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Decision Criteria for Rehabilitation of the Distribution Network

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Rehabilitation is the change in network design, administration, and hardware to reduce costs of operating existing telephone distribution plant. A set of models has been developed to help the plant engineer make economic decisions about rehabilitation. The first model is used to develop several competing rehabilitation plans. The second model calculates economic indices relating the benefits and costs of the competing plans. The final model helps make the decision as to which plan to implement when there are budget constraints.

I. INTRODUCTION

The decision criteria described in this paper constitute a method to plan rehabilitation of segments of the distribution network. Rehabilitation reduces the operating costs of an existing area of telephone outside plant through improvements in local network design, administration, and hardware. In operating costs, we include the repair costs to correct periodic failures in components of the network, as well as the costs of connecting the network to customers requesting service.

Figure 1 outlines the principal steps in this methodology. First, segments of the network with high operating costs are identified through monitoring and data tracking systems. This function provides the candidate areas for rehabilitation. For a given high-cost area, several improvement alternatives are then proposed. These alternatives differ in the investment costs they require and the expected savings they produce in future operating costs. The alternatives are designed economically to exploit the capacity and the remaining life of the existing facilities in the network. Section II presents the guidelines to develop the alternatives. The proposed improvement alternatives, along with a status quo alternative, are evaluated using economic indices such as the net present value and the benefit-to-cost ratio.

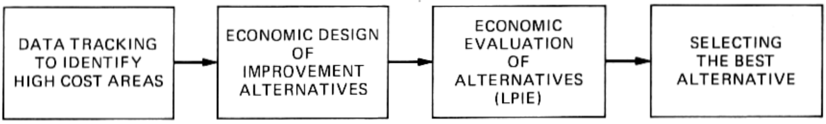

Fig. 1—The rehabilitation planning methodology.

Section III develops the models to estimate the project benefits and costs used in calculating these indices. Finally, a method is presented to select the most appropriate alternative when there are constraints on available capital expenditures.

Before presenting these models, some background information about the distribution plant is helpful.

1.1 Background

Figure 2 is a schematic of the loop network. The loop network connects telephone customers to a local switching office called a wire center. In general, groups of large cables extend outward from a wire center along four main routes. These cables are called feeder cables and usually provide accessibility of the telephone network to within half a mile of the customer's residence. From the feeder, lateral cables extend outward and further branch out into local cables that are connected to each customer's residence via distribution terminals. The local cables and terminals constitute the distribution network.

Feeder pairs are usually committed to segments of the distribution network called distribution areas. A distribution area serves as an administrative unit in the distribution network. It encompasses one or more lateral cables and should have 200 to 600 ultimate living units.

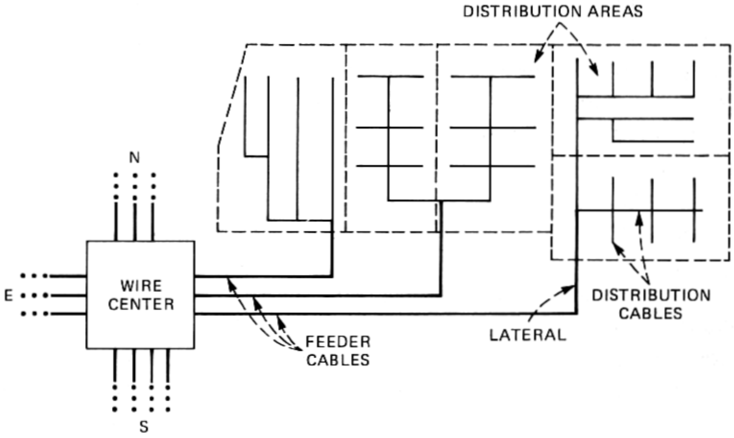

Fig. 2—A schematic of the loop network.

Distribution cables may be spliced wire by wire with the lateral or feeder cables or interconnected via an interface. In the latter case, the distribution area is called a serving area. A comprehensive overview of the loop plant has been given by N. G. Long.[1]

1.2 Problems in the distribution network

Much of the distribution network has been designed as multiple plant. In multiple plant, a telephone line (a pair of wires) starting from the wire center branches into several lines terminating at different locations in the distribution network. Telephone service can be rendered at any one (or more in the case of party line service) of these terminations. However, multiple plant requires network rearrangements to cope with increasing growth and customer movement. The costs involved in performing these rearrangements and in fixing the troubles often created during rearrangement work in splices and terminals contribute to increased costs in operating the network. Also contributing to the operating costs are cable troubles (these include faults in cables, splices, and terminals) due to normal deterioration of facilities with age.

