairs copper wire should be deployed.

Figure 7 shows the economic tradeoff when mode 2 slc-96 is deployed. As with the previous figure, the deployment of slc-96 raises the fixed cost of connecting a serving area to the central office (as shown by the value of the y-intercept). On the other hand, the slope of the curves associated with the slc-96 technology are flatter due to the lower additional cost per kilofeet of cable. The slope for copper increases with distance because for longer hauls more expensive, smaller gauge wire must be deployed (for example, 19-gauge wire--see Table VI, and associated discussion).

The graph indicates that for the first twenty-three kilofeet, copper is the technology of choice in the feeder plant. Beyond that distance, subscriber-line-carrier on copper should be deployed.

Pricing

Effective regulation requires that commissions consider the cost of service when establishing the prices for different services. While the primary purpose of this report was to develop a cost model, some of the pricing implications of our cost study are addressed below.²

Neoclassical economic theory argues that society's welfare will be maximized by pricing products equal to the incremental (marginal) cost of production. The cost data reported in Table XI through Table XVII suggest that the change from an analog to a

²See also David Gabel and Mark Kennet, "Pricing of Telecommunications Services," *Review of Industrial Organization* (forthcoming, 1992).

Figure 6

Local Loop: Copper v. SLC-96 Mode One

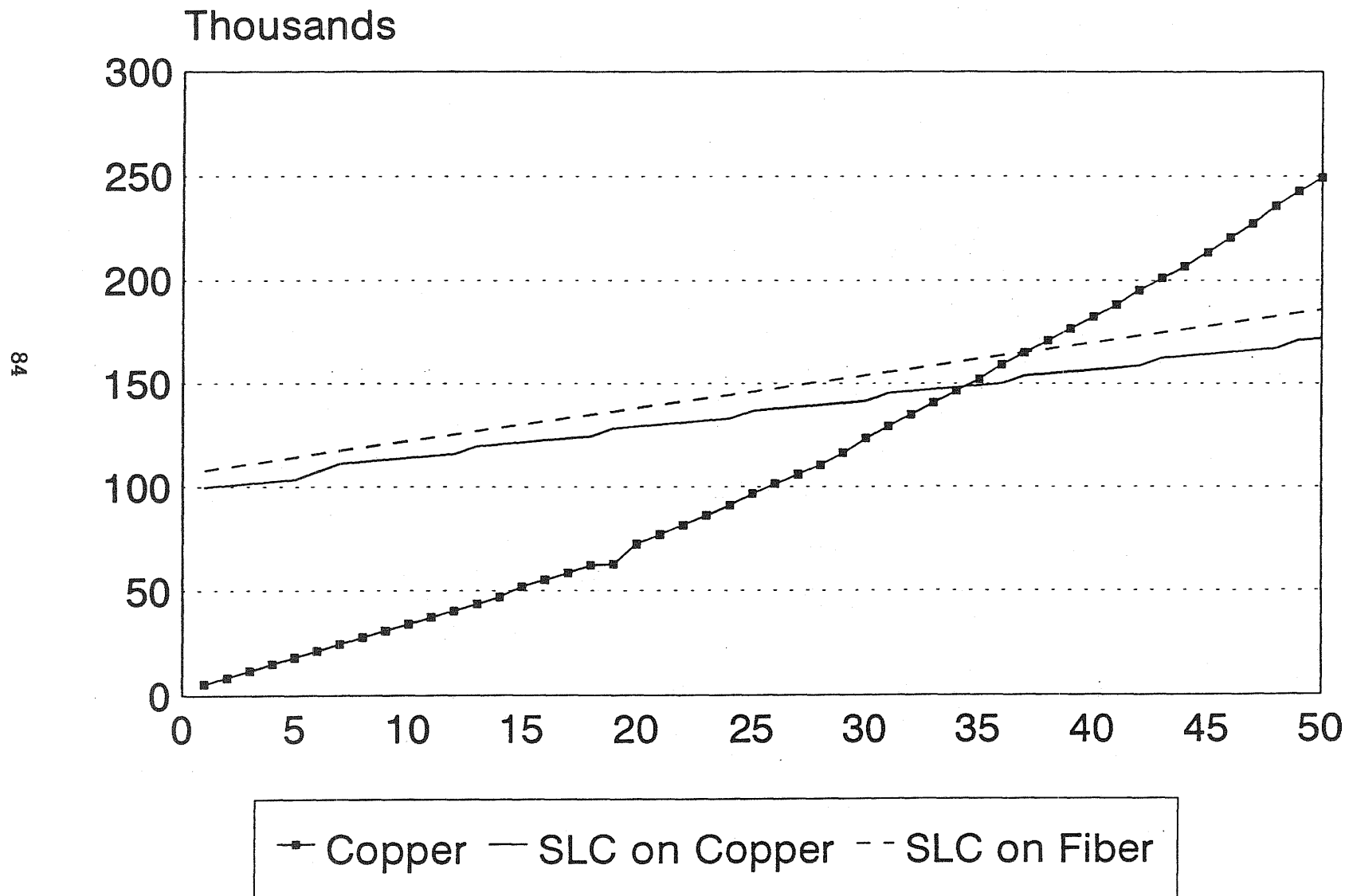
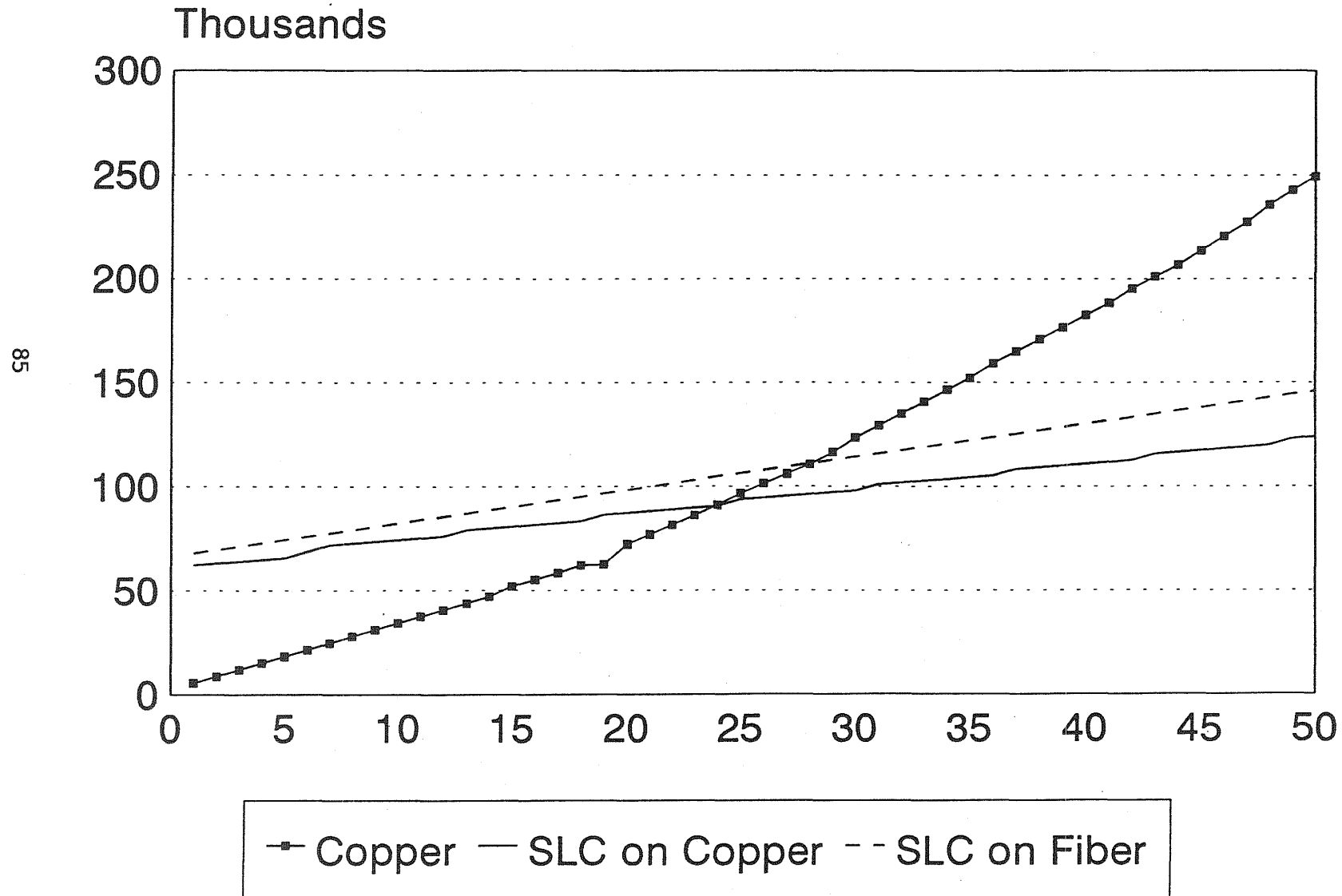


Figure 7

Local Loop: Copper v. SLC-96 Mode Two



digital environment raises the marginal cost of switched access and local and toll private line services. On the other hand, the incremental cost of exchange and toll switched services decline.

If prices during the analog era of telephony had equalled the incremental cost of production, the results from the digital cost model suggest a need to lower the price of switched services and raise the price of private line and switched access services. Before a more definitive statement can be made, a more detailed study of current prices must be undertaken.

Furthermore, while basic microeconomic theory argues that welfare is maximized by setting price equal to the marginal cost of production, theory also argues that this condition holds under restrictive conditions. Because of the externalities associated with telephone service, and because quality as well as quantity affects the cost of service, welfare will not be maximized by setting prices equal to the incremental costs of production.

While the role of externalities is well known, there has been a limited discussion of the role of quality in pricing telecommunication services. Economic theory stresses that to maximize society's welfare, basic telephone service should only bear a portion of the cost of upgrading the network to satisfy the more stringent requirements of nonbasic services. The additional charges to basic services should be based on the value of the improved, plain-old-telephone service.³

The incremental cost data reported in Table XI through Table XVII well illustrate this issue. Replacing analog with digital facilities improves the local exchange companies' ability to offer data and other enhanced services. The operation of the digital network requires that the analog voice signals spoken into the telephone transmitter be converted to digital signals. This analog-digital conversion is not required where analog facilities are used.

³Michael Spence, "Monopoly, Quality and Regulation," *Bell Journal of Economics* 6 (1975): 417-29; and Sickler, J. "A Theory of Telephone Rates," *Journal of Land and Public Utility Economics* 4, 177 (1928).

Since each switched access line must be equipped with an analog/digital converter, the cost of access is increased [see page 61 through 67, row "INCREMENTAL COST SWITCH ACCESS LINE (LOOP)"]. The telephone companies are willing to incur this additional cost because, once it is made, the cost of providing other services is reduced.

Since the divestiture of AT&T, the industry's pricing trend has been to recover the cost of switched access in the price of exchange service.⁴ Using the cost data from Table XIV, page 64, and assuming that the busy-hour usage per customer is 3.5 ccs, the change from the analog to digital environment raises the total cost of access and switched exchange service by \$34.55 (\$125.045 - \$90.495, see Table XXII).

Impact of Digital Technology on the Annual Cost of Providing
Access and Exchange Services
Table XXII

	Access	Usage @3.5 ccs	Total Cost
Analog network	\$51.12	$11.25 \times 3.5 = 39.375$	$51.12 + 39.375 = 90.495$
Digital network	112.69	$3.53 \times 3.5 = 12.355$	$112.69 + 12.355 = 125.045$

If the price of exchange service equals the incremental cost of access and exchange usage, the price of the service would increase over 30 percent. Since digital technology has little or no impact on the quality of exchange voice switched service, the welfare of subscribers to plain-old-telephone service would be reduced. To maximize society's welfare, plain-old telephone service subscribers should not be required to pay for improvements that provide little or no benefit.

⁴Federal Communications Commission, Third Report and Order, CC Docket No. 78-72, Phase I, December 22, 1982.

CHAPTER SIX

CONCLUSION AND SOME FUTURE USES FOR THE MODEL

Identified below are some areas where analysts may find it useful to use our cost model:

1. Calculating the long-run marginal cost of access, private line, exchange, and toll services.
2. Calculating the stand-alone cost of private line, toll, and exchange services.
3. Measuring the degree to which the industry is a natural monopoly.
4. Quantifying the impact of replacing analog with digital technology.
5. Quantifying the affect of different "fill" rates in the local loop.
6. Identifying the conditions were it is economical to deploy fiber optics in the local loop and on interoffice trunks.
7. Forecasting the future topology of the network.

These applications are described more fully below.

Marginal Cost of Service

In appendix one we report our econometric estimates of the cost function. The marginal cost of the different services can be derived by working with the estimated parameters of the cost function.

