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Feeder Planning Methods for Digital Loop Carrier

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This paper describes three new approaches to planning for digital loop carrier (DLC) in the exchange feeder loop network. Two of these are manual planning methods that are used to determine the most economical technology for satisfying facility shortages along a feeder route. Both are based on the concept of a distance-oriented crossover point beyond which DLC is the economic relief technology. One of the methods uses a global crossover point for all routes, and the other uses a route-specific crossover point. The third approach is a mechanized tool, the Pair Gain Planning (PGP) program. PGP, which is implemented as a module within the existing Bell System loop planning system, first identifies the appropriate technology for relief and then synthesizes a specific DLC implementation plan. A discussion of system performance and projected Bell System applications of the various methods is included.

I. INTRODUCTION

For most of the twentieth century the subscriber loop network has been dominated by cable technology. Although carrier systems have been applied successfully in the rural environment[1] for a number of years, it has only been in the very recent past that carrier has gained a foothold in the high-growth suburban environment. However, this situation is changing rapidly, and it is predicted that by the mid-to-late 1980s 50 percent of all loop growth will be served by digital loop carrier (DLC).[2]

To plan for this growth, a detailed study procedure, the Suburban Pair Gain Planning (SPGP) method, was developed.[3] SPGP was designed for general DLC applications where existing Bell System tools, which were designed for rural applications,[4] were not appropriate. The SPGP procedure uses six tabular forms and the existing Bell System planning tool for conventional cable and structure relief—the Exchange Feeder Route Analysis Program (EFRAP)[5]—to determine a DLC relief plan for a feeder route.

SPGP performs the two planning steps necessary for developing a relief plan. First, it determines the appropriate technology for satisfying facility shortages along a feeder route (i.e., cable or DLC). Second, it selects from the possible alternatives an economic implementation plan for the selected technology. Although not optimal, the method has been shown to produce good relief plans on a wide variety of Bell System feeder routes.

Since SPGP can be very time consuming to perform, three alternative planning systems have recently been developed for Bell System planning applications. Two of these are manual methods that address the technology decision question and provide at least limited evaluation of alternative implementation plans. The third is a mechanized system that performs both the technological decision-making and the implementation plan evaluation steps.

In this paper we describe both the manual and mechanized systems and discuss their applicability and performance. First, we describe the manual methods. Both are based on the concept of a distance-oriented crossover point, a point on a route beyond which DLC is the economic technology for relief. Second, we describe the mechanized system, the Pair Gain Planning (PGP) program. PGP has been developed as a module that is incorporated within the existing EFRAP system. We conclude the paper with a discussion of experience using the various methods and their projected Bell System applications.

II. A TECHNOLOGY DECISION AID—THE CROSSOVER POINT

2.1 Introduction

A simple decision aid is needed to provide telephone company managers with a rapid means of evaluating proposed feeder projects and to provide planning engineers with a simple scale by which they can measure the economic feasibility of any proposal. In the interoffice trunk-planning environment, this need has traditionally been filled by using a length-oriented crossover point. A similar approach for the feeder plant has been developed.

A carrier crossover point is defined as the point on a route beyond which it is generally more economical to relieve shortages with DLC than with cable. In contrast to the trunk network, which is a point-to-point network with uniform shortages and growths, the feeder plant is characterized as being branchy, with multiple gauges and demand points, tapering facilities, and shortages staggered over time. For this reason, it has been historically difficult to develop a crossover point for the feeder with any reliability. A new approach was needed.

The following sections describe two new approaches to the development of a crossover point. The first addresses the more traditional problem of defining a global point applicable for any feeder route in the Bell System. The second develops a crossover point unique to each feeder route, which is generally less than or equal to the global crossover point. The global crossover has the advantage of being simple to apply in comparison with a route-specific point. However, a global crossover cannot be applied to individual routes since it only applies in the aggregate. Hence, both points are needed, one to perform top-down DLC studies, the other for bottom-up studies.