Operating costs due to network design and congestion can be reduced by converting the network design to the Serving Area Concept[2] (SAC). In this conversion, an interface is placed between the feeder (or lateral) and the distribution cables serving the distribution area. At the interface, any feeder pair can be connected to any distribution pair, thus increasing the accessibility of the economically sized feeder network. The distribution cables can be sized for ultimate growth in the area or for some finite horizon. The SAC design restricts network rearrangement activity to the interface, while the feeder and distribution cable sizes determine the level of this activity. "Multipling" of the feeder pairs between the serving area and other distribution areas is eliminated or minimized.

The nature of the troubles in a distribution area can also suggest that the high operating costs are due to deteriorating plant. In such a case, troubles are localized to individual cable sections or terminals for selective replacement or renovation of deteriorated facilities. In many instances, design problems and deterioration exist together, and a rehabilitation plan will entail replacement or renovation of existing facilities to eliminate troubles as well as conform to the requirements of SAC design.

II. THE DESIGN OF REHABILITATION ALTERNATIVES

As shown in Fig. 1, the preliminary function in the rehabilitation methodology is to identify high-cost areas in the distribution network.

This function has been facilitated by available data tracking systems like the manual Facility Analysis Plan,[3] or a computerized data tracking system called the Loop Activity Tracking and Information System (LATIS). Based on the number and type of troubles and other operating costs in the recent past (usually the preceding 12 months), the engineer identifies high-cost distribution areas that are candidates for rehabilitation.

For a given high-cost area, the choice and the design of improvement alternatives are developed in the following three subsections. Application of these methods ensures that the proposed alternatives for the distribution area are economically designed and present a good set of choices for a comparative study to determine which of the alternatives, if any, should be implemented.

2.1 *Improvement alternatives*

Improvement alternatives for a distribution area typically entail repair or replacement of deteriorated facilities and/or conversion to SAC design. However, SAC design is a spectrum of alternatives depending on how generously the distribution cables are sized. Distribution cable sizes are measured in the number of pairs they provide per living unit. The greater the number of pairs per living unit, the less the expected rearrangement activity. Stiles[5] has investigated optimal sizing of distribution cables by balancing capital investments against savings in operating costs. For residential areas with aerial plant, the optimal size may range from 1.2 to 2 pairs per living unit. The optimal sizing criterion is applied to the number of living units forecast at some planning horizon, t. For example, when t is infinite, the cables are sized optimally for ultimate demand and the SAC design is referred to as "ultimate SAC."

While an engineer is free to propose any improvement plan, the set of all the proposed alternatives should reflect a wide variation in investment costs and the associated benefits. This variation permits us to evaluate incremental benefits as we go from a modest investment alternative to more expensive alternatives.

Experience in the field and with sample data has shown that a modest investment alternative with relatively high payoff is usually the "physical rehabilitation" (repair or replacement) of all deteriorated facilities with no change in network design. The most expensive and complete alternative is "physical rehabilitation" plus conversion of network design to "ultimate SAC." Between the modest and the most expensive alternatives, we propose, at minimum, one other alternative with intermediate investment. This alternative will be "physical rehabilitation" plus "intermediate SAC" where all facilities in the area are optimally sized at least for demand forecast at a horizon $\tau = 2$ to 5 years.

2.2 Facility diagnosis and improvements

The distribution area is subdivided into its component facilities (e.g., sections of cables). For a given improvement alternative, we now consider every facility one by one. We diagnose the facility as "ok" or deteriorated, and/or undersized with respect to the minimum capacity requirements of the alternative. Table I gives the remedial options to improve facilities judged deficient in one way or the other.

A facility is considered deteriorated if the annuity associated with renovation or replacement is less than the annual cost of expected troubles. Due to the small incidence of troubles that are associated with a particular facility, estimates of expected trouble rates lack statistical confidence. Hence the engineer complements the trouble history of the facility with personal judgment, inspection, and sometimes testing to determine if a facility is deteriorated or not. A facility is considered undersized for the "ultimate SAC" or "intermediate SAC" alternative if it is not sized optimally for the demand forecast at planning horizon, τ.