We have also shown that the marginal cost of different services can be derived directly from LECOM. In Table XI through Table XVII we provided comparative results from the digital and analog model.

In appendix two we have provided work sheets and instructions that will allow the user to estimate the marginal cost of toll and exchange busy-hour ccs, local and toll private-line as well as switched access services.

Calculating the Stand-Alone Cost of Service

The model may be used to calculate the stand-alone cost for private line, toll, and exchange services. The stand-alone cost provides a bench mark of the maximum revenues that can be collected from a service in a contestable market. If the revenues for a service are larger than the stand-alone cost, the users of the service have an

economic incentive to establish a private network. The stand-alone cost of a service is obtained by setting the level of all other services equal to zero.¹

Natural Monopoly

In Table XVIII through Table XXI we have shown how the data from the LECOM can be used to test if the industry is a natural monopoly. We have provided an example where high customer density markets may find it less expensive to have two firms supply service than one. We also have shown that in a less densely populated city the cost of production may be minimized when only one firm supplies local telecommunication services.

Analog v. Digital Technologies

There has been considerable debate in the industry over the economics of replacing analog with digital switching. Since we have developed separate optimization models for the analog and digital environment, a tool is now available to compare the relative advantages of both technologies.

These advantages can be ascertained either by working with the statistical cost function or by running LECOM. The statistical cost function provides a convenient estimate of the difference in the cost of service attributable to a change in technology.

Alternatively, LECOM can provide the data for the comparison. Table XI through Table XVII show the total and marginal cost of service under the assumption of analog and digital technology. In general, replacing analog with digital technology raises the total cost of service, lowers the cost of switched toll and exchange services, and raises the cost of providing private line services and switched access.

¹For example, the stand-alone cost of an exchange network is estimated by setting the percent of toll usage and the percent of private line loops equal to zero (see subdirectory varfiles, file variable.317. This file was generated by the work sheet stadalone.wk1, subdirectory lotus22).

Effect of Fill on the Cost of Service

The model can be used to identify the cost impact of various fill (utilization) levels. For example, the user of the model can vary the fill factor on outside plant in the local loop through variables "LOOPUTIL" (maximum percent cable fill), "FPPERCUST" (feeder pairs per customer), "DPPERCUST" (distribution pairs per customer), and "FPSLCPERCUST" (feeder communication channels per customer served by SLC-96®). In the switch, the effect of different fill factors can be evaluated through variable "SWITCHUTIL." For interoffice facilities, variable "TUTIL" allows the user to study the effect of varying fill factors on t-carrier systems.

Economics of Fiber Optics

As discussed earlier the optimization model can be used to evaluate the cost savings available by using fiber optics for interoffice trunks or the local loop. In our study, in general, t-carrier on copper was less expensive than t-carrier on fiber.

Forecasting the Future Network Topology

The model can be used to evaluate how new technology will effect the network's topology. The results reported in tables XI through XVII suggest that replacing analog with digital switches will lead to an increase in the number of switches, and offers no clear pattern in the length of the local loop.

APPENDIX ONE

ECONOMETRIC RESULTS

Summarizing the results of repeated simulations of our cost model using the traditional translog estimation of Christensen, Jorgenson, and Lau (1973) provides a number of insights into the advantages of the process model approach. The translog cost function is given by

$$\begin{aligned}
 C(w, y) = & \alpha_0 + \sum_{i=1}^P \alpha_i w_i + \sum_{i=1}^Q \beta_i y_i + \sum_{i=1}^P \sum_{j=1}^P \gamma_{ij} w_i w_j + \sum_{i=1}^P \sum_{j=1}^Q \rho_{ij} w_i y_j \\
 & + \sum_{i=1}^Q \sum_{j=1}^Q \delta_{ij} y_i y_j + \sum_{i=1}^R \lambda_i z_i + \epsilon
 \end{aligned}$$

where:

w = P-vector of the natural logarithms of factor prices;

y = Q-vector of the natural logarithms of outputs;

z = R-vector of other cost factors and their interactions;

$$\alpha_0 = \text{constant};$$

$$\alpha, \beta, \gamma, \delta, \rho, \lambda = \text{estimable parameters};$$

and

$$\epsilon = \text{disturbance term.}$$

It is useful here to recall that the translog function can be regarded as a second order Taylor expansion in logs which approximates the true underlying cost function. Thus, the disturbance term is simply an error resulting from the imprecision of the fit of the quadratic approximation, and not a stochastic unobservable as is often assumed.

Among the useful properties of the translog function is the fact that it is in principle possible to test various results from production theory, among which is homogeneity of degree 1 in prices. The homogeneity restrictions and the related symmetry restrictions are

$$\sum_{i=1}^P \alpha_i = 1;$$

$$\sum_{j=1}^P \gamma_{ij} = 0;$$

$$\sum_{i=1}^P \rho_{ij} = 0;$$

and

$$\gamma_{ij} = \gamma_{ji}.$$

Table E-1 gives results for the restricted and unrestricted translog estimation for both analog and digital technology. All price and output variables have the expected sign in both models for both technologies. The mean and standard deviation of the variables are reported in table E-5. Variable mnemonics are as follows.

Variable Mnemonics

Constant:

CONST constant

Price variables--first order terms:

PRICELAB price of labor
PRICECAP price of capital
PRICEMAT price of materials

Price variables--squared values:

PL2 PRICELAB * PRICELAB
PK2 PRICECAP * PRICE CAP
PM2 PRICEMAT * PRICEMAT

Output variables--first order terms:

ACCLINE access lines
EXCCSEC hundreds of exchange busy-hour calling seconds
TLCCSEC hundreds of toll busy-hour calling seconds
LCPLCUST local private lines
TLPLCUST toll private lines

Output variables--squared values

AL2 ACCLINE * ACCLINE (ACCLINE squared)
EXC2 EXCCSEC * EXCCSEC
TLC2 TLCCSEC * TLCCSEC
LPL2 LCPLCUST * LCPLCUST
TPL2 TPLCUST * TPLCUST

Geographical Size of the Market:

AREA area of the city in square kilofeet
AR2 AREA * AREA (AREA squared)

Interaction terms:

ARPK AREA * PRICECAP
ARPL AREA * PRICELAB
ARPM AREA * PRICEMAT
ARAL AREA * ACCLINES
AREXCCS AREA * EXCHCCS
ARTLCCS AREA * TLCCSEC
ARPLP AREA * LCPLCUST
ARTPL AREA * TPLCUST
PKPL PRICECAP * PRICELAB
PKPM PRICECAP * PRICEMAT
PKAL PRICECAP * ACCLINES
PKEXCCS PRICECAP * EXCHCCS
PKTLCCS PRICECAP * TLCCSEC
PKLPL PRICECAP * LCPLCUST
PKTPL PRICECAP * TLPLCUST
PLPM PRICELAB * PRICEMAT
PLAL PRICELAB * ACCLINES
PLEXCCS PRICELAB * EXCHCCS
PLTLCCS PRICELAB * TLCCSEC
PLLPL PRICELAB * LCPLCUST
PLTPL PRICELAB * TLPLCUST
PMAL PRICEMAT * ACCLINES
PMEXCCS PRICEMAT * EXCHCCS
PMTLCCS PRICEMAT * TLCCSEC
PMLPL PRICEMAT * LCPLCUST
PMTPL PRICEMAT * TPLCUST

ALEXCCS	ACCLINES * EXCHCCS
ALTLCSS	ACCLINES * TLCCSEC
ALLPL	ACCLINES * LCPLCUST
ALTPL	ACCLINES * TPLCUST
EXCTLCCS	EXCHCCS * TLCCSEC
EXCLPL	EXCHCCS * LCPLCUST
EXCTPL	EXCHCCS * TPLCUST
TLCLPL	TLCCSEC * LCPLCUST
TLCTPL	TLCCSEC * TPLCUST
LPLTPL	LCPLCUST * TPLCUST

TABLE E-1
Translog Estimation Results
T-Statistics in Parentheses

VARIABLE	Analog Technology		Digital Technology	
	Unrestricted	Restricted	Unrestricted	Restricted
const	-0.1300 (-4.078)	0.01533 (2.250)	-0.1050 (-3.566)	4.938E-05 (0.007901)
area	0.1390 (9.350)	0.2006 (44.24)	0.09648 (7.020)	0.1409 (33.67)
pricecap	15.93 (4.699)	0.2852 (4.470)	11.64 (3.719)	0.2194 (3.742)
pricelab	0.07529 (1.647)	0.08862 (2.476)	0.4192 (9.904)	0.3609 (11.01)
pricemat	0.3695 (2.890)		0.2680 (2.268)	
acclines	0.4502 (31.24)	0.4368 (29.10)	0.5273 (37.68)	0.5214 (36.16)
exchccs	0.1474 (12.69)	0.1548 (12.70)	0.1261 (11.06)	0.1320 (11.15)
tlccsec	0.07536 (10.29)	0.08497 (11.37)	0.07976 (11.70)	0.08290 (12.04)
lcplcust	0.1274 (24.45)	0.1274 (23.48)	0.1372 (28.16)	0.1377 (27.47)
tlplcust	0.07306 (11.40)	0.08008 (11.94)	0.08031 (13.47)	0.08503 (13.79)
ar2	0.04849 (30.32)	0.04781 (28.70)	0.03048 (20.59)	0.02948 (19.34)
arpk	7.706 (4.871)	0.2400 (3.954)	5.638 (3.862)	0.2438 (4.389)
arpl	-0.1004 (-2.200)	0.04006 (1.075)	-0.04601 (-1.094)	0.02778 (0.8161)
arpm	0.02262 (0.3962)	-0.06154 (-2.182)	-0.07161 (-1.359)	-0.09454 (-3.669)
aral	-0.04909 (-5.834)	-0.03481 (-4.078)	-0.01837 (-2.362)	-0.01052 (-1.348)

arexccs	0.01014 (1.760)	0.007430 (1.233)	0.007762 (1.436)	0.007756 (1.388)
artlccs	-0.007463 (-1.809)	-0.01223 (-2.906)	-0.01967 (-5.142)	-0.02089 (-5.417)
ar1pl	-0.02068 (-3.738)	-0.02413 (-4.390)	0.001921 (.3747)	-4.856E-05 (-0.009647)
artpl	-0.01799 (-4.683)	-0.01905 (-5.042)	-0.009905 (-2.782)	-0.01086 (-3.137)
pk2	0.6741 (1.526)	-0.1962 (-1.007)	0.9344 (2.289)	-0.1899 (-1.068)
pkpl	1.247 (1.951)	-0.5959 (-3.048)	0.5057 (0.8587)	-0.3261 (-1.827)
pkpm	3.328 (2.449)	-0.8394 (-5.794)	3.273 (2.606)	-0.7227 (-5.463)
pkal	0.3724 (5.882)	0.1318 (2.548)	0.3222 (5.493)	0.1413 (2.976)
pkexccs	-0.01116 (-0.2668)	-0.06034 (-2.477)	0.03803 (.9833)	-0.07440 (-3.342)
ptlccs	-0.03682 (-0.8555)	-0.08261 (-3.005)	-0.008023 (-0.2017)	-0.07507 (-2.989)
pk1pl	-0.001226 (-0.02702)	-0.04045 (-1.522)	-0.04524 (-1.079)	-0.09002 (-3.709)
pktpl	-0.2216 (-4.759)	-0.2012 (-5.301)	-0.2304 (-5.357)	-0.1915 (-5.526)
pl2	-0.4852 (-2.252)	-0.6561 (-4.054)	-0.2065 (-1.038)	-0.6156 (-4.167)
plpm	1.728 (2.011)	-0.1177 (-1.018)	-0.1994 (-0.2513)	-0.1429 (-1.355)
plal	0.05141 (0.9707)	-0.1036 (-2.039)	-0.008273 (-0.1677)	-0.09945 (-2.122)
plexccs	0.1160 (2.92)	0.01155 (0.3846)	0.1239 (3.370)	0.05417 (1.958)
ptlccs	-0.1817 (-6.375)	-0.1044 (-0.030)	-0.08295 (-3.133)	-0.04473 (-1.878)
pl1pl	-0.02375 (-0.6519)	-0.05869 (-1.812)	-0.02172 (-0.6456)	-0.008901 (-0.3008)
pltpl	0.1060 (2.459)	-0.06982 (-2.569)	0.04190 (1.054)	-0.06684 (-2.694)
pm2	0.8332 (5.087)		0.5526 (3.652)	
pmal	-0.02469 (-0.4044)		-0.03645 (-.6458)	
pmexccs	0.005688 (0.09828)		0.04304 (.8048)	
pmtlccs	0.1371 (2.62)		0.1155 (2.390)	
pmlpl	0.1015 (1.800)		0.07677 (1.474)	