2.2 Global crossover model

A global crossover point can be developed from two approaches: (*i*) from sample statistics of feeder route economics, and (*ii*) from a model representation of a feeder route. The approach described here uses a model representation because we felt a model is more amenable to parametric "what-if" studies. The accuracy of the model can be verified by comparing results with a sample of actual routes. Development of such a model, its results, and verification are reported below.

The Global Crossover Point model presumes an existing two-gauge cable loop from a central office (CO) to a variable end point. Forecasted growth is collected at the end of the loop and at the gauge change point. Relief requirements under both a cable-only and a DLC plan are then determined to meet this growth rate and associated present worth of expenditures (PWE) costs are computed for each plan.

The model provides the means of evaluating the changes in crossover points by determining the PWE differences between an all-cable and a DLC relief solution. The model predicts the impact on the crossover point of relief growth, loop length, and the shortage sequence.

A significant feature of this model is the presence of fine-gauge cable requirements in the DLC plan. This recognizes that any growth between the CO and the crossover point must be served by cable, even in the DLC plan. However, the timing of this "residual cable" is determined by the sequence with which shortages occur along the length of the route. Two different relief-shortage sequences were used in the model, namely: (*i*) CO to field and (*ii*) field to CO. For simplicity, no conduit or other structure costs are assumed in the model. Economic sizing of cables for each growth rate[6] and the most current estimates of costs, inflation rates, and the impact of special services are used.

To determine the crossover point, a PWE is computed for each loop length, growth rate, and relief sequence studied for both a cable and a DLC relief plan. These PWEs can then be plotted against growth for each loop length. The crossover point for any growth rate is the point where the PWE for the cable and DLC relief plans are equal. The locus of such points across different length routes provides the desired function of crossover length versus growth rate.

One advantage of this model is the ease of evaluating the impact of different cost assumptions. By graphically shifting the PWE curves, the impact on the crossover point is quickly determined. For example, a net circuit cost advantage was assumed for provisioning special services on DLC rather than cable, and the crossover points were recalculated. The study also looked at the effect on the crossover point of the intangible advantages of digital technology. Such advantages might include lower overall maintenance costs and possibly additional revenues from new services. Results of this study for a typical model and for the two relief sequences mentioned above are shown in Table I.

These results show that adding intangible DLC effects and special service advantages can move a crossover point distance by about 10 percent. The relief sequence assumption has a much larger impact.

A number of routes previously selected as candidates for DLC application were used to verify the model. The PGP program (see Section III) was then run on each route. No PWE penalty or DLC advantage for special services was assumed. All conduit requirements were assumed to be satisfied. The distance from the CO to the closest PGP target section was determined. (A target section is a feeder section that is more economical to relieve with DLC than with cable.) Since we are interested in near-term crossovers, only targets that required DLC relief in the first five years were selected.

The verification confirmed the Sequence 1 (34 kft) worst-case crossover. Of all routes studied (and several major branches on some routes), none had the closest PGP target section beyond 34 kft. Target sections ranged, however, from 8 kft to 34 kft. This suggests that a global crossover can only be used as an upper bound, as in Sequence 1 above. Therefore, Sequence 2 results are not useful as a global crossover.

Table I—Typical model results

	Nominal Crossover Point	With 10% DLC Advantage	With Special Service Advantage
Relief Sequence 1	34 kft	32 kft	31 kft
Relief Sequence 2	28 kft	26 kft	25 kft

2.3 Prescription design approach for route planning

Prescription design (PD) is a manual planning tool that uses a PWE per line criterion to select one or more route-dependent crossover points. It requires a cable and structure relief plan for the route and a schematic layout showing the PWE for cable and structure (P_i) and the average cumulative growth (g_i) in each feeder section over the study period, as shown in Fig. 1.

PD is intended for a non-EFRAP environment. Therefore, the cable and structure plan for the route is obtained using manual cable and structure sizing curves and economic study tools. These data can be used to develop a route economic profile (the piecewise linear curve in Fig. 2) that indicates the approximate cost per growth line to provide cable and structure relief from any point on the route to the CO.

To obtain a similar economic measure for DLC, a separate calculation is performed. The PWE for providing DLC relief during the same study period for various growth rates is represented by the continuous cost curve in Fig. 2.