2.3 Economic criteria for facility improvement

We now develop the criteria for choosing the best remedial option for facility improvement. First, consider the case where the facility is undersized and the choice is between reinforcement with additional capacity and replacement with a new and properly sized facility.

Consider a cable section of capacity x pairs and an estimated remaining life of t years. To increase the capacity of this cable to y pairs, we have two options:

(i) Reinforce the section with a $y - x$ pairs cable
(ii) Replace the section with a y pair cable.

Let

$c(n)$ = the cost of placing a cable of size n pairs and
$V(x, t)$ = minimum total discounted cost of providing y pairs, given x pairs with remaining life t. This includes the present as well as all future investments.

Then the better option is determined by the recursive relation:

$$V(x, t) = \text{Min}\begin{cases} c(y) + e^{-rT}V(0, 0) & \text{(replace now)} \\ c(y-x) + e^{-rt}V(y-x, T-t) & \text{(reinforce now),} \end{cases} \qquad (1)$$

where r is the discount rate and T is the life of the new cable.

Table I—Options

Diagnosis	Remedial Options
Deteriorated	Renovate vs replace
Undersized	Reinforce vs replace
Deteriorated + undersized	Renovate + reinforce vs replace

To interpret relation (1), note that if we choose to "replace now" (and therefore abandon the existing x pairs cable), then at time T the new cable will expire and we will have zero life and zero pairs. This decision will entail an immediate investment of $c(y)$ plus the discounted value of future investments which is $e^{-rT}V(0, 0)$. Also observe that

$$V(0, 0) \equiv c(y) + e^{-rT}V(0, 0) \equiv \frac{c(y)}{1 - e^{-rT}}.$$

However, if we choose to "reinforce now" with a $y - x$ pairs cable, then at time t the existing cable will expire and we will have a $y - x$ pairs cable left with a remaining life of $(T - t)$. This decision will entail an immediate investment of $c(y - x)$ plus the discounted value of future investments which is $e^{-rt}V(y - x, T - t)$.

If known additional expenses are associated with maintaining two sheaths of cable, they can be added to the costs associated with "reinforce now" decision in relation (1). This simple formulation has also overlooked the stochastic nature of the life of the cable. However, relation (1) does have the explicit solution:

$$V(x, t) = \text{Min}\begin{cases} \dfrac{c(y)}{1 - e^{-rT}} \\ \qquad (i) \rightarrow \text{Replace always.} \\ c(y - x) + e^{-rt}\dfrac{c(y)}{1 - e^{-rT}} \\ \qquad (ii) \rightarrow \text{Reinforce now, replace in the future.} \\ \dfrac{c(y - x)}{1 - e^{-rT}} + e^{-rt}\dfrac{c(x)}{1 - e^{-rT}} \\ \qquad (iii) \rightarrow \text{Reinforce always.} \end{cases} \tag{2}$$

In the above relation, if (i) is the minimum, the optimal decision is to replace the existing cable with a new y pairs cable. If (ii) or (iii) is the minimum, the optimal decision is to reinforce the existing cable at present with a $y - x$ pairs cable. Using some sample data, Fig. 3 illustrates the costs (i), (ii), and (iii) as the remaining life, t, of the existing facility varies from 0 to 40 years.

If the diagnosis from Table I indicates that the choice of improvement options is "Replace" versus "Renovate + reinforce," then renovation expenses are added to the costs associated with the "Reinforce now" decision in relation (1). In this case, "t" becomes the remaining life of the renovated facility.

When the facility is sized properly but is deteriorated, the choice is between renovation and replacement. The engineer compares the