pmtpl	0.04758 (0.8032)		0.06817 (1.246)	
al2	0.1025 (8.209)	0.08036 (6.351)	0.06459 (5.602)	0.05222 (4.521)
alexccs	0.03611 (3.383)	0.04642 (4.189)	0.05268 (5.322)	0.05750 (5.660)
altlccs	-0.006761 (-0.7405)	0.001947 (0.2090)	0.009515 (1.128)	0.01397 (1.643)
allpl	-0.01873 (-2.068)	-0.03221 (-0.670)	-0.04644 (-5.535)	-0.05186 (-6.450)
altpl	-0.1115 (-14.51)	-0.1178 (-14.64)	-0.1331 (-18.72)	-0.1370 (-18.63)
exc2	0.007618 (2.049)	0.006171 (1.574)	0.005702 (1.648)	0.005148 (1.428)
exctlccs	-0.02936 (-4.937)	-0.03587 (-5.782)	-0.01958 (-3.562)	-0.02400 (-4.236)
exclpl	0.01889 (3.678)	0.02630 (5.112)	0.02570 (5.403)	0.02893 (6.143)
exctpl	-0.008962 (-2.012)	-0.007179 (-1.536)	-0.01158 (-2.810)	-0.01080 (-2.526)
tlc2	0.02199 (9.149)	0.02465 (9.917)	0.02377 (10.70)	0.02488 (10.95)
tlclpl	-0.01766 (-5.176)	-0.01333 (-3.949)	-0.004663 (-1.475)	-0.003130 (-1.012)
tlctpl	0.009630 (2.111)	0.01172 (2.439)	0.02421 (5.732)	0.02525 (5.744)
lpl2	0.04205 (11.46)	0.04219 (12.21)	0.03324 (9.802)	0.03329 (10.55)
lpltpl	-0.02178 (-4.286)	-0.01779 (-3.384)	-0.02239 (-4.765)	-0.01877 (-3.908)
tpl2	0.03863 (19.09)	0.03981 (18.72)	0.04646 (24.74)	0.04719 (24.20)
DF:	455	455	455	455
R-squared:	0.9998	0.9998	0.9998	0.9998
R-bar squared:	0.9998	0.9997	0.9998	0.9998
F statistic:	38959.	40765	40522	43478
tail probability:	0.0	0.0	0.0	0.0
F-stat for restrictions:		5.329		4.302

Numerous authors, including Evans and Heckman (1982), have found that their data reject the homogeneity hypothesis but have been unable to determine whether the failure lay in the lack of fit of the translog model or in the absence of cost minimization behavior on the part of the firm(s). Our approach enables an answer to this riddle. Our translog parameter estimates for both analog and digital data sets would reject the

homogeneity and symmetry hypothesis at any reasonable level of significance. However, the raw data suggests that the cost function is homogeneous. Performing the experiment of doubling prices at varying levels of output gives us the result that cost doubles consistently. Table E-2 reports the results of the experiment. Although we would need to perform this experiment more times with scalar multiples other than 2 to draw firm conclusions, the results shown are strongly suggestive: the unrestricted translog cost function seems to be a poor approximation to the true cost function in that it fails to capture the homogeneity property.

TABLE E-2
Homogeneity Experiment Results
ANALOG RUNS

Experiment run number	Cost at 2 x price	Cost at base price	Computed multiple
1	22869521	11389766	2.0079
2	13401533	6700767	2.0000
3	79614019	40031981	1.9887
4	35112968	17269047	2.0332
5	2481061	1240531	1.9999
6	39536617	19930502	1.9837
7	32255607	16102487	2.0031
8	11453032	5727779	1.9995

DIGITAL RUNS

1	25303515	12828382	1.9724
2	17794843	8897422	2.0000
3	89641129	43487947	2.0612
4	40408481	20207034	1.9997
5	3663404	1831702	2.0000
6	44579706	22116003	2.0157
7	42422396	21211198	2.0000
8	15970583	7985291	2.0000

The Evans and Heckman (1982) paper also reports another common problem, one which partly inspired this research. It is difficult to find orthogonal nonexperimental data for the telecommunications industry (or many other industries, for that matter).

Our experimental design alleviates that problem for first order terms in the translog model; however, we have been unable to generate orthogonal data once quadratic terms are incorporated. The effect is that t-statistics reported in table E-1 suffer from the usual problems of multicollinearity. However, several reasons lead us to suggest that any t-statistics reported here should be interpreted with caution. First, the disturbances estimated here are calibration errors and not stochastic, and interpreting calibration errors probabilistically seems problematic. Second, if our conclusion in the previous paragraph that the unrestricted translog approximation may be a poor one is in fact true, then the estimates from the restricted model may be biased to some degree and there seems no a priori reason to expect the bias to be systematic. That is, we cannot say for sure that estimates (or t-statistics) are likely to be either too high or too low.¹ Despite this possible bias, we are encouraged by the fairly stable coefficient estimates.

Many authors attempt to address the multicollinearity problem by removing explanatory variables using one or more of several criteria that have been developed.² These criteria include removing variables where the R-square of a regression of that variable on other explanatory variables is higher than the R-square for the entire regression. A more recent approach is to compute the condition number for the explanatory data matrix, which is defined as the square root of the ratio of the maximum absolute eigenvalue to the minimum absolute eigenvalue, and to remove variables with a large contribution to that condition number. This body of literature suggests that condition numbers greater than about twenty reflect potential problems with multicollinearity. Another approach is more indirect: Remove variables whose coefficients are not statistically significant. While this approach does not address the multicollinearity problem directly, it attacks one of the symptoms: the high standard errors that result from it. Table E-3 shows results employing each of these approaches.

¹This potential bias problem is limited to the translog parameter coefficient estimates.

²William H. Greene, *Econometric Analysis* (New York: Macmillan Publishing Co., 1990), 277-285.

However, for the remainder of this discussion, we will not use these results but rather those in tables E-1 and E-4, where it is possible to impose the homogeneity/symmetry restrictions; it is not possible to impose these restrictions when variables are removed.

TABLE E-3
Analog Translog Estimates With Interaction Terms Removed
According to Various Criteria
T-Ratios in Parentheses

VARIABLE	Significance Criterion	Partial Correlation	Condition Number Criterion
const	-0.1076 (-6.445)	0.02207 (3.797)	0.3084 (27.42)
area	0.1428 (16.95)	0.2047 (50.71)	0.2047 (24.21)
pricecap	13.96 (8.253)	0.07150 (1.108)	-0.7234 (-4.671)
pricelab	0.09133 (2.956)	0.1996 (6.684)	0.2515 (2.267)
pricemat	0.2933 (13.18)	0.3694 (17.08)	-0.07470 (-0.5330)
acclines	0.4395 (35.02)	0.4335 (32.38)	0.5903 (19.54)
exhcacs	0.1513 (16.44)	0.1567 (15.97)	-0.1077 (-6.504)
tlccsec	0.08741 (14.91)	0.09187 (14.73)	-0.007970 (-0.7123)
lcplcust	0.1240 (25.03)	0.1189 (22.64)	0.04860 (4.609)
tlplcust	0.07887 (13.16)	0.08215 (12.85)	0.2492 (25.41)
ar2	0.04903 (34.74)		
arpk	6.799 (8.216)	0.04908 (32.55)	
arpl	-0.1182 (-4.706)	.009519 (0.4516)	0.5974 (11.11)
arpm			0.5237 (6.922)
aral	-0.03260 (-5.476)	-0.03023 (-4.757)	
artlccs	-0.008249 (-2.198)	-0.01144 (-2.868)	
arlpl	-0.02575 (-5.153)	-0.02761 (-5.176)	
artpl	-0.01916 (-5.635)	-0.01688 (-4.662)	
pkpl	1.880	-0.9879	-0.6574

	(4.784)	(-5.123)	(-1.645)
pkpm	2.596	-0.3688	-3.069
	(6.382)	(-1.839)	(-11.39)
pkal	0.1797	0.06121	
	(7.353)	(2.904)	
pktpl	-0.2030	-0.1903	
	(-7.193)	(-6.320)	
pl2	-0.3549	-0.2404	
	(-3.500)	(-2.240)	
plpm	1.744	0.7856	
	(5.157)	(2.317)	
plal			-0.7845
			(-9.103)
plexccs	0.1649	-0.05132	
	(5.162)	(-2.653)	
pltlccs	-0.1806	-0.1152	
	(-9.698)	(-6.405)	
pltpl	0.1358	-0.06950	
	(4.568)	(-4.039)	
pm2	0.8556	0.5549	
	(7.770)	(5.001)	
pmal			-1.579
			(-10.23)
pmtlccs	0.1231	0.1464	
	(4.412)	(4.936)	
pmlpl	0.1327	0.04966	
	(2.891)	(1.038)	
al2	0.08208	0.06573	
	(12.95)	(10.22)	
alexccs	0.04338	0.04856	
	(6.632)	(6.980)	
allpl	-0.02473	-0.02232	
	(-3.472)	(-2.934)	
altpl	-0.1239	-0.1282	
	(-26.61)	(-25.90)	
exc2	0.007835	.009957	
	(2.584)	(3.085)	
exctlccs	-0.03020	-0.03930	
	(-7.473)	(-9.464)	
exclpl	0.02079	0.02399	
	(4.775)	(5.176)	
tlc2	0.02286	0.02586	
	(10.92)	(11.74)	
tlclpl	-0.01313	-0.01253	
	(-5.260)	(-4.697)	
tlctpl	0.01083	0.02373	
	(2.622)	(5.816)	
lp12	0.04326	0.04113	
	(13.41)	(11.97)	
lp1tpl	-0.02161	-0.02539	
	(-4.430)	(-4.893)	

tpl2	0.04026 (22.33)	0.04000 (20.77)	
DF:	468	469	493
R-squared:	0.9998	0.9997	0.9769
R-bar squared:	0.9998	0.9997	0.9762
F statistic:	49954	44843	1304
tail probability:	0.0	0.0	0.0

Table E-4 presents results when access lines are not treated as an output. This exclusion results from a debate between regulators and telephone company economists; the companies maintain that access to the telephone network should be treated as a separate output, while many regulators doubt if customers place any value on a "product" which, by itself, is useless. Again we report unrestricted and restricted estimates, where the restriction refers to homogeneity and symmetry implied by cost minimization.

TABLE E-4
Translog Estimates With Access Lines Not Treated as a Product
T-Statistics in Parentheses

	Analog Technology			Digital Technology		
	Unrestricted (density)	Restricted (density)	Restricted (no ACCLINE)	Unrestricted (density)	Restricted (density)	Restricted (no ACCLINE)
const	-0.01738 (-0.9891)	-0.01741 (-1.004)	0.01513 (2.249)	-0.04330 (-2.336)	-0.04272 (-2.326)	-9.016E-05 (-0.01455)
area			0.2046 (44.44)			0.1438 (33.68)
pricecap	-1.441 (-3.039)	0.1971 (1.218)	0.1428 (1.933)	-1.670 (-3.362)	0.05628 (0.3299)	0.1152 (1.691)
pricelab	-0.05866 (-0.4032)	0.2068 (2.270)	0.08504 (2.407)	0.1475 (0.9618)	0.4083 (4.244)	0.3583 (11.02)
pricemat	0.5904 (1.412)			0.5781 (1.320)		
acclines	-0.1128 (-9.183)	-0.1219 (-10.31)	0.4445 (29.72)	-0.04900 (-3.811)	-0.05888 (-4.742)	0.5272 (36.52)
exchccs	0.6750 (33.10)	0.6766 (33.67)	0.1492 (12.30)	0.6840 (31.68)	0.6880 (32.25)	0.1278 (10.80)
tlccsec	0.1564 (7.222)	0.1356 (6.616)	0.08212 (11.07)	0.1482 (6.478)	0.1215 (5.585)	0.08081 (11.77)
lcplcust	0.08678 (5.133)	0.08824 (5.220)	0.1258 (23.41)	0.1000 (5.595)	0.1029 (5.735)	0.1365 (27.36)
tlplcust	0.1554 (7.972)	0.1532 (7.829)	0.07812 (11.77)	0.1550 (7.526)	0.1522 (7.337)	0.08360 (13.63)

