Planning studies in telecommunication networks are both for manufacturers and for operating companies powerful methods to evaluate ex ante the possible consequences of a set of strategies chosen in order to face the possible future scenarios: demand evolution, systems capabilities and costs, networks topologies, competition and finance. For manufacturers such evolution has the purpose to decide as sharply as possible which, when and how many products are profitable to be offered to the operating companies in order to maximize the wealth of manufacturer's shareholders.

In order to carry out significant planning studies oriented to such evaluation, it is necessary to rely on some simulation tools describing the future evolution of the network as a function of the chosen strategies and of the future scenarios. Such simulation tools must also include some computation tools able to correlate in an optimal way the output of a certain step or of a certain component of the simulation to the input of subsequent steps or components.

In the first part of this paper we develop the above arguments, and in the second part we describe the algorithm on which the computational tool is based: this algorithm produces a dynamic circuit routing and an assignment optimization. In the third part we give some results in order to illustrate the performances of the computational tool in terms of usability and of trust worthiness/reliability of planning studies.

1. TELECOMMUNICATION NETWORK PLANNING STUDIES

The goal of this paper is to satisfy algorithmic necessity of strategic network studies conducted by manufacturers. Thus it emphasizes the requirements that such studies impose to methodologies, simulation tools, computational tools and algorithms.

The network planning studies may be conducted, for strategical or tactical purposes, by manufacturers or by operating companies or by customers. A strategical network planning study conducted by a manufacturer must take into account the planning behaviour, both strategical and tactical of other participants to the planning game, but must be oriented to the specific objectives of the manufacturer itself. So it may be different from a strategical network planning study conducted by other participants, and also different from a tactical network planning study conducted by the same manufacturer.

The purpose of strategical network studies conducted by a manufacturer is to support the decision about which products must be developed and produced, in which quantity, at which costs, year by year along a rolling period, in order to maximizing the shareholders wealth, taking into account the demand dynamic and the dynamic strategies of the operating companies and of the other manufacturers.

A manufacturer planner must consider the scenarios concerning:
- his own product strategy;
- the product strategies of other manufacturers;
- the operating companies strategies;
- the customers service demand.

The planner is aware that the interaction among these four scenarios is very complex and knows the different degrees of information responsibility and decision power about the different scenarios. These considerations envisage a rather complex feedback decision system which in turn depends on the decisions themselves.

From the system engineering point of view this is still a huge work to be done. To this purpose a synthesis is needed among the methods of industrial dynamic (1), game theory (2), program evaluation (3), hierarchical planning (4) and methods for modeling strategic-financial planning processes (5).

Whatever synthesis will be reached, the planner will still face the following considerations referring to:
1) the demand scenarios, which can be considered under the point of view of the convolution of the "topological" and the "quality" (i.e. type of required services) distributions;
2) the systems scenarios (i.e. the life cycle costs of systems, the learning, technology progress and economies of scale effects, etc.);
3) the financial scenarios;
4) the constraints scenarios, such as (a) network state already predetermined, (b) maximum budget that can be invested; (c) maximum number of circuits that can be produced for each system;
5) the decision processes scenario (e.g. timing of decisions, such as producing, investing, installing, price/cost revisioning etc.);
6) the implementation processes scenario (e.g. how to schedule the various phases of an installation);
7) the value assigned by the planner to the output variables (e.g. percentage of penetration of a system, level of economies of scale achievable by using a system, etc.).
The factors on which the planner has a final decision power are considered as parameters (P), the factors on which the planner has no decision power are considered as variables (V), the factors on which the planner has a conditioned power are considered as relaxed variables (RV). Fig. 1.2 shows a possible decision power scenario. A picture of a possible view of the planning process for the manufacturer planner is given in fig. 1.2.

The complexity of strategical planning studies is rather evident, even though considerable efforts are being made for simplifying it. To this purpose, a good policy is that of ranking the different factors according to the level of criticalness, so that most efforts can be devoted to the most critical factors. Nevertheless, the computational tools must be as efficient as possible. Moreover, to obtain reliable and trustworthy results the computational tools must be effective in discriminating among different alternatives. Therefore a good compromise has to be found between complexity and efficiency on one side and criticalness, effectualness, trustworthiness and reliability on the other. This compromise can be achieved by modelling the real world at three different levels. Two of them, the industrial dynamic level and the dynamic optimization computational tool level are explicitly shown in fig. 1.2. The components of the algorithmic level act as operators for the computational tools. All the computational tools necessary for the industrial dynamic model can be obtained using only two types of optimization algorithms: one for optimal dynamic routing which is also an optimal disaggregation algorithms of primary demand in demands for single capacities, and another for optimal dynamic assignment of demand for single capacities to alternative systems. These two fundamental algorithms are tied together in the algorithm, used by a dynamic optimization computational tool for transmission planning purpose, which is described in the following section. Our analysis on the nature of the problem of strategical planning and its solution have been deeply influenced by the studies of Hall(6), Melody(7), Yaged(8), Ellis(9) and recently of Com(10), Bell Northern(11), CNET(12), Bell Laboratories(13).