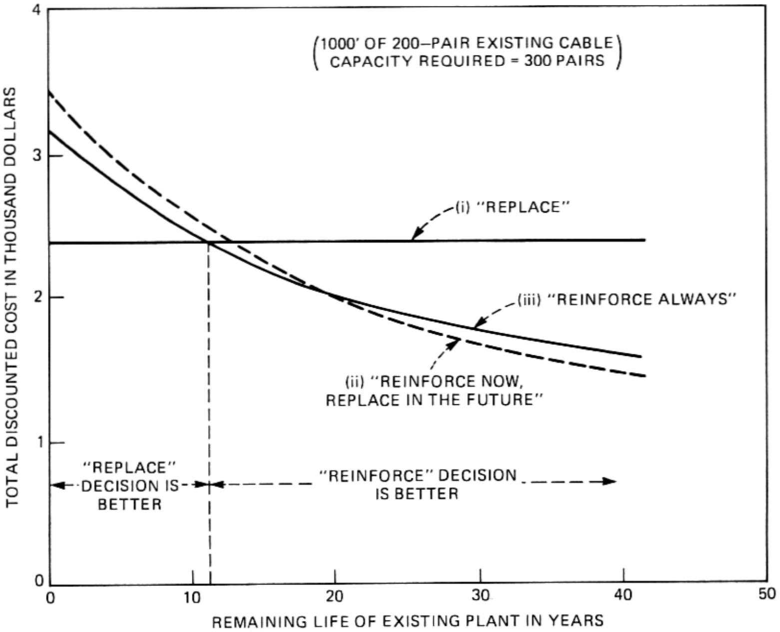

Fig. 3—The optimal way to increase the capacity of an existing cable changes with the remaining life of the existing cable.

annuity of the replacement costs over (0, T) with the annuity of the renovation costs over (0, t) and chooses the action with the lower annual costs.

Using the principles described above, decision charts for various scenarios have been generated based on broadgauge costs of materials and common assumptions about cost of money, inflation, and taxes. These charts help the field engineer quickly choose the best remedy for facilities needing improvement.

2.4 Summary of alternatives

In designing a rehabilitation alternative, every component facility is judged separately and, if necessary, upgraded in the most economic way. This process is repeated for each proposed alternative. For example, Table II shows a summary of possible decisions and the associated costs in upgrading facilities to conform to the three broad improvement alternatives described before. Note that the same facility may require different treatments for different alternatives. For example, Facility 1 was judged in good physical condition. Hence, for the "physical rehabilitation" alternative, no improvement was required. However, it was undersized for the "intermediate SAC" design requirements. By applying the economic decision criterion, replacement with

Table II—Summary of alternatives

	Best Improvement Option (and Cost) When Designing···		
	Physical Rehabilitation	Physical Rehabilitation + Intermediate SAC	Physical Rehabilitation + Ultimate SAC
Facility 1	Do nothing (C_{11})	Replace (C_{12})	Replace (C_{13})
Facility 2	Renovate (C_{21})	Renovate (C_{22})	Replace (C_{23})
⋮	⋮	⋮	⋮
Total Costs	$\sum_i C_{i1}$	$\sum_i C_{i2}$	$\sum_i C_{i3}$

the larger-sized facility was preferred over reinforcement of the existing facility to meet "intermediate SAC" and "ultimate SAC" requirements.

The total costs associated with the alternatives are summed up in Table II. The remaining sections develop the benefits and the comparative analysis of the alternatives.

III. EVALUATION OF ALTERNATIVES

Once the rehabilitation alternatives have been developed as described in the previous sections, an economic analysis is performed to determine which, if any, alternative should be implemented. This analysis has been mechanized as a computer program called the Loop Plant Improvement Evaluator (LPIE). The models underlying this economic analysis are described here.

The economic analysis evaluates the tradeoff between the cost of an investment and the benefit of future cost savings. These future cost savings come primarily from reductions in upkeep and rearrangement work operations in the plant (operating costs). The operating costs can be broken down into three major components: (*i*) the facility modifications (moving pairs to where they are needed), (*ii*) the cable troubles (fixing defective pairs), and (*iii*) the assignment changes (costs incurred when the pair assigned for service cannot be used). These components are further broken down into a total of 15 work operations (also known as activities). A more detailed description of the activities and the method for tracking their occurrences can be found in Ref. 3.

The economic analysis models consist of five parts—creating a status quo alternative, providing an end-of-study adjustment, calculating the reduction in activity levels and costs, calculating a credit for deferral of future feeder capacity expansion, and determining the economic indices. In this paper, we describe only the modeling effort in determining the reduction in activities which is the heart of the analysis.