ar2			0.04774			0.02942
			(29.04)			(19.46)
arpk			0.1602			0.1854
			(2.516)			(3.165)
arpl			0.04990			0.03498
			(1.353)			(1.033)
arpm			-0.1337			-0.1473
			(-3.929)			(-4.717)
aral			-0.04248			-0.01613
			(-4.896)			(-2.024)
arexccs			0.008672			0.008650
			(1.456)			(1.558)
artilccs			-0.009668			-0.01901
			(-2.296)			(-4.901)
arlp1			-0.02224			0.001332
			(-4.083)			(0.2656)
artpl			-0.01824			-0.01026
			(-4.885)			(-2.984)
pk2	-2.216	-1.022	0.005240	-2.117	-1.269	-0.04230
	(-2.221)	(-2.056)	(0.02623)	(-2.024)	(-2.426)	(-0.2306)
pkpl	1.587	0.1995	-0.7219	1.918	0.5770	-0.4183
	(1.109)	(0.4515)	(-3.685)	(1.279)	(1.243)	(-2.327)
pkpm	-2.401	-0.09305	-0.6969	-2.007	-0.03360	-0.6183
	(-1.240)	(-0.2348)	(-4.706)	(-0.9899)	(-0.08051)	(-4.549)
pkal	-0.2076	-0.3860	0.2329	-0.2069	-0.4320	0.2154
	(-1.485)	(-3.053)	(4.019)	(-1.412)	(-3.248)	(4.033)
pkexccs	-0.2617	-0.1765	-0.07822	-0.2785	-0.2152	-0.08751
	(-2.415)	(-2.536)	(-3.191)	(-2.453)	(-2.939)	(-3.885)
pktlccs	0.05181	0.1367	-0.1013	0.08064	0.1376	-0.08876
	(0.4376)	(1.822)	(-3.671)	(0.6503)	(1.744)	(-3.503)
pklp1	-0.4325	-0.1936	-0.05185	-0.5099	-0.2538	-0.09836
	(-3.381)	(-2.587)	(-1.964)	(-3.804)	(-3.227)	(-4.058)
pktp1	-0.2505	0.1248	-0.2124	-0.2862	0.1307	-0.1996
	(-1.710)	(1.427)	(-5.652)	(-1.865)	(1.421)	(-5.790)
pl2	-1.262	-0.4378	-0.7125	-1.162	-0.3861	-0.6568
	(-1.923)	(-0.9128)	(-4.442)	(-1.692)	(-0.7662)	(-4.462)
plpm	1.621	-0.5199	-0.2914	0.6582	-0.4854	-0.2702
	(0.6311)	(-1.437)	(-2.361)	(0.2448)	(-1.276)	(-2.386)
plal	0.1047	0.01334	-0.05484	0.1093	0.03564	-0.06391
	(1.014)	(0.1575)	(-1.058)	(1.009)	(0.4002)	(-1.331)
plexccs	0.04669	0.04734	-0.02280	0.04409	0.07555	0.02908
	(0.5921)	(0.9745)	(-0.7344)	(0.5315)	(1.469)	(1.012)
pltlccs	-0.2243	-0.1936	-0.1156	-0.1643	-0.1605	-0.05286
	(-3.032)	(-3.750)	(-4.490)	(-2.117)	(-2.951)	(-2.222)
pllp1	0.01817	-0.05780	-0.06399	0.05966	-0.01038	-0.01279
	(0.1765)	(-0.6768)	(-2.000)	(0.5528)	(-0.1157)	(-0.4356)
pltp1	-0.03365	-0.08741	-0.08635	-0.04417	-0.06661	-0.07894
	(-0.3511)	(-1.268)	(-3.176)	(-0.4393)	(-0.9168)	(-3.164)
pm2	0.8170			0.6962		
	(1.547)			(1.258)		
pmal	0.1661	0.1697	0.1116	0.1796	0.1832	0.06052

	(0.9955)	(1.809)	(2.030)	(1.028)	(1.858)	(1.199)
pmexccs	0.1009			0.1138		
	(0.5852)			(0.6298)		
pmtlccs	0.1806			0.2157		
	(1.052)			(1.199)		
pmlpl	0.1555			0.1457		
	(0.8131)			(0.7270)		
pmtpl	0.05095			0.04191		
	(0.2562)			(0.2012)		
al2	0.05547	0.05492	0.08923	0.03786	0.03698	0.05871
	(11.52)	(11.38)	(7.018)	(7.500)	(7.280)	(5.033)
alexccs	-0.08966	-0.08738	0.04266	-0.09020	-0.08899	0.05476
	(-10.59)	(-10.67)	(3.884)	(-10.11)	(-10.27)	(5.412)
altlccs	0.04595	0.04574	-0.003239	0.06373	0.06323	0.01019
	(4.896)	(4.992)	(-0.3483)	(6.469)	(6.549)	(1.194)
allpl	-0.005365	-0.004878	-0.02182	-0.03314	-0.03186	-0.04424
	(-0.3495)	(-0.3343)	(-2.397)	(-2.057)	(-2.072)	(-5.277)
altpl	0.06756	0.06204	-0.1148	0.06396	0.05736	-0.1348
	(6.255)	(6.033)	(-14.39)	(5.648)	(5.301)	(-18.39)
exc2	0.1045	0.1064	0.007067	0.1102	0.1124	0.005797
	(17.73)	(18.33)	(1.824)	(17.74)	(18.29)	(1.618)
exctlccs	-0.01899	-0.03888	-0.03398	-0.01223	-0.03429	-0.02262
	(-1.582)	(-3.486)	(-5.532)	(-0.9716)	(-2.921)	(-4.011)
exclpl	-0.02324	-0.01693	0.02102	-0.01826	-0.01087	0.02506
	(-2.670)	(-1.957)	(3.985)	(-1.994)	(-1.190)	(5.163)
exctpl	-0.02553	-0.02618	-0.008318	-0.03119	-0.03201	-0.01164
	(-3.064)	(-3.129)	(-1.800)	(-3.561)	(3.625)	(-2.739)
tlc2	0.03213	0.03053	0.02438	0.03006	0.02773	0.02467
	(5.196)	(4.966)	(9.933)	(4.623)	(4.274)	(10.95)
tlclpl	-0.004332	-0.004984	-0.01678	0.009912	0.009070	-0.005656
	(-0.5707)	(-0.6637)	(-4.849)	(1.245)	(1.148)	(-1.775)
tlctpl	-0.05101	-0.03876	0.01222	-0.03997	-0.02700	0.02560
	(-3.807)	(-2.929)	(2.577)	(-2.844)	(-1.937)	(5.870)
lp12	0.03477	0.03150	0.04179	0.02614	0.02316	0.03299
	(2.956)	(2.949)	(12.25)	(2.120)	(2.061)	(10.53)
lp1tpl	-0.07654	-0.07901	-0.01963	-0.08960	-0.09192	-0.02012
	(-4.800)	(-4.972)	(-3.767)	(-5.348)	(-5.483)	(-4.203)
tpl2	0.07940	0.07585	0.03940	0.09056	0.08626	0.04689
	(12.47)	(11.95)	(18.75)	(13.55)	(12.90)	(24.21)
DF:	465	465	455	465	465	455
R-square:	0.9974	0.9973	0.9998	0.9968	0.9967	0.9998
R-bar square:	0.9971	0.9971	0.9997	0.9964	0.9964	0.9998
F-statistic:	4015	4625	41003	3246	3717	43277
tail prob:	0.0	0.0	0.0	0.0	0.0	0.0
F-stat for restrictions:	1.738		4.077*	-	2.072	3.835*

* The unrestricted model that serves as the base case for this F-stat is the same as the corresponding unrestricted model in table E-1.

TABLE E-5
Mean Values and Standard Deviations for Variables Used

VARIABLE	Digital Data		Analog Data	
	MEAN	STANDARD DEV	MEAN	STANDARD DEV
Total cost	1.54555E+07	1.19776E+07	1.24430E+07	9960642
Square kilofeet	438.995	555.109	438.995	555.109
Price of capital	9.91045	2.05647	9.91045	2.05647
Price of labor	10.0217	1.81813	10.0217	1.81813
Price of materials	9.97148	1.84565	9.97148	1.84565
Switched access lines	86877.7	67105.0	86884.4	67109.2
Exchange busy-hour ccs	190410.	172522.	190551.	172637.
Toll busy-hour ccs	45509.4	62877.5	45527.0	62890.5
Local private-line customer	8849.21	12208.7	8841.98	12205.8
Toll private-line customer	5181.36	10649.5	5181.90	10649.8

Using the Model to Calculate the Marginal Cost of Service

One reason to summarize the results of our simulation using the translog functional form is that it is a quicker way to estimate the cost of service than by repeated runs of the optimization model. The R-squared values for the fitted translog are all sufficiently high that the user can use any of them with confidence.

Consider the following example. Our LECOM data base includes the following values:

Results from two runs of the Simulation Model

	Simulation one	Simulation two
Total cost	32408560.	32817908.
Area	1225.0000	1225.0000
Price of capital	10.000000	10.000000
Price of labor	10.000000	10.000000
Price of materials	10.000000	10.000000
Access lines	154348.00	154348.00
Exchange ccs	411772.38	475597.09
Toll ccs	68820.961	68820.961
Local private lines	15395	15395
Toll private lines	8289	8289

The optimization model allows us to calculate the average incremental cost of these two outputs:

average incremental cost of exchange ccs = $(32817909 - 32408560) / 63825 = 6.41$, where 63825 is the additional exchange ccs.

In the absence of the optimization model, we can estimate the total cost for both simulation one and two, and hence the marginal cost by using the translog estimates in the following painstaking fashion. First, divide all the explanatory data by the means found in table E-5. Now take the natural logarithms of the results. Because we are assuming homogeneity and symmetry, a number of corrections must be made (or you can use the restricted beta estimates), the first of which involves the sum of alphas = 1: You must subtract (the natural log of) pricemat from the (natural logs of) total cost, pricecap, and pricelab. Again using the natural logs, compute the interaction terms described earlier in this section (for example, area x area, area x price of capital, and so on). The following adjustments are required to the interaction terms:

Sum of gammas = 0:

Subtract pkpm from pk2 and pkpl; and subtract plpm from plpk and pl2.

Define pmpl = plpm - pm2; and
 pmpk = pkpm - pm2.

Symmetry restrictions:

Add plpk to pkpl; pmpk to pkpm; and pmpl to plpm.

Sum of rhos = 0:

Subtract pmexccs from pkexccs and plexccs; subtract pmtlccs from pctlccs and pltlccs; subtract pmlpl from pkpl and pllpl; and, finally, subtract pmtpl from pktpl and pltpl.

The following is a summary of these computations.

Using the Translog Parameters to Estimate the Cost of Service

	Simulation one	Simulation two
const	1.00000	1.00000
area	1.02621	1.02621
pricecap	0.00613900	0.00613900
pricelab	-0.00501977	-0.00501977
acclines	0.574709	0.574709
exchccs	0.771289	0.915389
tlccsec	0.413589	0.413589
lcplcust	0.553689	0.553689
tlplcust	0.469911	0.469911
ar2	1.05310	1.05310
arpk	0.00923057	0.00923057
arpl	-0.00222065	-0.00222065
arpm	0.00293068	0.00293068
aral	0.589770	0.589770
arexccs	0.791502	0.939379
artlccs	0.424428	0.424428
arlpl	0.568200	0.568200
artpl	0.482226	0.482226
pk2	5.52194E-05	5.52194E-05
pkpl	-5.84364E-05	-5.84364E-05
pkpm	4.32198E-05	4.32198E-05
pkal	0.00352814	0.00352814
pkexccs	0.00473494	0.00561958
pctlccs	0.00253903	0.00253903
pkpl	0.00339910	0.00339910
pktpl	0.00288478	0.00288478
pl2	1.08624E-05	1.08624E-05
plpm	-2.05155E-05	-2.05155E-05
plal	-0.00288490	-0.00288490

plexccs	-0.00387169	-0.00459504
pltlccs	-0.00207612	-0.00207612
pllpl	-0.00277939	-0.00277939
pltpl	-0.00235884	-0.00235884
al2	0.330290	0.330290
alexccs	0.443266	0.526082
altlccs	0.237693	0.237693
allpl	0.318210	0.318210
altpl	0.270062	0.270062
exc2	0.594886	0.837937
exctlccs	0.318997	0.378595
exclpl	0.427054	0.506841
exctpl	0.362437	0.430151
tlc2	0.171056	0.171056
tlclpl	0.229000	0.229000
tlctpl	0.194350	0.194350
lpl2	0.306571	0.306571
lpltpl	0.260184	0.260184
tpl2	0.220816	0.220816

Now, using the coefficients from the homogeneous model in table E-1, multiply the coefficient for each variable times the value in the table above, and sum the result. Take the inverse natural logarithm of the result, and multiply it by the mean value for cost from table E-5. The result for simulation one is 32,228,900 and for simulation two 33,085,000. Now we can compute the marginal cost in the same manner as for when we have the simulation data available to us, except that these estimated costs are not as accurate. Using the parameter estimates from the translog model we find that the incremental cost of a busy-hour ccs is $(33,085,000 - 32,228,900) / 63825 = \$13.41/\text{bhccs}$ per year.

Lumpy Investments and Discontinuities

While it is well known that investments in telephone equipment are inherently lumpy (for example, a switching machine), the cost of adding large, discrete units has rarely

been discussed. This section illustrates the source of the cost lumps and explains how they affect the cost of providing service.