The area above the DLC curve depicts where DLC is more economical, and the area below the DLC curve depicts where cable is more economical. The portions of the route profile that fall in this region identify the portions of the feeder route that should be relieved by DLC.

In the example, DLC should be used for relief in route sections 3 and 4. Once the sections for DLC relief are identified, potential remote terminal (RT) sites are located at the field ends and are then timed and sized.

In prescription design, timing and sizing algorithms are provided for two DLC deployment strategies, namely: (*i*) "growth only," where only growth lines are committed to the RT; and (*ii*) "growth plus existing," where growth lines plus some existing lines are cut over to the RT to make pairs available to relieve shortages closer to the CO. The timing and sizing procedure is straightforward with the growth-only strategy, but the algorithm is more complex if a growth plus existing strategy is employed.

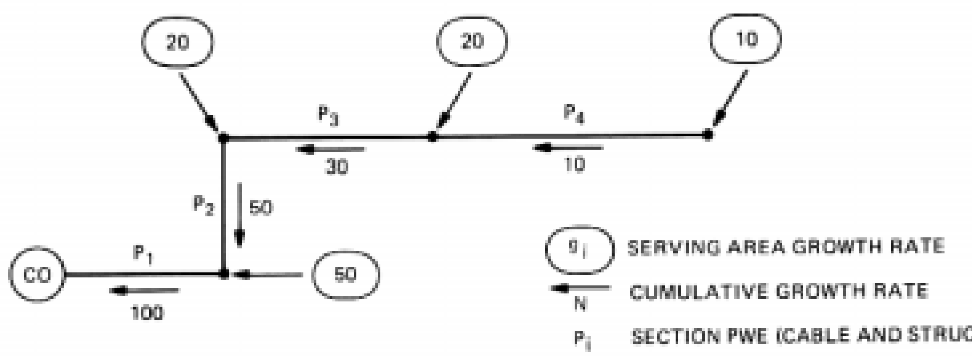

Fig. 1—Route schematic model.

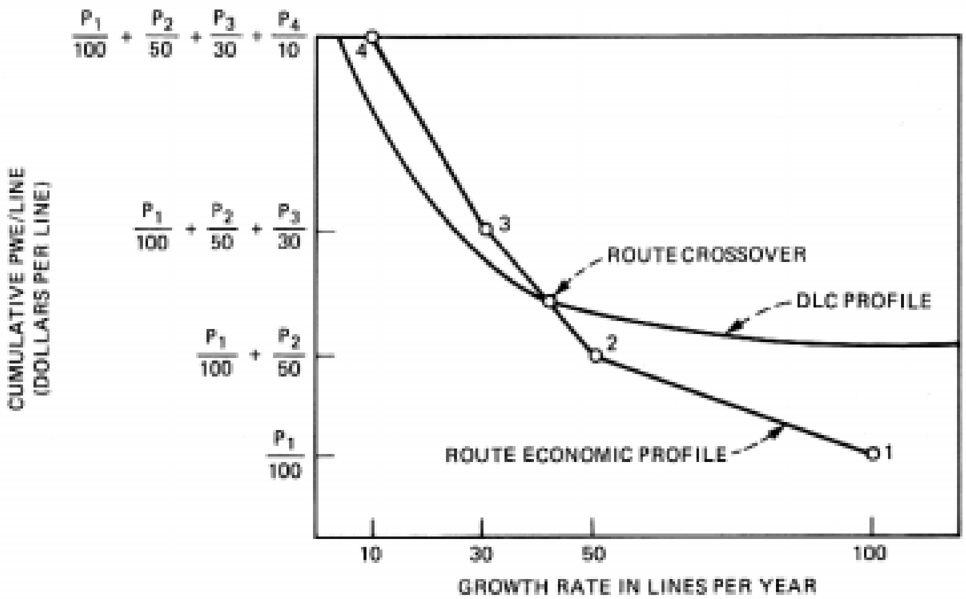

Fig. 2—Prescription design.