In particular our algorithm is an extension of Yaged algorithm(14). In fact it can use both the initial costs of the installation of the transmission media, and the life cycle events functions. It is possible to consider the purchase, installation costs and the costs due to maintenance (depending upon the MTTR and MTBF). The unavailability costs are also considered (costs due to traffic losses, deriving from MTTR, MTBF of major paths and loss per circuit out of order). Moreover, the different levels of investments are considered separately: infrastructures (e.g. radio stations, coaxial cable ducts, etc.), carriers (e.g. coaxial cables, antennas, etc.) and transmission systems (electronic equipments).

Furthermore, it is possible to consider the costs of the transmission media in the nodes, distinguishing between the case where all the circuits are demultiplexed at the node to the case where some of them pass over it only geographically.

Finally the model is able to consider the obsolescence of the transmission medium.

2. THE ALGORITHM

2.1 The model

The dynamic planning problem for a transmission network may be modelled as follows. Assume we are given the period which we have to plan in number of years and for each year the new circuit requirements between every pair of nodes of the network. Moreover we assume to know the various costs and the capacities of the possible transmission links which may be installed during the period. It is required to find for each year, the routing of the new circuit requirements, and the new installation needed to satisfy the global requirements with a minimum total cost, taking into account its actualization, that is the influence of a fixed annual interest on later expenditures. Therefore we may formulate the problem as follows.

Given
- the planning period
- the circuit requirements
- costs and capacities of possible installations
- sequence of installations
- circuit requirements
- capacity constraints

minimize
- the total actualized cost over
- routing

satisfying
- costs vs. number of circuits, which is obtainable from the input data once the length of the direct connection between i and j is known. This allows a greater closeness to reality than the usual (8) linearized cost-length model. The function cost-number of circuits comprehends:
- a first installation cost CF
- a maintenance cost CM

Finally the model is able to consider the obsolescence of the transmission medium.
- a unavailability cost $C_I$.

For what concerns $C_I$, two possibilities are considered: a linear model and a staircase model. The first is easier to handle but it is more accurate in high capacity long-distance networks. The second model is more detailed and is most suitable in the case of a limited amount of possible installations.

The maintenance cost $CM$ is a fixed annual account which has to be considered for the whole life of the corresponding carrier or system. It can incorporate the sinking funds cost. The unavailability cost $C_I$, taking into account the cost due to failure of a carrier or system, is also a fixed amount per year and per circuit. As already mentioned, all costs have to be actualized, with respect to the first year of the planning period. This means that when the corresponding expenditures are dated at year $t$, their costs - being the annual interest rate.

Note that since we consider only cost functions of the number of circuits and systems, respectively.

The dynamic planning can now be stated as follows. Determine $Z$, $w_m$, $y_{km}(t)$ so that

$$
Z = \min_{k,m} \sum_{t=1}^{T} w_m C_{km}(t,y_{km}(t)) \quad \text{s.t.}
$$

with the following constraints:

1. $y_{km}(t) \geq 0$ for $m,k \in \mathbb{N}$.
2. $y_{km}(t) \leq c_{pk,m}$ or $H_{km} \leq c_{pk,m}$
3. $y_{km}(t) \leq \sum_{h=1}^{H} c_{sh}(\pi_{km})$
4. $y_{km}(t) = \sum_{h=1}^{H} c_{sh}(\pi_{km})$
5. $y_{km}(t) = 0$ for $t > T_k,m$
6. $y_{km}(t) = 0$ for $m,k \notin t > T_k,m$
7. $y_{km}(t) = 0$ for $t > T_k,m$
8. $y_{km}(t) = 0$ for $m,k \notin t > T_k,m$
9. $y_{km}(t) = 0$ for $m,k \notin t > T_k,m$
10. $y_{km}(t) = 0$ for $m,k \notin t > T_k,m$
11. $y_{km}(t) = 0$ for $m,k \notin t > T_k,m$

2.2 Basic Algorithm

The problem previously stated is too complex
to be solved by an exact method and therefore we make use of a heuristic algorithm, as for the problems treated in (14,15,16). This algorithm reaches a local optimum by means of the iterative process shown in fig. 2.1, where TASK 1 performs the routing of the circuit requirements and TASK 2 provides an optimal planning sequence for each link. The interaction between the routing and the planning sequence is taken into account by a feedback, performed by TASK 3, which recomputes the link costs according to the results of TASK 2. For ease of exposition, but without loss of generality, we make the following assumptions:

a) Link costs coincide with the installation costs;
b) The life of carriers and systems in longer than T;
c) each traffic requirement is non-negative and is routed on a single path;
d) no more than one installation per year is allowed on each link.