The switching equipment in a central office is placed on frames, which have varying degrees of line and usage capacity. Once a frame is installed, the marginal cost of using the facility is small. But if the capacity of the frame is exhausted, a new, costly frame must be installed.

For example, in a large digital switch (for example, DMS100®), customers lines are terminated on line modules. A line module can terminate approximately 1,200 lines.

The volume of busy-hour traffic per customer determines the number of network frames required for making connections between line modules or connecting customers to interoffice trunks.

If the busy-hour usage per customer is 3.00 ccs, two network frames may be needed to serve five line modules.³ If busy-hour ccs usage increases to 3.10, two network frames still would satisfy customers' peak usage requirements. But if the busy-hour increases beyond a critical point, assumed to be 3.20 bhccs, an additional network frame will be required. The addition of a third network frame leads to a significant increase in the cost of service. The cost impact of this lumpy investment is illustrated in Table XXIII. For a city with approximately 37,000 customers, we estimated the average incremental cost of an increase in 2,100 toll busy-hour ccs. The incremental cost, per busy-hour ccs is reported below.⁴

³The equipment engineering numbers used in this example are hypothetical.

⁴The data include the cost of interoffice transport and toll tandem switching.

Table XXIII Variations in the Incremental Cost of Service	
Yearly Incremental Cost-of-Toll	Service per Busy-Hour ccs
	9.880515
	9.880515
	9.837279
	9.722218
	9.882046
	9.901549
	57.24641
	9.743405
	9.710315
	56.66322
	56.44547
Average	
Standard 19.24675	
Deviation 18.85457	
Source: LECOM output.	

Table XXIII shows that the busy-hour cost per ccs was approximately \$9.90. But in three cases, additional network frames were required to satisfy peak usage. When the additional network frames were required, the incremental cost increased to approximately \$56.78 per busy-hour ccs.

The average value for these eleven scenarios is \$19.25, with a standard deviation of \$18.85. If a t-statistic was calculated (by dividing the mean by the standard deviation) the quotient would be 1.02. This value is not statistically different than zero at any standard level of confidence. The low value is due to the large jump in costs when additional network frames are added.

There are two lessons that can be induced from this example. First, because of the lumpy nature of investments, there is a great deal of variation in the incremental cost of service. There is no unique incremental cost of service. Furthermore, as we discuss in the econometrics results, it is difficult to interpret a t-statistic involving data generated from a nonstochastic process. But if standard statistical criteria were used, an analyst might incorrectly conclude that, due to the low t-statistic, that toll usage has no

statistically significant affect on the cost of service. This would be an incorrect conclusion--the low t-statistic would merely reflect the large variation in the incremental cost of service.⁵

⁵The discontinuity can not be easily taken into account by adding dummy variables--there are too many discontinues in the cable, switching and trunking engineering algorithms.

APPENDIX TWO

LECOM MANUAL

I. INTRODUCTION

This manual describes the structure and operation of LECOM (Local Exchange Cost Optimization Model). This software has been developed by D. Mark Kennet of Tulane University and David J. Gabel of Queens College, partially funded by a contract with The National Regulatory Research Institute. The PC version of the programs were developed and compiled in Turbo Pascal, a product of Borland International, Inc.

A. What do the programs do?

The programs take as input demographic data for a city, price data on the technological options available, and usage data for the three types of consumers to optimally site switching facilities on a stylized map of the city.

B. How do the programs work?

The programs compute the annualized cost of service for a given switch location/technology configuration and adjust the location using a derivative-free algorithm until the cost of service is at its minimum value. An exhaustive search over technological configurations is performed, with the location optimization performed for each one until the cost-minimizing technology and location are identified.

C. What are the programs good for?

The programs have a number of uses. The authors are currently involved in a study which estimates an economic cost function using program output simulated repeatedly; other similar uses can be anticipated. Other uses are long-range planning for utility executives, assessment of long-run marginal costs of service for utility regulators, and information for rate-case intervenors.

D. What do I need to run the programs?

An MS-DOS based PC with 8086, 80286, or 80386 processor,

640 K of RAM,

Math coprocessor (optional but very helpful),

Hard disk (also optional),

Accurate data,

Time and patience (especially if you have a machine running at a relatively low clock speed).

E. What are the limitations of the programs?

The programs can locate up to thirty central offices with the PC

version, serving up to 300 serving areas. This is equivalent to a city size of approximately 180,000 customers (assuming 600 customers per serving area).

Contact the authors of this report regarding use of the program for larger cities.

F. Where can I go for help if I need it?

Support for the programs is provided by the authors.

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New Orleans, LA 70017

504-865-5321

David Gabel

Queens College

Department of Economics

Flushing, NY 11367

718-997-5452

We recommend that frequent users of the program mail David Gabel their name and address. We will send them a notice regarding any subsequent changes to the program.

II. GETTING STARTED

A. Hard disk systems

1. Create a subdirectory for the software; for example, TELEPHON. Do this by first making sure that you are in the root directory of your hard disk (that is, observe that the DOS prompt is 'C:\'. If the prompt is 'C>', you need to type the command

```
prompt $p$g <Enter>
```

to have DOS tell you which subdirectory you are in). To get to the root directory, type the command

```
cd \ <Enter>
```

which takes you to the root. Now create the subdirectory TELEPHON by entering

```
md telephon <Enter>.
```

2. Create two subdirectories within TELEPHON: DIGITAL and ANALOG. You can do this by typing

```
cd \telephon <Enter>
```

and then

```
md digital <Enter>
```

```
md analog <Enter>.
```

3. Copy the analog programs:

```
copy a:\analog\*. * c:\telephon\analog\*. * <Enter>
```

4. Copy the digital programs:

```
copy a:\digital\*. * c:\telephon\digital\*. * <Enter>
```

You are now ready to use the programs.

B. Floppy-disk only systems

The programs are ready to run if your system is a floppy-disk only machine. However, you may wish to make a backup of the diskette containing the software before you use it. Simply make a backup copy of your software on another formatted empty disk. To learn how to format a disk, see your DOS manual. To accomplish the copying, put the original diskette in Drive A, and the new formatted diskette in Drive B, if you have a Drive B.

Now if your computer has two floppy drives, type

```
xcopy a: b: /s <Enter>
```

or, if your machine has one floppy drive, type

```
xcopy a: a: /s <Enter>
```

and follow any directions your computer gives you (this last statement is relevant to owners of one-floppy systems). After you complete these tasks, put the original diskette in a safe place and put the new copy in floppy Drive A.

III. EDITING DATA FILES

There are three data files required by each of the digital and analog programs. Two of these files can be the same for both analog and digital computations; however, the third is specific to the technology being examined. For the analog programs, the files required are POPULATN.DAT, RECTANGL.DAT, GAUGEDST.DAT, and VARIABLE.DAT. POPULATN.DAT is a file containing map information for the city of interest, projected number of customers in each serving area, and the number of customers in each classification: business, medium density, and residential. RECTANGL.DAT is a file that can either be created by the user or automatically using the program CITYINIT.EXE. RECTANGL.DAT contains the number of serving areas in the city, and data arranged serving area by serving area on the number of customers, the type of customer, and coordinates of the northeast and southwest corners of the serving area (setting the origin equal to the southwest corner of the city). It is recommended that new users NOT attempt to change RECTANGL.DAT but instead allow the CITYINIT.EXE program to make any changes.

GAUGEDST.DAT contains data on the recommended mix of gauges for various lengths of cables; it can be modified by using any text editor, but it is also recommended that new users not alter this file. Finally, VARIABLE.DAT contains the price, usage, and capacity data as well as data required by the program for technical reasons. The first four digital data files are identical to the analog files. The corresponding file to VARIABLE.DAT is called DVARIABLE.DAT. The digital program requires one other file, DXOVER.DAT. This file is created by the program DXINIT.DAT; once again, the user is free to modify this text file containing two numbers, but we strongly recommend against doing so.

To edit any of the files, simply use your favorite text editor.

The files come complete with "comments" embedded within so that you can see what each variable is and what its definition is. The program's input is format-free, so that you don't have to worry about lining up any numbers; however, there must always be a space or a carriage return between any two numbers in the data file. The data files **MUST BE SAVED AS ASCII TEXT FILES.**

A sample DVARIABLE.DAT file follows (a VARIABLE.DAT file is similar but has somewhat different entries and somewhat fewer of them):

```

0.313000000000 * ac211 = carrying charge for land
0.326900000000 * ac212 = carrying charge for buildings
0.301400000000 * ac22157 = carrying charge for circuit
0.375300000000 * access = carrying charge for analog switches
0.280800000000 * ac244 = carrying charge for conduit
0.281200000000 * ac2422 = carrying charge for underground cable
0.316600000000 * ac2423 = carrying charge for buried cable
0.316600000000 * ac815 = carrying charge for underground fiber
0.343100000000 * ac845 = carrying charge for buried fiber
3.400000000000 * ccs_per_res_line = ccs per residential customer
3.400000000000 * ccs_per_med_line = ccs per medium density customer
3.400000000000 * ccs_per_bus_line = ccs per business customer
0.900000000000 * perund_bus = fraction cable underground, business
0.500000000000 * perund_med = fraction cable underground, mixed
0.350000000000 * perund_res = fraction cable underground, residential
0.050000000000 * perpl[1] = fraction private lines for residential customers
0.050000000000 * perpl[2] = fraction private lines for mixed customers
0.050000000000 * perpl[3] = fraction private lines for business
                    customers
0.450000000000 * plcost = cost markup fraction for private lines
0.000000000000 * tollper = fraction toll traffic
0.200000000000 * pltollper = private line toll fraction
1.682445000000 * f1526 = fixed investment per foot of underground 26
                    gauge copper cable
1.919396000000 * f1524 = fixed investment per foot of underground 24
                    gauge copper cable
1.742692000000 * f1522 = fixed investment per foot of underground 22
                    gauge copper cable
2.575937000000 * f1519 = fixed investment per foot of underground 19
                    gauge copper cable
2.172250000000 * f4526 = fixed investment per foot of buried 26
                    gauge copper cable
2.411098000000 * f4524 = fixed investment per foot of buried 24
                    gauge copper cable
2.233562000000 * f4522 = fixed investment per foot of buried 22
                    gauge copper cable

```

3.06785100000	* f4519 = fixed investment per foot of buried 19 gauge copper cable
0.00752700000	* m1526 = marginal investment per pair foot of underground 26 gauge copper
0.00966400000	* m1524 = marginal investment per pair foot of underground 24 gauge copper
0.01343800000	* m1522 = marginal investment per pair foot of underground 22 gauge copper
0.01305500000	* m1519 = marginal investment per pair foot of underground 19 gauge copper
0.00990300000	* m4526 = marginal investment per pair foot of buried 26 gauge copper
0.01204000000	* m4524 = marginal investment per pair foot of buried 24 gauge copper
0.01581200000	* m4522 = marginal investment per pair foot of buried 22 gauge copper
0.01543500000	* m4519 = marginal investment per pair foot of buried 19 gauge copper
1.00000000000	* misc15 = miscellaneous investment related to underground copper
1.00000000000	* misc45 = miscellaneous investment related to buried copper
300000.000000	* dms100cap = calling capacity of a DMS100 digital switch
38000.000000	* dms10cap = calling capacity of a DMS10 digital switch
0.90000000000	* switchutil = utilization of switch capacity
1.00000000000	* looputil = utilization of loop line capacity
0.60000000000	* blockwidth = width of city block, in kilofeet
0.07000000000	* build22157 = investment loading for building, applied to circuit
0.07000000000	* build22177 = investment loading for building, applied to switch
0.00500000000	* land22157 = investment loading for land, applied to circuit
0.00500000000	* land22177 = investment loading for land, applied to switch
53.0000000000	* mdfcost = main distribution frame cost per customer
1.60000000000	* intraht = holding time for intraoffice call
1.60000000000	* interexcht = holding time for interoffice call
1.80000000000	* tollht = holding time for toll call
0.00001000000	* ftol = function tolerance for downhill simplex routine
1	* itmax = maximum number of AMOEBA iterations

0	* number_of_restarts for AMOEBA when minimum is found
1.03592000000	* droptpi = drop wire tpi 1985 to 1990
1.04484300000	* tpiund80 = tpi underground cable 1990/1985
1.03592000000	* tpibur80 = tpi buried cable 1990/1985
1.11913400000	* tpicond80 = tpi conduit 1990/1985
0.00572000000	* condpf = 1985 conduit cost per pair foot of copper cable
0.70645160000	* dig100tp = tpi analog ess 1990/1985
0.57783640000	* dig10tp = tpi analog ess 1990/1984
21.37000000000	* tandem = 1990 tandem inv per ccs. 1985 30.25*tpi
1.07960700000	* tpiosp80 = tpi outside plant 1990/1982
1.18198000000	* tpi5780 = tpi circuit plant 1990/1982
4.60000000000	* loadc = 1990 load coil investment
1.50000000000	* fppercust = feeder pairs per customer
1.05000000000	* fpslcpercust = feeder pairs per slc customer
2.00000000000	* dppercust = distribution pairs per customer
1.57546000000	* ufibfix = fixed cost of underground fiber
0.18781060000	* ufibmc = per foot cost of underground fiber
2.77804500000	* bfibfix = fixed cost of buried fiber
0.19762650000	* bfibmc = per foot cost of buried fiber
30.00000000000	* fcond = cost per foot of conduit (total investment)
5	* max_remotes = max number of remotes attachable to DMS100
14260.0000000	* remotecap = ccs capacity of remote switches
1.00000000000	* remotetpi = 1990/1990 price index for remote switches
1.00000000000	* TPIOSP90 = price index 1990/1990 outside plant
2	* slc_mode = SLC-96 mode, 1=unconcentrated; 2=concentrated
1.00000000000	* tpi5790 = price index circuit 1990/1990
1.00000000000	* pricelab = price of labor
1.00000000000	* pricecap = price of capital
1.00000000000	* pricecomat = price of central office material
1.00000000000	* priceosmat = price of outside plant material
1.00000000000	* tpiundf90 = 1990/1990 tpi for underground fiber cable
1.00000000000	* tpiburf90 = 1990/1990 tpi for buried fiber cable
1.00000000000	* tpicond90 = 1990/1990 tpi for conduit
0.79166666667	* tutil = t-carrier utilization factor
1.10000000000	* cbd_factor = multiplier for land in CBD
1.00000000000	* meddens_factor = multiplier for land in MDD
0.90000000000	* lowdens_factor = multiplier for land in LDD
0	* min_extra dms10
2	* max_extra dms10

See the data requirements appendix (page 145) for the precise definitions of these variables.