IV. REDUCTION IN ACTIVITY LEVELS AND COSTS

After an investment in rehabilitating the plant, the operating costs in a distribution area will decrease and then grow at some new rate as

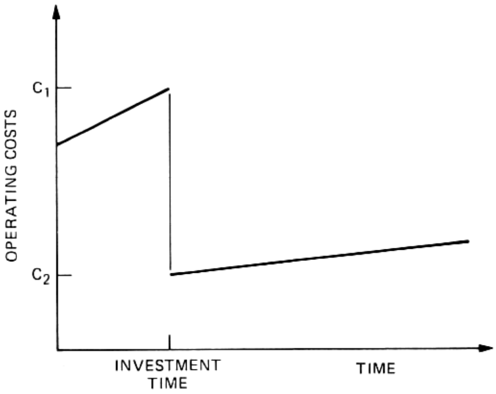

Fig. 4—Operating cost functions. The fraction of costs eliminated is $1 - C_2/C_1$.

illustrated in Fig. 4. The amount of this decrease must be determined. Unfortunately, tracking operating cost data by distribution area has only recently gained acceptance with the availability of the LATIS program. To predict reductions in operating costs in the absence of such data, we relied on the opinion of loop plant experts. The Delphi technique[5] was used to obtain consensus among the experts. The Delphi technique consists of a sequence of questionnaires sent to the participating experts, with each questionnaire after the first containing feedback about the responses to the previous round's questions. After several iterations, a consensus is usually obtained.

Our first round survey asked for a matrix of numbers, where entry i, j, k is the expert's assessment of the fraction of activities of type j which are eliminated when investment i is made and the original plant is of type k. There were 11 investment options (the three described earlier plus various partial conversion options), 15 activities, and three types of plant (aerial lead, aerial PIC,* buried). It was suggested to the participants that the activities be grouped into the three major components—facility modifications, cable troubles, and assignment changes—to make the task easier, but the flexibility to assess each item separately was maintained. In addition to the numbers, space was provided for discussion of any of the items for use in the feedback in the second round. Consensus of response was considered to be achieved when the span of the inner two quantiles was less than 0.20. In this case, the median was chosen as the fraction of activities eliminated.

Our survey was sent to 42 experts, of which 19 responded. Consensus on the first round was achieved on 35 percent of the items. The second

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* PIC = Plastic Insulated Conductor.

round required estimates of only the remaining items and required a written justification for the estimates of the more controversial items. Another 40 percent of the original items achieved consensus after round 2. The reduction factors for the remaining items would normally be obtained through subsequent iterations, but due to time constraints a third round was not feasible. However, the written justifications from the round 2 responses provided enough information for us to mediate the dispute and select a reduction factor. It should be noted that, for the three most commonly used alternatives (the ones described earlier), consensus on the first round was achieved for the majority of the items. This was both expected (since the experts are most familiar with these investments) and heartening (we have the greatest confidence in the most commonly used estimates).

These expert assessments were based on "typical" distribution areas. Since local conditions may vary, our models allow the user to override the built-in estimates by explicitly specifying the post-improvement levels for any activities. The output of our economic analysis is a set of indices for each alternative. The two indices useful for project selection with no budget constraint are the present worth of expenditures (PWE) and the net present value (NPV). With unlimited funds, the project with the largest NPV should be selected; this will also be the one with the lowest PWE. When there is a budget limit, a benefit/cost ratio index is used to help decide on project selection. The next section describes this procedure in more detail.

V. PROJECT SELECTION WITH BUDGET LIMITS

Once the economic analysis has been completed, a decision has to be made as to which, if any, project should be implemented. The decision criterion we develop is based on an incremental benefit/cost ratio defined in the next subsection. Then the conceptual framework for the algorithm is provided and, finally, the actual decision rule is developed.

5.1 Incremental benefit/cost ratios

Figure 5 illustrates graphically the meaning of a benefit/cost ratio (also known as the Long Term Economic Evaluator[6]). On a plot of the total benefit (which is really the net present value plus cost) versus cost, the slope of the line from the origin to the point representing the project equals the benefit/cost ratio. Note that a project with no net benefit would have a benefit/cost ratio of 1.