III. THE PAIR GAIN PLANNING PROGRAM

3.1 Introduction

The Pair Gain Planning (PGP) program is a new, mechanized planning tool that integrates the technology decision and the selection of the best implementation plan into one mechanized process. After a base EFRAP run, which determines a near optimal all-cable relief plan for a study route, the PGP program uses a network flow model of all existing feeder capacity, proposed cable additions, and potential DLC implementations to find the best combination of cable and carrier to relieve the route, i.e., to make the technology decision. The application of network flow methodology to DLC planning provides near-optimal solutions quickly and efficiently.

After the network flow algorithm has identified sections for DLC relief and a list of potential carrier serving areas (CSAs)[7] for activation, extensions of SPGP algorithms are used to find the theoretical RT sites that will be activated. The program then times the placement of DLC systems at those sites.

As shown in Fig. 3, the PGP program is designed to be an interactive tool. After the program has developed a carrier relief solution, the user is given the option of modifying the solution to establish a relief plan that is most appropriate to the immediate local environment. When the user is satisfied with the solution, the PGP program creates a modified EFRAP input file that reflects the addition of DLC relief on the route so that EFRAP can be used to determine a new cable relief plan that satisfies any residual shortages that are not economic to relieve with DLC.

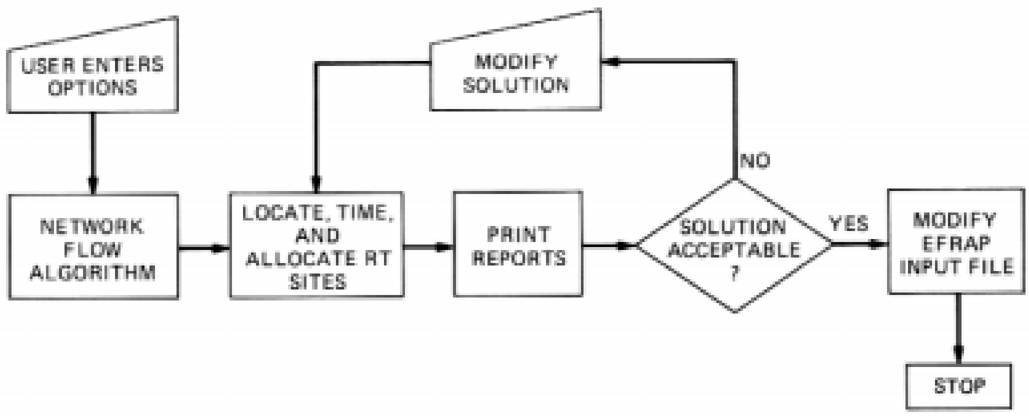

Fig. 3—PGP terminal session.

3.2 Network flow algorithm for target-section selection

The program's first task is to decide which cable and structure placements, as determined by a base EFRAP study, can be relieved more economically with DLC. Generally, it is not economical to use DLC to replace all cables on the route, and the program must locate the economical DLC placements. Since it is not possible to look at each EFRAP section individually to compare cable and DLC alternatives—as EFRAP does in its cable analysis—a global algorithm that examines the entire route at once must be used.

This problem of finding cable relief projects that are more economically relieved with DLC can be solved by a number of algorithms, but the one chosen for the PGP program considers the problem as a minimum-cost network flow problem. The advantages to this approach are that many efficient, easily programmable algorithms have been developed for solving this class of problem[8] and that standard software already existed for this purpose,[9] thus shortening the PGP program development time.

The minimum-cost network flow problem has been applied to a wide range of situations, including transportation of goods, design of pipeline systems, and production scheduling.[8,10,11] The general form of this problem is concerned with the flow of a commodity through a network, which is a directed graph defined by a set of nodes and a set of arcs connecting the nodes. The term "directed" implies that the commodity being studied can flow in only one direction, from a tail node to a head node. For each arc, there is a piecewise linear convex function that defines the cost per unit of flow over this arc as a function of its present flow. Upper and lower bounds of flow are also defined for each arc. Each node is identified as one of three types: (*i*) a supply node, where flow enters the network; (*ii*) a demand node, where flow leaves; or (*iii*) a transshipment node. No storage is permitted at nodes. There is also an objective function that usually minimizes the total cost with flows that satisfy the upper and lower bounds on each arc and preserve the conservation of flow at each node.