Among the variables over which the user has control in this file are three which pertain to the nonlinear optimization routine used to optimize the locations of the switches. These are `ftol`, `itmax`, and `number_of_restarts`. The first, `ftol`, is simply the convergence value for the routine: when the optimization routine finds what it "thinks" is the cost minimizing location, it will check to make sure that it cannot improve the solution by more than this amount. You should not make this number smaller than $1e-6$ or so; few computers can improve on this level of precision. The variable `itmax` is the maximum number of iterations the optimization routine will try before concluding that it cannot locate the cost minimizing location. Five hundred is a reasonable number to use; however, some users may find, particularly with larger cities, that a larger number is desirable, while others may find that reducing this number is a way of speeding up the program when an exact solution is not important.

The user-defined `number_of_restarts` is the number of times the program will attempt to reoptimize once a solution is found. Reoptimizing is necessary because of the nonconcave nature of the objective function being minimized: It is theoretically possible that any given location solution is only a local, rather than a global, minimizer. We recommend a value of 1 to 4 for this number, although any nonnegative integer will work.

IV. OPERATING THE PROGRAMS

Once you have edited the data files and you feel sure that you have set up the data in the way you would like, you are ready to run the modules. In the case of the analog programs, there are two programs you must run in sequence; in the case of digital programs, three.

A. Analog program operation

If you are running the modules for the first time or if you have changed any of the data in POPULATN.DAT, you must run the program CITYINIT.EXE (unless you wish to create and edit the file RECTANGL.DAT manually; see the data requirements appendix for instructions on how to do this. After the file RECTANGL.DAT has been created either by CITYINIT.EXE or by hand, you can run ANALOG.EXE. Step by step instructions follow.

1. This step is necessary the first time you run the program and EVERY TIME YOU CHANGE THE FILE POPULATN.DAT. If this does not apply to you, go to step

2. Type the command

```
cd\telephon\analog <Enter>
```

and make sure that the files POPULATN.DAT, VARIABLE.DAT, and GAUGEDST.DAT are in the directory by typing

```
dir *.dat <Enter>
```

which will result in your screen presenting the names of these files if they are present. If the files are there, type

```
cityinit <Enter>
```

and continue to step 2.

2. Type the command

analog <Enter>

and you will receive a reminder about running CITYINIT.EXE. Press the <Enter> key to remove this message, and you will receive a query regarding where you want output to go. You may choose screen, printer, or file. Choosing the screen is generally not recommended unless you are sure that the output from the model run will not be needed in the future.

You will now receive a query regarding the level of output you would like to have. Level 1 is the simplest output; it will present the minimum cost for each switch configuration the program tries and report more detailed information for the best configuration it finds.¹ Level 2 reports the same level of information for all configurations tried. Level 3 is the same as level 2 except that when the global minimum cost is found, much more specific, highly detailed information is reported. Level 4 reports this level of information for every cost computation and is not recommended. Finally, level 5 reports the data in a file suitable for data analysis; for example, statistical estimation. The variables reported in level 5 are as follows: total cost, number of offices, number of dms100 offices (number of 1AESS in analog case), number of remotes (digital only), distribution cost, feeder cost, switching cost, interoffice cost, MDF cost, number of serving areas, target customers per serving area, actual customers per serving area, number of business customers, number of mixed customers, number of residential

¹The cost of connecting a remote to a host switch is included in the digital switching costs. Therefore when remotes are deployed, the user should not consider the reported switching costs as exclusively related to the cost of the switch, for they also include the cost of the interoffice trunks. For the same reason, when remotes are deployed, the reported interoffice trunk costs do not include all of the interoffice trunk costs. The cost of the host-remote connection is excluded.

The print-out reports, as a separate item, the cost of the host-remote connection. This transport costs can be subtracted from the switching cost in order to derive the cost of the switching machines and supporting structures.

customers, number of private line customers, private line cost markup, private line toll percentage, business private line percentage, mixed private line percentage, residential private line percentage, intraoffice message volume, exchange interoffice message volume, toll message volume, intraoffice ccs, exchange interoffice ccs, toll ccs, toll percentage, business ccs per line, mixed ccs per line, residential ccs per line, loop length², length of slc-96 (digital only); price of labor (index), price of capital (index), price of central office materials (index), price of outside plant materials (index), central business district coordinates (upper right, lower left), medium density district coordinates (upper right, lower left), city upper right coordinates, locations of switches.

Note that the program may run for quite some time--sometimes as long as several days.

B. Digital program operation

If you are running the modules for the first time or if you have changed any of the data in POPULATN.DAT, you must run the program CITYINIT.EXE (unless you wish to create and edit the file RECTANGL.DAT manually; see the data requirements appendix for instructions on how to do this. After the file RECTANGL.DAT has been created either by CITYINIT.EXE or by hand, you can run DIGITALEXE. Step by step instructions follow.

1. This step is necessary the first time you run the program and EVERY TIME YOU CHANGE THE FILE POPULATN.DAT. If this does not apply to you, go to step

²In order to determine the loop length per customer, divide the loop length by the number of serving areas. The quotient is the kilofoot loop length per customer. The same procedure should be used for the slc-96 length (the next variable in the digital model). For both items in the file, they are calculated by summing the average loop length of reaching one customer in each serving area.

2. Type the command

```
cd\telephon\digital <Enter>
```

and make sure that the files POPULATN.DAT, DVARIABLE.DAT, and GAUGEDST.DAT are in the directory by typing

```
dir *.dat <Enter>
```

which will result in your screen presenting the names of these files if they are present. If the files are there, type

```
cityinit <Enter>
```

and continue to step 2.

2. Type the commands

```
dxinit <Enter>
```

```
digital <Enter>
```

and you will receive a reminder about running CITYINIT.EXE. Press the <Enter> key to remove this message, and you will receive a query regarding where you want output to go. You may choose screen, printer, or file. Choosing the screen is generally not recommended unless you are sure that the output from the model run will not be needed in the future.

You will now receive a query regarding the level of output you would like to have. Level 1 is the simplest output; it will present the minimum cost for each switch configuration the program tries and report more detailed information for the best configuration it finds. Level 2 reports the same level of information for all

configurations tried. Level 3 is the same as level 2 except that when the global minimum cost is found, much more specific, highly detailed information is reported. Level 4 reports this level of information for every cost computation and is not recommended. Finally, level 5 reports the data in a file suitable for data analysis; for example, statistical estimation.

Note that, as in the analog case, the program may run for quite some time--sometimes as long as several days.

V. Spreadsheets for Generating Data Files and Analyzing Results

Creating Files for the Model

In our computer study of the cost function we analyzed the effect of increasing the demand of one service while holding all other variables constant. By holding all but one variable constant, we constructed what are known as orthogonal data. There are a few advantages to constructing orthogonal data. First, the average incremental cost of a service can be determined without doing any regression analysis (the incremental cost is divided by the incremental usage of the one service whose demand has not been held constant).

Second, when undertaking regression analysis, the construction of an orthogonal data set reduces the collinearity in the data. This makes it easier to invert the matrix of independent variables, and reduces the standard deviation of the estimated coefficients.

Finally, because of the orthogonal nature of the data, it is a straightforward project to test the reasonableness of the results. We use the following procedure to test the reasonableness of the results.

We assume there are five services.

X(1) = exchange ccs

X(2) = toll ccs

X(3) = local private line

X(4) = toll private line

$X(5)$ = switched access lines³

On the enclosed computer disk you will find Lotus spreadsheets that can be used to create the files. Subdirectory LOTUS22 contains file "nrriexam.wk1."⁴ In order to create files, the user should make entries in the cells identified in the following chart.

³We use the term "service" loosely. More precisely, we study the impact on cost of four services, and the joint input switched access.

⁴This worksheet is for illustrative purposes only. For actual study work, the user should use the other spreadsheets in the subdirectory. NRRIEXAM.WK1 has been modified so that the model provides cost estimates without conducting an exhaustive location search. This was done by setting the number of iterations to one and the number of restarts to zero.

Creating Files

CELL	DEFINITION
C10	CUSTOMERS IN BUSINESS DISTRICT (BOTH PRIVATE LINE AND SWITCHED)
C11	CUSTOMERS IN MIXED BUSINESS/ RESIDENTIAL DISTRICT
C12	CUSTOMERS IN RESIDENTIAL DISTRICT
D10	PERCENT OF CUSTOMERS IN BUSINESS DISTRICT WHOM ARE PRIVATE LINE CUSTOMERS
D11	PERCENT OF CUSTOMERS IN MIXED DISTRICT WHOM ARE PRIVATE LINE CUSTOMERS
D12	PERCENT OF CUSTOMERS IN RESIDENTIAL DISTRICT WHOM ARE PRIVATE LINE CUSTOMERS
E10 - E11 - E12	PERCENT OF PRIVATE LINES WHICH ARE TOLL PRIVATE LINE (USE SAME VALUE FOR ALL THREE CELLS)
J10	CCS BUSY-HOUR USAGE PER SWITCHED BUSINESS SUBSCRIBER
J11	CCS BUSY-HOUR USAGE PER SWITCHED MIXED SUBSCRIBER
J12	CCS BUSY-HOUR USAGE PER SWITCHED RESIDENTIAL SUBSCRIBER
F14	STIMULATION FACTOR (DETERMINES THE AMOUNT BY WHICH USAGE WILL BE INCREASED. A VALUE OF 1.05 HERE WOULD INCREASE USAGE BY FIVE PERCENT)

Working with file NRRIEXAM.WK1, we can see how to estimate the marginal cost of different services.

The worksheet has been used to export file numbers variable.452 through variable.468, as well as populatn.166 through populatn.172 (these files appear, respectively, in subdirectories VARFILES and POPULATN).

The steps for exporting files are identified below.

1. The variable files were exported by first going to cell C157. In cell C157 an arbitrary number was placed for identifying the different variable files that were created. In cell C1484 a number was placed to initiate the number of the population files.

Movement is expedited by using the F5 function key.

2. Push F9 (the calculate button for LOTUS).

3. move to cell a157. You will see the following:

	A	B	C	D	E
157	variable		452	233	
158	0.3130000000		* ac211		
159	0.3268000000		* ac212		
160	0.2986000000		* ac22157		
161	0.2868000000		* access		
162	0.2808000000		* ac244		
163	0.2812000000		* ac2422		
164	0.3166000000		* ac2423		

4. Use the cursor key to move down to cell A158.

5. Note the entry in cell D157. This tells us the end of the range that we want to export for our first variable file. In this example, the number is 233.

6. Execute the following LOTUS commands:

a. /P F (PRINT A FILE)

b. variable.452 (this is the name of the file. We always use the prefix variable, and the identifying number for our first file appears in cell C157.

c. /O (SELECT OPTIONS)

d. M (MARGINS OPTION)

E. R (MODIFY RIGHT HAND MARGIN)

F. 100 (SET RIGHT-HAND MARGIN EQUAL TO 100)

G. M (MODIFY TOP MARGIN)

H. T (T FOR TOP)

I. 0 (0 TOP MARGIN)

J. M (B MODIFY TOP MARGIN)

- K. 0 (0 TOP MARGIN)
- L. Q (QUIT OPTION MENU)
- M. R (SET RANGE FOR VARIABLE.452)
- N. A158.H233 (SET RANGE OF FILE FOR A158.H233)
- O. G (GO)
- P. Q (quit the print menu)

Bingo! The first file has been created.