If we have several mutually exclusive projects, however, the index of interest is the incremental benefit/cost ratio (IBCR). In the algorithm we use, the choice for a given distribution area is generally not between each project and the status quo, but between each project and the next

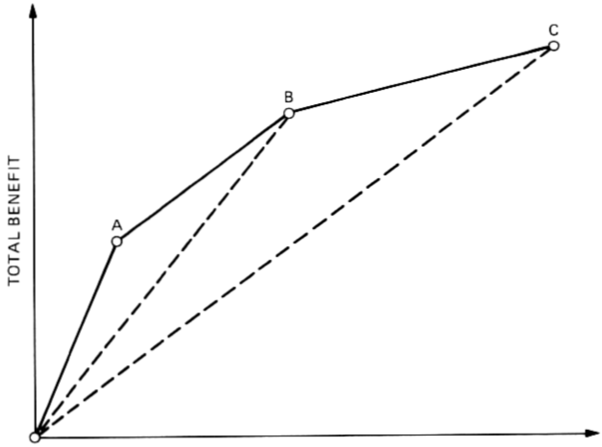

Fig. 5—Incremental benefit/cost ratios are the slopes of the solid lines. Benefit/cost ratios are the slopes of the dashed lines.

least expensive one. Thus, in Fig. 5, the slopes from A to B and B to C (which are the incremental benefit/cost ratios for projects B and C, respectively) are more useful than the slopes from 0 to B and 0 to C.

A further complication in defining the IBCR is that our algorithm requires that for a set of mutually exclusive projects, the IBCRs decrease as the project benefits increase. If this were not the case, then there would be some project, C, with both a better return in benefit per unit incremental cost and a higher total benefit than some other project, B. Since our algorithm attempts to simultaneously maximize both these objectives, project B (which is inferior on both) could clearly be eliminated from consideration. Figure 6 illustrates this case. To determine the incremental benefit/cost ratio for the projects in any distribution area, we eliminate any projects that are inferior on both the above objectives (not in the convex hull) and then calculate the IBCR for the remaining projects. Thus the slope of the line from A to C in Fig. 6 would be the IBCR for project C, and project B would be assigned an IBCR of 0. The IBCR as defined here is an output of the economic analysis models described in Section IV.

5.2 Conceptual framework

The general problem consists of a budgetary entity with a known amount $C_{\max}$ of dollars to be spent. There are N distribution areas in the budgetary entity and in each one there are M possible mutually exclusive investment options (including the status quo). Associated with each option i in each distribution area j are a benefit B_{ij} (given by the net present value of the option) and a cost C_{ij}. The benefit

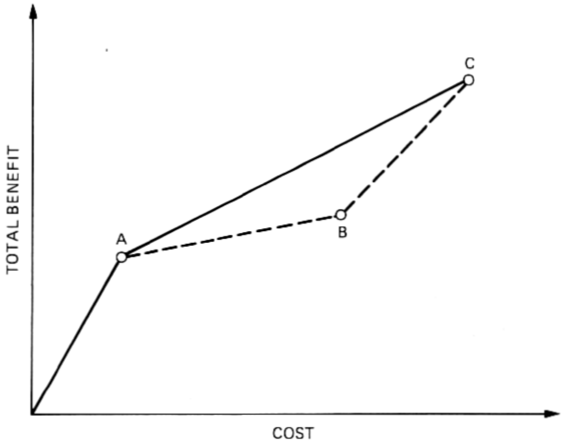

Fig. 6—Project *B* is not in the convex hull and is excluded. The IBCR for project *C* is the slope of the line from *A* to *C*.

maximization problem can then be formulated as:

$$\operatorname*{Max}_{x} \sum_{i=1}^{M} \sum_{j=1}^{N} B_{ij}X_{ij}$$

$$\text{such that } \sum_{i=1}^{M} \sum_{j=1}^{N} C_{ij}X_{ij} \leqslant C_{\max} \qquad (i)$$

$$\sum_{i=1}^{M} X_{ij} \leqslant 1 \quad \text{for each } j \qquad (ii)$$

$$X_{ij} = 0 \text{ or } 1 \quad \text{for all } i \text{ and } j \quad (iii)$$

where

$X_{ij} = 0$ means project i is not implemented in area j.
$X_{ij} = 1$ means project i is implemented in area j.

This problem has been studied extensively in the literature (see, for example, Refs. 7–9) and is known as the $0 - 1$ knapsack problem. There are many solution techniques and heuristics available.