In mathematical form, the network is stated by a node-arc incidence matrix[8] **A** (an $I \times J$ matrix if the network has I nodes and J arcs), with elements

$$A_{ij} = \begin{cases} +1 \text{ if arc } j \text{ directed out of node } i, \\ -1 \text{ if arc } j \text{ directed into node } i, \\ \ \ 0 \text{ otherwise.} \end{cases}$$

The problem is then stated as:

$$\min cx$$

$$\text{such that } Ax = r$$

$$1 \leq x \leq u,$$

where

x_j is flow on arc j
u_j is upper bound on arc j
l_j is lower bound on arc j
c_j is cost for arc j (need not be linear in the general case)
r_i is supply (>0) or demand (<0) at node i.

Figure 4 shows a typical EFRAP feeder route layout, with appropriate dummy sections added for the DLC RT site at the field end of section 1106. The network model for the same route is shown in Fig. 5, including additional arcs used to represent existing and future DLC capacity at potential RT sites.

In the PGP program, the objective function is the PWE cost to provide relief to the route. The commodity flowing in the network is the

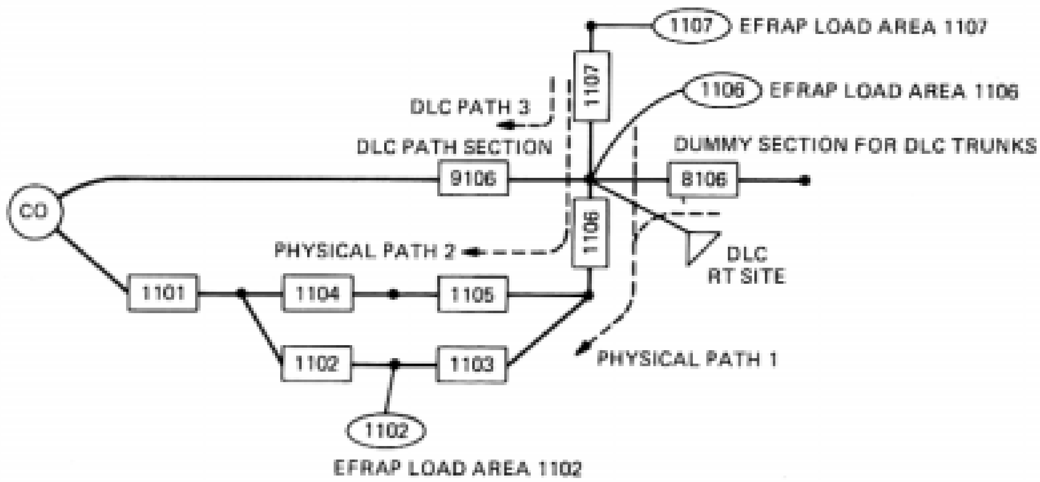

Fig. 4—Typical EFRAP feeder route layout.