Now use the F5 key to go to the next variable file.

7. F5 a234

8. note in cell C235 you see the number of the next variable file (variable.453).

In cell E235 you see the last row that is to be included in variable.453 (311)

	A	B	C	D	E	F
227	1.000000000000		* priceosmat = outside plant material			
228	1.050000000000		* coleceng			
229	1.100000000000		* cbd_factor			
230	1.000000000000		* meddens_factor			
231	0.900000000000		* lowdens_factor			
232	0		* min_2bess			
233	0		* max_2bess			
<hr/>						
235	variable		453		311	
236	0.313000000000		* ac211			
237	0.326800000000		* ac212			
238	0.298600000000		* ac22157			
239	0.286800000000		* acess			
240	0.280800000000		* ac244			
241	0.281200000000		* ac2422			
242	0.316600000000		* ac2423			

9. Export file variable.453 by taking the following steps:

- a. /p f (print file)
- b. variable.453 (variable name, variable.453)
- c. /r (define the range)
- d. a236.h311 (range cell a236 through h311)
- e. g (go)
- f. q (quit the print menu)

10. Note that after the options were set in step six, they did not need to be redefined.

11. Use the F5 function key to move to cell 312.

12. Follow step 9 in order to export variable.454 (making the appropriate adjustment for the range).

The same procedures need to be followed for creating the population files. The last variable file, variable.468 ends at line 1481.

	A	B	C	D	E	F	G	H
1478	1.000000000000		* meddens_factor					
1479	0.900000000000		* lowdens_factor					
1480	0		* min_2bess					
1481	0		* max_2bess					
1482	-----							
1483	populatn files							
1484	populatn		166					
1485	600							
1486	7.5		7.5					
1487	3		3	4.5	4.5			
1488	1.5		1.5	6	6		SW and NE MDD	
1489	2600		2700	2800			BUS,MIXED,RES POP	
1490								
1491								
1492							distances	
1493	-----							
1494	populatn		167					
1495	600						SA CUSTOMERS	
1496	7.5		7.5				NE corner	
1497	3		3	4.5	4.5		SW and NE CBD	
1498	1.5		1.5	6	6		SW and NE MDD	

The first population file to be exported is populatn.166. The following steps must be taken.

1. /P F (PRINT FILE)
2. POPULATION.166 (FILE NAME POPULATION.166)
3. /R (RANGE)
4. A1485.H1489 (RANGE DEFINED AS A1485.H1489)
5. G (GO)
6. Q (QUIT)
7. F5 A1494 (GO TO A1494)

8. /P F (PRINT FILE)
9. POPULATION.167 (FILE NAME POPULATION.167)
10. /R (RANGE)
11. A1495.H1499 (RANGE DEFINED AS A1495.H1499)
12. G (GO)
13. Q (QUIT)
14. Follow the same steps to create population.168 through 172.

In order to verify that you have correctly exported the files, you may compare your files with the files that appear in subdirectories varfiles and population.

Running the Files

Running the program is a simple matter and is described at page 121. For the files just created, the appropriate combination of files are identified at the bottom of NRRIEXAM.WK1
(cells A1557 through C1573)

	A	B	C
	populatn	variable	
1556			
1557	166		452
1558	166		453
1559	166		454
1560	167		455
1561	168		456
1562	166		457
1563	170		458
1564	169		459
1565	171		460
1566	167		461
1567	168		462
1568	170		463
1569	167		464
1570	168		465
1571	170		466
1572	172		467
1573	166		468

To run the first combination of files (populatn.166 and variable.452), do the following steps (at the DOS prompt):

1. copy populatn.166 *.dat
2. copy variable.452 *.dat
3. cityinit
4. analog
5. return
6. choose the level of output--for this exercise, we have chosen level 5.
7. When the program has completed running, you will want to save the results.

Do this by typing

```
rename analog.oda v452p166.pc
```

That's all. If you want to look at the results in somewhat greater detail, you may want to take a glance at file analog.out.

When you are ready to do the next combination of files, take the following steps.

8. copy populatn.166 *.dat⁵
9. copy variable.453 *.dat
10. cityinit
11. analog
12. return
13. choose the level of output--for this exercise, we have chosen level 5.
14. When the program has completed running, you will want to save the results.

Do this by typing

```
rename analog.oda v453p166.pc
```

⁵Since the population file is not changing (its remaining number 166, this step, as well as step ten can be skipped. We list it here so that the user will be sure to follow these steps when the population file changes.

Output Evaluation

You can compare your results with the results that appear in subdirectory ANALRESU.

We have also provided you with a LOTUS spreadsheet that aids in the calculation of the incremental cost of service (ANALEXAM.WK1). The files that have just been created should be loaded on to the worksheet. In row one of ANALEXAM, we identify the variable name.

The following steps are followed.

1. Go to cell A2
2. /F I N (import number file)
3. V452P166.PC
4. Go to cell B2
5. /F I N
6. V453P166.PC
7. follow the remaining steps for files v453p166.pc through v468p166.pc.
8. When all of the files have been loaded onto the spreadsheet, delete all rows below row 32. This is done by taking the following steps:
 - a. /w (worksheet)
 - b. d r (delete rows)
 - c. a33.z100 (delete area a33.z100)
9. Now we need to load the formulas from analexam.wk1. This is done by:
 - a. go to a33
 - b. /f c c (combine file)
 - c. a33.z100 (define range)
 - d. analexam.wk1 (define worksheet from which formulas will be obtained).
10. F9 (calculate)

The results may now be analyzed. The reader should focus on the calculations that appear on lines 41 through 65.

	A	B	C	D	E	F	G	H	I	J	K
	exchange				toll	ccs	local	private	line		
41	b-a	5.456		C-A	28.25		d-a	80.22			
42				F-B	28.25						
43											
44	j-d	5.461									
45	k-e	5.467		M-D	27.84		m-c	43.85			
46				N-E	28.31		j-b	80.21			
47				O-G	19.76		h-e	83.61			
48	l-g	.4780					i-g	67.22			
49											
50											
51	f-c	5.425									
52											
53											
54							AVERAGE			REVENU	
55	TOLL	PRIVATE	LINE	SWITCHED	ACCESS		INCREM	T	BASE	H*J	
56	E-A	191.0		G-A	47.82		COST	STATIS	VOLUME		
57							exchan	4.457	2.240	932.5	4157.
58							toll	26.48	7.876	14609	3.9e5
59							pl loc	71.02	4.832	407.4	28934
60							pl tol	188.9	27.81	271.6	51301
61							access	44.24	6.861	7423	3.3e5
62	H-D	196.0		I-D	47.31						.6576
63	K-B	191.0		L-B	47.20						
64	N-C	190.5		O-C	31.35						
65	P-G	175.9		P-E	47.51						
66											

The following table identifies were the output for the various services is found on the spreadsheet.

Spreadsheet With Outputs Summarized

Service	Individual Run	Average of Runs	T-Statistics
Exchange ccs	B41..B53	H56	I56
Toll ccs	E41..E53	H57	I57
Local Private Line	H41..H53	H58	I58
Toll Private Line	B56..B65	H59	I59
Switched Access	E56..E65	H60	I60

The spreadsheet also identifies the level of revenue that would be generated if the five services identified above were priced at their marginal cost. These calculations appear in cells K56 through K60. Cell K61 provides the ratio of the revenue generated from incremental cost pricing, divided by the total cost of service.

Creating Variable Files for the Digital Program

The digital model requires the creation of a different set of variable files. Because the inputs are different, the variable files can not be used with the digital program.

We have written a program in UNIX that converts the variable files to dvariabl (digital variable) files. The program (DVTOOL) is in sub-directory dvarfile. We have also written a program in UNIX that converts the variable files to dvariabl (digital variable) files. The program (DVTOOL) is in sub-directory dvarfile.

When running the digital model, the user should use the same combination of files that were created for the analog model (for example, dvariabl.452 with populatn.166).

Running the Digital Model

To run the first combination of files (populatn.166 and dvariabl.452), do the following steps (at the DOS prompt):

1. copy populatn.166 *.dat
2. copy dvariabl.452 *.dat
3. a. cityinit
 b. dxinit
4. digital
5. return
6. choose the level of output--for this exercise, we have chosen level 5.
7. When the program has completed running, you will want to save the results.

Do this by typing

```
rename digital.oda d452p166.pc
```

That's all. If you want to look at the results in somewhat greater detail, you may want to take a glance at file digital.out

When you are ready to do the next combination of files, take the following steps.

8. copy populatn.166 *.dat

9. copy dvariabl.453 *.dat

10. a. cityinit

b. dxinit

11. digital

12. return

13. choose the level of output--for this exercise, we have chosen level 5.

14. When the program has completed running, you will want to save the results.

Do this by typing

rename digital.oda d453p166.pc

Evaluating the Results from the Digital Model

The results from the digital program can be evaluated in the same manner as with the analog program. In sub-directory LOTUS22 you will find the appropriate spreadsheet (DIGEXAM.WK1). When importing the data (subdirectory digresul), the user should again start by putting the data in cell A2 (that is, place the results from D452P166.pc in cell A2).

The following steps are followed.

1. Go to cell A2

2. /F I N (import number file)

3. D452P166.PC

4. Go to cell B2

5. /F I N

6. D453P166.PC

7. follow the remaining steps for files D453p166.pc through D468p166.pc.

8. When all of the files have been loaded onto the spreadsheet, delete all rows below row 33. This is done by taking the following steps:

a. /w (worksheet)

- b. d r (delete rows)
- c. a34.z100 (delete area a34.z100)
- 9. Now we need to load the formulas from DIGEXAM.wk1. This is done by:
 - a. go to a34
 - b. /f c c (combine file)
 - c. a34.z100 (define range)
 - d. DIGEXAM.wk1 (define worksheet from which formulas will be obtained).
- 10. F9 (calculate)

The results may now be analyzed. The reader should focus on the calculations that appear on lines 42 through 66.

Other Spreadsheets Used to Create Files and Evaluate Results

The spreadsheets that we have discussed up to this point were created so that the user could get a quick feel for how the model operates. NRRIEXAM.WK1 was created so that there was only 1 iteration of the model, and no restarts. The following additional files have been provided:

List of Spreadsheets

<u>Spreadsheet</u>	<u>Use</u>
varsmall.wk1	same as nrriexam, but 500 iterations, 1 restart and 4 extra 2BESS switches.
varlarge.wk1	varsmall can be used to create 17 files. varlarge is set up to create 26 files
vreslarg.wk1	Same as analexam.wk1, but used with varlarge.wk1
dreslarg.wk1	Same as digexam.wk1, but used with the 26 varlarge and dvtool
stdalone.wk1	Creates variable and population files for calculation of stand-alone costs

Correcting for Local Minimum

The search algorithm, the downhill-simplex method, may not locate the global minimum network configuration. Sometimes the model will select switch locations that do not minimize the cost of production.

A nonoptimal selection can be detected by using VRESLARG.WK1, DRESLARG.WK1, ANALEXAM.WK1, or DIGEXAM.WK1. If a negative marginal cost shows up on these worksheets in blocks A41 to H52, or if the marginal cost appears to be abnormally high (relative to the other estimates), the data should be further analyzed.

For example, suppose that when using ANALEXAM.WK1, cell B41 indicates that the marginal cost of exchange service is negative. For the combination of files that we have been working with, this would occur if the total cost associated with v452p166.pc was less than the total cost of v453p166.pc. V453p166.pc should be greater than V452p166 because the level of exchange usage is higher by 233 ccs (cell B34--worksheet ANALEXAM.WK1).

The total cost reported in file V452P166.pc could be greater than V453P166.pc because for V543p166 the model found a better location for the central offices. To correct for this problem, the locations from file V543p166 are used to determine the cost of combination V452p166. The mechanics for this process are explained in the next section.

INSTRUCTIONS FOR USING THE RECALCULATING PROGRAMS

In addition to the nested technology/location search programs, ANALOG and DIGITAL, we have provided four additional programs which perform some of the subsidiary tasks of ANALOG and DIGITAL. Two of these programs are ARECALC (for analog systems) and DRECALC (for digital), which will compute ONLY the cost of service for a given technology and location--no optimization is performed. These programs are useful for benchmarking an existing system, or if you are simply curious about how much a configuration other than the one resulting from the optimization would cost.