One heuristic which is useful to understand the development of our decision rule is a very simple type of "greedy" algorithm. Although we have not been able to find this algorithm in the literature, it is so simple that it has undoubtedly been used by many others in the past. We assume (for now) that all projects have been identified and evaluated to obtain their benefits, costs, and IBCR.

Step 1: Rank all projects by IBCR from highest to lowest. Discard any projects with IBCR $\leqslant 1.0$.

Step 2: Accept the projects one at a time (from the ranked list) and keep track of the accumulated cost of all accepted projects. If a project being added is from a distribution area where a project has already been accepted, replace the previously accepted project with the current one (to uphold constraint (*ii*) in the above formulation).

Step 3: Stop when accepting a project would cause the accumulated cost to exceed the cost constraint (to uphold constraint (*i*) in the above formulation).

This algorithm provides only an approximate solution to the knapsack problem, but our experience with it shows the approximation to be a good one. The result is closest to the optimal solution when the costs of the individual projects are much smaller than the budget constraint limit, which is the case in our distribution area rehabilitation problem. Table III shows an example with four distribution areas where the cost constraint is $50,000. The notation is such that $C1$ means project type 1 in distribution area C. Note that after $A1$ is added, the next project is $C2$. Since there already is an accepted project in distribution area C, $C2$ replaces $C1$ and the accumulated cost only increases by the difference between $C2$ and $C1$. Next, an attempt to add $D1$ fails as this would cause the accumulated cost to exceed $50,000, and so the algorithm stops. The solution is to implement $A1$, $B1$, $C2$, and to leave the status quo in D.

5.3 Project implementation decision rule

Although this simple procedure will solve the knapsack problem, our decision problem differs from the knapsack formulation in one important way. Although $C_{\max}$ is set for a given year, the projects are evaluated sequentially over the course of the year, so that decisions must be made in January without specific knowledge of the benefits and costs of the projects that will be coming along in the remainder of the year. The next paragraph describes how we resolve this problem.

In our example, the stopping criterion was a limit on the accumulated cost. However, we could just as easily have used a limit on the incremental benefit/cost ratio to determine where to stop. That is, we would add projects one at a time, stopping when the IBCR of some project fell below the specified cutoff. In fact, if our IBCR limit had

Table III—Project selection example

Project	IBCR	Cost	Net Benefit	Cumulative Cost	Cumulative Net Benefit
$C1$	5.69	5377	25243	5377	25243
$B1$	3.57	6082	15625	11459	40868
$A1$	3.36	11327	26688	22786	67556
$C2$	2.33	14345	37130	31754	79443
$D1$	1.64	30912	19883	—	—
$C3$	1.36	29372	42576	—	—
$B2$	1.13	17689	17093	—	—

been anywhere between 1.65 and 2.32 we would have gotten the same answer as when we used the accumulated cost limit of $50,000. For every cost limit there is an equivalent IBCR cutoff. If this cutoff corresponding to the actual budget limit could be determined *a priori*, then as each distribution area is analyzed, the alternative with the highest NPV from among those with an IBCR greater than the cutoff should be selected. From the way the IBCR was defined, the selected project will be the one with the lowest IBCR greater than the cutoff. There is no need for additional information about future projects—all the relevant information is contained in the cutoff IBCR.

Can the cutoff IBCR be obtained? Yes. Based on actual operating costs in a budgetary entity and estimates of the distribution of costs and benefits obtainable from rehabilitation projects, the set of projects for a given year can be simulated before the year begins. The algorithm described above is used to optimize this simulated set of projects for a given budget constraint; the cutoff IBCR for this set is obtained as an output of the optimization. By repeatedly simulating sets of projects and finding the corresponding IBCRs, a good estimate of the actual cutoff IBCR for the given budget constraint can be obtained. This simulation/optimization model can be applied to any size budgetary entity prior to the start of the budget year, to determine the cutoff IBCR. The project implementation decisions for any *DA* in the budgetary entity at any time during the year can then be made by selecting the project with the lowest IBCR greater than the cutoff value.

VI. SUMMARY

This paper has presented a set of models useful for decisions about distribution network rehabilitation. These models help to define several alternative projects for a given high cost distribution area, to economically evaluate these alternatives, and to decide which project should be implemented when there are constraints on available capital expenditures. The models have been combined in a user-oriented system of methods and software and are currently being used by engineers in many Bell System telephone companies.

VII. ACKNOWLEDGMENTS

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