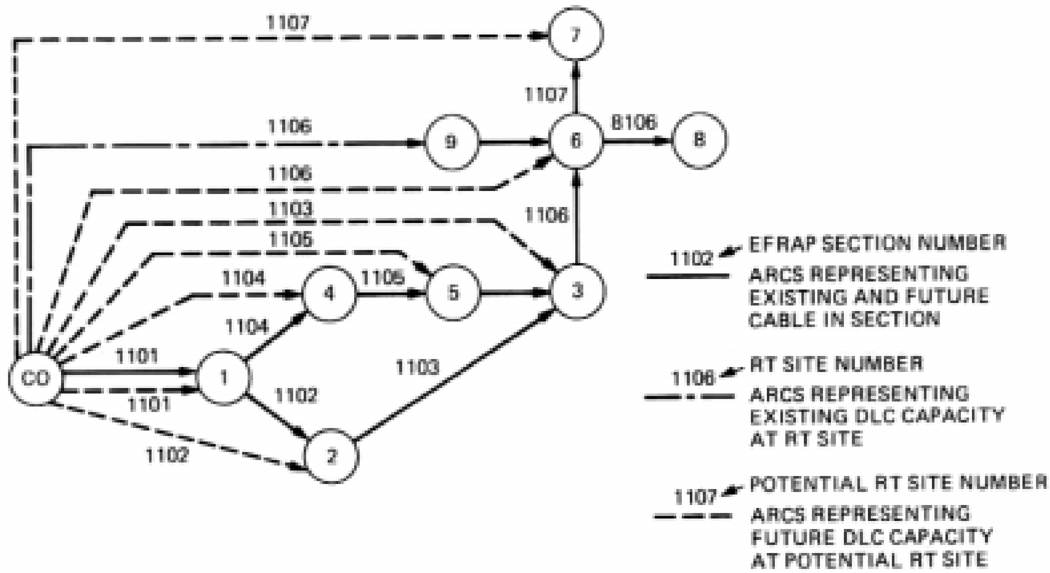

Fig. 5—Network model for typical EFRAP feeder route layout.

demand for loop feeder capacity, both existing and future, which must find its way from the supply node at the CO to the nodes representing the various EFRAP load areas. The demands are the projected requirements for facilities at the end of the study period (typically 20 years). To simplify implementation, this model assumes that all capacity additions and demands for the entire study period occur at the start of the study. The arcs of the model correspond to either (*i*) EFRAP sections with upper bounds representing existing facilities plus future cable additions from the base EFRAP study, or (*ii*) future DLC placements with RT sites at their head nodes. All lower bounds are zero.

The cost function is zero for flows below the existing capacity on arcs representing cables or existing DLC in EFRAP sections. When this value is exceeded, a cost is incurred for the facilities that must be placed to support this flow. On cable arcs, this cost increases linearly using the per-pair cost of the cables placed by EFRAP, starting with the least expensive cable placed during the study period. This procedure yields a convex cost function. The cost function for future DLC arcs uses the DLC cost model described above to obtain a per-unit cost with the common equipment and site costs averaged over a full system.

When the solution to the network problem is obtained, those physical arcs whose flow does not exceed their existing capacity are the target sections where DLC relief should be used since the network flow algorithm has found it more economical to route flow over DLC arcs rather than increase flow through these cable arcs (which is equivalent to placing new cable). Also, those future DLC arcs with positive flows represent potential RT sites, since they indicate places where it is more economical to route flow via DLC. The timing and sizing routines discussed below will select the actual RT sites used in the DLC relief plan from this group.

3.3 Timing and sizing algorithms for RT locations

The procedure of timing and sizing of CSA theoretical RT locations is divided into four parts: (*i*) the selection of RT sites to activate; (*ii*) the determination of the amount of DLC, by time, to be placed at the location; (*iii*) the calculation of the PWE for the electronics placed; and (*iv*) the production of EFRAP data for the residual cable-relief recommendations.

The following algorithm determines the order for activating RT sites. The goal is to eliminate the earliest shortages on the route first. The route is examined for target sections using the EFRAP path model for the route as a tree. The algorithm searches from the CO to the ends of the route for the branch of the tree that has the target sections with the earliest shortage dates. The RT site that will be activated to relieve this branch is the potential RT site that is on the field side of the most recently selected target section and closest to that target section.

The next step is to determine the amount of DLC needed to be placed at this location. The upper bound on the amount of DLC that is useful to place at that location is determined by the number of assigned pairs and growth pairs in the CSA associated with the RT site and with the cutover strategy that will be used for this RT site. The PGP program allows either a cutover strategy, which places all of the pairs in the CSA on DLC or places just enough pairs to assure that no cable will be needed in the target sections affected by this RT site. To be realistic, this upper bound is decremented to allow for DLC trunk pairs. For each year, the PGP program attempts to cover the shortages in the target sections on this branch with the available DLC.

When enough theoretical RT sites are activated to relieve all target sections, DLC placements at the RT sites are used to revise the original EFRAP input data to reflect the DLC systems placed. These data are processed, and the EFRAP program determines the PWE for the residual cable needed for the relief solution. A comparison of the all-cable and the cable-and-DLC plan PWEs then indicates the DLC savings.