The other two programs are ALOCATE (for analog) and DLOCATE (for digital). These programs will optimize location ONLY for a given technology configuration. For example, if you want to know what the cost and optimal location for, say, 3 DMS100® switches attached to 3 remote switches would be in a given city, you would run the program DLOCATE.

The programs run similarly to the main programs; that is, follow the same sequence of steps with one exception. Prior to the sequence of steps, you must create (in the analog case) a file called ANALOG.LOC or (in the digital case) DIGITAL.LOC. This file is formatted as follows:

LINE 1: n (= number of central offices (including remotes)) LINE 2: x1 x2 x3 x4
x5...xn (= switch types of central
offices; see below.

LINE 3 l11 l12 (= (x,y) location for switch #1)
 l21 l22 (= (x,y) location for switch #2)
 .
 .
 .
 .
 LINE n+2 ln1 ln2 (= (x,y) location for switch #n)

The switch types are coded as follows. In the digital case, 1=DMS100; 2=DMS10; and 3=remote. In the analog case, 1=1AESS; and 2=2BESS.

For example, consider the following digital.loc file.

DIGITAL.LOC

```

6
1 3 3 3 3 3
12.6825 12.3529
6.0541 5.0482
20.1771 16.9141
19.4684 5.6313
13.1777 20.3409
5.1405 19.7397
  
```

The file indicates that six switches should be deployed. The first switch, located at 12.6825 12.3529 is a DMS100®. The remaining 5 switches are remotes, and are located at,

```

6.0541 5.0482
20.1771 16.9141
19.4684 5.6313
13.1777 20.3409
5.1405 19.7397
  
```

Once you have created the location file, follow exactly the steps for either the ANALOG or DIGITAL program until you reach the last step. For the last step, enter the name of the recalc program you want rather than either ANALOG or DIGITAL. That is, the last step is

ARECALC <Enter> (for analog cost computation)
or
DRECALC <Enter> (for digital cost computation)
or
ALOCATE <Enter> (for analog location optimization) or
DLOCATE <Enter> (for digital location optimization).

Data Needed to Run the Model

The following data should be obtained to run the model. All of the data identified in this section is used on a regular basis by the telephone companies and are, or have been, used in their own cost studies.

1. Carrying charges for the study year. The data should be provided at the sub-account level (for example, the telephone plant index series for underground copper cable; underground fiber cable; analog switching; digital switching; circuit equipment and so on).

2. Telephone plant indexes from 1980 through the study year. The data should be provided at the sub-account level (for example, the telephone plant index series for underground copper cable; underground fiber cable; analog switching; digital switching; circuit equipment etc).

The user may want to adjust these carrying charges to reflect higher/lower capital costs.

3. Broad-gauge unit costs for outside plant. The data should be provided for different gauges of wire (at a minimum, underground and buried cable). In addition, data should be provided for fiber cable of different sizes (at least ranging from four to 144 pairs--both underground and buried fiber cable).

4. T-carrier utilization rate.
5. The pair-design standards used for feeder and distribution pair. What is the design ratio for feeder and distribution pairs per customer (for example, two pairs per household in the distribution plant, 1.5 pairs per household in the feeder plant, 1.05 pairs in the feeder plant when customers are served by subscriber line carrier)?
6. Percent of cable that is underground in (a) residential neighborhoods, (b) downtown district, (c) mixed/residential district.
7. Percent of switched busy-hour traffic that is toll traffic (both interLATA and intraLATA).
8. Percent of lines that are private line. If possible obtain the ratio for (a) residential neighborhoods, (b) downtown district, (c) mixed/residential district.
9. Percent of private lines that are toll private lines.
10. Land and building loading factors for circuit and switching investment (the ratio that is multiplied against the primary investment in circuit and switching in order to determine the investment in the supporting land and buildings).
11. Main distribution frame investment per subscriber. Obtain this data for both analog and digital switches. The cost differs by technology.
12. Average busy-hour holding time for local and toll calls.
13. Load coil investment per pair.
14. Tandem busy-hour switching investment per ccs.
15. Current cost of installed conduit/per foot.
16. Investment for conduit used for underground per copper-pair foot (loading factor for conduit per underground copper pair-foot).
17. Busy-hour ccs usage for business, residential and mixed residential/business areas.
18. Loading for miscellaneous investment for underground and buried cable. This should reflect items that are not included in either the broad gauge cost data (# 3) or load coil investment (#13). Typically this value will be equal to one.

In the chart below, we map which variables should be based on the data provided in the previous information questions.

Information Requests and Variable Names

Request Number	variable names ⁶
One	ac211; ac212; ac22157; acess; ac244; ac2422; ac2423; ac815; ac845
Two	tpiund80; tpibur80; tpicond80; condpf; digl00tp; digl0tp; tpiosp80; tpi5780 TPIOSP90; tpi5790 tpiundf90; tpibur90; tpicond90
Three	f1526; f1524; f1522; f1519; f4526; f4524; f4522; f4519; m1526; m1524; m1522; m1519; m4526; m4524; m4522; m4519; ufibfix; ufibmc; bfibfix; bfibmc
Four	tutil
Five	fppercust fpslcpcust dppercust
Six	perund_bus; perund_med; perund_res
Seven	tollper
Eight	perpl[1]; perpl[2]; perpl[3]
Nine	pltollper
Ten	build22157; build22177; land22157; land22177
Eleven	mdfcost
Twelve	intraht; interexcht; tollht
Thirteen	loadc
Fourteen	tandem
Fifteen	fcond
Sixteen	condpf
Seventeen	ccs_per_res_line; ccs_per_med_line; ccs_per_bus_line
Eighteen	misc15; misc45

⁶Variable definitions are provided in the appendix.

APPENDIX THREE

USER INPUTS

In this appendix we provide a list of the user inputs for the analog and digital models. The user of the model can either work with the values that we have selected, or choose user specific values.

Carrying Charge Factors:

ac211 = carrying charge for land
ac212 = carrying charge for buildings
ac22157 = carrying charge for circuit
acess = carrying charge for analog switches
acess = carrying charge for digital switches
ac244 = carrying charge for conduit
ac2422 = carrying charge for underground cable
ac2423 = carrying charge for buried cable
ac815 = carrying charge for underground fiber
ac845 = carrying charge for buried fiber
pricelab = price of labor
pricecap = price of capital
pricemat = price of central office material
priceosmat = price of outside plant material

The price of labor, capital, central office, and outside plant material (input prices) can be used to modify the values of the carrying charge factors. The user should start with the existing telephone company carrying charge factors. The model then can be used to explore such issues as how the cost-of-service would be affected by a user-chosen percentage increase (decrease) in one or more of the four factor prices. The model is set up so that if the price of labor increases by 10 percent, for example, appropriate adjustments are made to the different carrying charges. The adjustment to each carrying charge factor is based on the weighted cost of the four input prices.

Usage Inputs:

ccs_per_res_line = busy-hour ccs per residential customer

ccs_per_med_line = busy-hour ccs per medium density customer

ccs_per_bus_line = busy-hour ccs per business customer

perpl[1] = fraction of residential neighborhood lines that are
private lines

perpl[2] = fraction of mixed neighborhood lines that are
private lines

perpl[3] = fraction of business neighborhood lines that are
private lines

tollper = percent of switched traffic that is toll traffic

pltollper = percent of private lines that are toll lines
(special access)

intraht = holding time for intraoffice call

interexcht = holding time for interoffice exchange call

tollht = holding time for toll call

Outside Plant Inputs:

perund_bus = fraction cable underground, business neighborhood

perund_med = fraction cable underground, mixed neighborhood

perund_res = fraction cable underground, residential
neighborhood

plcost = cost markup fraction for private line loops

f1526 = fixed investment per foot of underground 26 gauge cable

f1524 = fixed investment per foot of underground 24 gauge cable

f1522 = fixed investment per foot of underground 22 gauge cable

f1519 = fixed investment per foot of underground 19 gauge cable

f4526 = fixed investment per foot of buried 26 gauge cable

f4524 = fixed investment per foot of buried 24 gauge cable

f4522 = fixed investment per foot of buried 22 gauge cable

f4519 = fixed investment per foot of buried 19 gauge cable

m1526 = marginal investment per pair foot of underground 26 g.

m1524 = " " " " " " " 24 "

m1522 = " " " " " " " 22 "

m1519 = " " " " " " " 19

m4526 = " " " " " " buried 26 "

m4524 = " " " " " " buried 24

m4522 = " " " " " " buried 22

m4519 = " " " " " " buried 19

ufibfix = fixed investment per foot cost of underground fiber

ufibmc = marginal investment per foot of underground fiber
(per fiber)

bfibfix = fixed investment per foot cost of buried fiber

bfibmc = marginal investment per foot of buried fiber (per
fiber)

misc15 = miscellaneous investment related to underground copper

misc45 = miscellaneous investment related to buried copper

looputil = utilization of copper loop line capacity
 blockwidth = width of city block, in kilofeet
 loadc = 1990 load coil investment (per copper pair)
 fppercust = feeder pairs per customer copper wire
 fpslcpercust = feeder pairs per customer, slc-96
 dppercust = distribution pairs per customer
 fcond = cost per foot of conduit (total investment)
 slc_mode = SLC-96 mode, 1=unconcentrated; 2=concentrated

The fixed and marginal cost of outside plant is obtained by running a linear regression: $\text{cost} = A + B \cdot \text{cable size}$.

Where:

A = the fixed investment per foot of cable

B = the marginal investment per foot of cable

Central Office Inputs:

dms100cap = calling capacity of a DMS100 digital switch
 dms10cap = calling capacity of a DMS10 digital switch
 aess1cap = calling capacity of a 1AESS type analog switch
 bess2cap = calling capacity of a 2BESS type analog switch
 remotecap = ccs capacity of remote switches
 max_remotes = max number of remotes attachable to DMS100
 coleceng = central office telco engineering analog switches
 switchutil = utilization of switch capacity
 build22157 = investment loading for building, applied to circuit
 build22177 = investment loading for building, applied to switch
 land22157 = investment loading for land, applied to circuit
 land22177 = investment loading for land, applied to switch
 cbd_factor = multiplier for land in CBD
 meddens_factor = multiplier for land in MDD
 lowdens_factor = multiplier for land in LDD
 mdfcost = main distribution frame cost per customer (separate values analog and digital switch)
 tandem = 1990 tandem investment per ccs.
 tutil = t-carrier utilization factor
 min_2bess = minimum number of "extra" 2BESS machines tried in the analog model.

We recommend a value of 0 in the analog environment.¹

max_2bess = number of "extra" 2BESS machines tried in the analog model. We recommend a value of 4 in the analog environment.

mix_dms10 = minimum number of "extra" dms10 machines tried in the digital model. We recommend a value of 0 in the digital environment.

max_dms10 = number of "extra" dms10 machines tried in the digital model. For large cities, we recommend a value of 0 in the digital environment. "Extra" switching is added in the digital environment via remotes. For smaller cities (for example, less than 30,000 customers), the user may want to experiment with max_dms10 at 2 or 3.

Amoeba Inputs:

ftol = function tolerance for downhill simplex routine

itmax = maximum number of AMOEBA iterations number_of_restarts for AMOEBA when minimum is found

Telephone Plant Indexes:

droptpi = drop wire tpi 1985 to 1990

tpiund80 = tpi underground cable 1990/1985

tpibur80 = tpi buried cable 1990/1985

tpicond80 = tpi conduit 1990/1985

condpf = 1985 conduit cost per pair foot of copper cable

dig100tp = tpi analog ess 1990/1985

dig10tp = tpi analog ess 1990/1984

anal2B = tpi analog ess 1990/1980

tpiosp80 = tpi outside plant 1990/1982

tpi5780 = tpi circuit plant 1990/1982

remotetpi = 1990/1990 price index for remote switches

TPIOSP90 = price index 1990/1990 outside plant

tpi5790 = price index circuit 1990/1990

tpiundf90 = 1990/1990 tpi for underground fiber cable

tpiburf90 = 1990/1990 tpi for buried fiber cable

tpicond90 = 1990/1990 tpi for conduit

POPULATN.DAT

LINE 1 (x,y) coordinates for city's northeast corner

LINE 2 (x,y), (x,y) coordinates for south-west and northeast corner of

¹The term "extra" switches is used to indicate that more than the minimum number of switches needed to serve a city is evaluated by a model. The deployment of "extra" switches may lower the cost of service because of the saving in loop costs.

business district

LINE 3 (x,y), (x,y) coordinates for south-west and northeast corner of
mixed district

LINE 4 business population, mixed area population, residential area population

LINE 5 planned customers per serving area

RECTANGL.DAT

LINE 1 Number of serving areas in city

LINE 2 (x,y) (x,y) coordinates for northeast and southwest corner of
serving area; type of customers (1=residential; 2=mixed; 3=business); number of
customers in serving area

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LINE N+1

where N=number of serving areas in city.