3.4 Interactive features

The PGP program is an interactive system. The interactive alternatives are designed to assist the outside plant engineer in forming a DLC relief plan. The user has the choice of calling for an "automatic" solution or of hand-tailoring a solution. Several options are available to modify a solution or to demand a solution. These options create a broad spectrum of possible user control over the program solution. The PGP program interactive options are invoked within a framework that allows the user to save the status of the work and return to that point at a later date.

3.4.1 Automatic run

The PGP program has the capability of producing a DLC relief plan with very little input from the user at the terminal. The user need only specify the run number of the EFRAP data that will be studied for DLC applications and the name of the DLC system that will be studied. From this input, the PGP program will execute an entire DLC study, producing a summary report that includes:

- RT sites activated
- Number of DLC systems placed
- Schedule for DLC placements
- PWE for DLC placements.

The automatic run of the PGP program produces excellent DLC relief plans and is the recommended starting point for developing a final project.

3.4.2 Solution modification

In addition to the brief output reports given at the terminal with the automatic run, the user can request detailed reports for every RT site that is activated. After studying the output reports for a solution, the outside plant engineer might want to more accurately reflect in the study some conditions of the route. This is accomplished by choosing any of the modifying options:

- Change the DLC cutover strategy
- Change the list of target sections being considered for DLC relief
- Change the list of potential RT sites
- Change the list of forbidden RT sites
- Change the DLC data associated with a particular RT site.

3.4.3 Demand solutions

To compare the costs of making working-pair transfers to the costs of activating additional CSAs, the PGP program demand option is available. During the terminal session, the user associates a first year of activation and a DLC cutover strategy with each demanded RT site. All demanded RT sites are activated by the PGP program in the years specified by the user before any other RT sites that may be necessary. For demanded sites, the timing and sizing algorithm will select either a growth-only cutover strategy or one that cuts all assigned-plus-growth pairs in the CSA onto DLC.

3.5 Results

A side-by-side comparison of the PGP program network flow solution with the PD method was conducted using (EFRAP) route data for ten

Bell System routes. The PGP program DLC plus residual cable and structure solutions were generally lower in cost than was the equivalent PD solution; on an average the network flow solution showed a 7-percent lower PWE. (PWE figures do not include rearrangement costs, which were not computed for either study.)

The PGP program is valuable in that the network flow algorithm provides very good starting solutions, and that the interactive options can be used to easily modify the starting solution to satisfy local requirements. During the PGP program field trial, which was conducted in three Bell System operating companies, users evaluated as many as ten alternative relief plans for a single route. Because the PGP program is a mechanized tool, they were able to do this within two or three days, whereas equivalent SPGP studies would have taken over a month of engineering time.

IV. STUDY PROCEDURE SUMMARY

Since the PGP program performs both phases of feeder planning in an integrated fashion with little manual effort, the Bell System has recommended its use as the primary feeder-planning vehicle for DLC. However, global crossover points and PD both have a place in the planner's arsenal.

Global crossover points are still used in project review to rapidly assess the planner's technology decision. As such, they effectively shift the burden of proof to cable on longer routes. The global crossover can also be used to guide the engineer in the interactive portion of PGP studies. Since many implementations of DLC with similar cost are possible on a route, the crossover can guide the planner to the solution that best meets company objectives, while PGP can measure the economic implications.

For those engineering districts that have not yet implemented the prerequisite EFRAP, PD provides an effective interim procedure for planning digital carrier. (Although circumstances are changing quickly, a private 1981 survey showed that about one third of all Bell System engineering districts fell into this category.) The global crossover can be used in combination with PD to split the route into two parts. Only sections between the crossover and the CO need to be evaluated with PD.

V. CONCLUSION

This paper described three tools for studying feeder relief in the digital age. Each tool has advantages and disadvantages, each has its place. There can no longer be a valid excuse for "business as usual" and the placement of metallic cable exclusively. We expect these tools to provide significant stimulus to the advancement of the digital age.

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