Furthermore, in order to utilize a dynamic programming technique in TASK 2, we assume to add circuits to a system (systems to a carrier) only before the next system (carrier) installation.

**TASK 1 (Routing)**

The goal of this task is to route the circuit requirements \( r_{ij}(t) \) between each pair of nodes and to provide the demand of new circuits \( d_m(.) \) from \( t_0 \) to \( t \), given that system \( s \) has been installed on each link.

The routing is performed along the shortest paths between each pair of nodes which can be efficiently obtained by simple algorithms (17,18,19).

**TASK 2 (Link development)**

The goal of this task is to compute for each link \( m \) the optimum sequence of installations \( \omega_m \). This is obtained by means of a two-level dynamic programming method, whereby the development of each transmission link is optimized both in terms of carriers and of systems.

Let

\[
Z^*(t) = \text{minimum planning cost of a link from } t_0 \text{ to } t; \quad f_p(t_0,t) = \text{minimum planning cost to satisfy the demand } d_m(.) \text{ from } t_0 \text{ to } t, \text{ given that carrier } p \text{ has been installed at } t_0 \text{ and no other carrier installation occurs in } t_0,t;\]

Therefore

\[
Z^*(t) = \min_{t_0, 0 \leq t_0 \leq t} \left( Z^*(t_0-1) + \min_{p \in P(t_0)} f_p(t_0,t) \right) \quad (12)
\]

where \( Z^*(-1) = 0 \) and \( P(t_0) \) is the set of carriers available at \( t_0 \).

As far as the computation of \( f_p(t_0,t) \) is concerned, we utilize a second level of dynamic programming, which is implemented differently according to whether the carrier capacity is in number of circuits or of systems.

In the first case we have

\[
f_p(t_0,t) = \begin{cases} 
0 & \text{if } d_m(.) > C_p \\
\min_{t_0, 0 \leq t_0 \leq t} \left( f_p(t_0,t-1) + \min_{s \in S_p(t)} f_s(s,p,t) \right) & \text{otherwise} \end{cases} \quad (13)
\]

where \( f_p(t_0,t-1) = \sum_{p \in P} A_p, S_p(t) \) is the set of systems available in \( t_0 \) for carrier \( p \), and \( f_s(s,p,t) \) is the minimum planning cost to satisfy \( d_m(.) \) from \( \tau \) to \( t \), given that system \( s \) has been installed on carrier \( p \) in \( \tau \) and no other system installation occurs in \( \tau, t \). Therefore

\[
f_s(p,\tau,t) = \begin{cases} 
Y(t) - Y(\tau-1) \geq C_p & \text{if } Y(t) - Y(\tau-1) > C_p \\
0 & \text{otherwise} \end{cases} \quad (14)
\]

where \( C_p \) and \( a_p \) are respectively the capacity and the installation cost of system \( s \) on carrier \( p \).

If the carrier capacity is in terms of systems, we define a directed graph as follows. \( T \) contains a "source" node \( s_0 = (t_0) \), a "sink" node \( s_f = (t) \) and a node \( s_k = (t_k) \) for each \( t_k \), with \( t_0 < t_k < t \). \( T \) contains an edge \((s_h,s_k)\) iff \( t_h < t_k \). If we let

\[
\lambda_{hk} = \min_{s \in S_p(t_h)} f_s(p,t_h,t_k)
\]

be the length of edge \((s_h,s_k)\), \( f_p(t_0,t) \) is the minimum length of a path in \( T \) from \( s_0 \) to \( s_f \) having no more than \( C \) edges. This path can be efficiently found in time proportional to \( C(t-t_0)^2 \) by Bellmann-Ford algorithm, as described in (20).

**TASK 3 (Link costs computation)**

The values of the costs \( \hat{c}_m(t) \) for each link \( m \) are crucial for improving the convergence speed of the method. Similarly as in (14), such costs have been obtained by equating the total actual cost to \( C_m(t) \) times the present value of the number of circuits. Specifically

\[
FP(t_{k,m},t) = \sum_{i=t_{k,m}}^{t} w_i d_m(\tau) \quad (20)
\]

where \( w_\tau \) is the set of carriers available at \( t_0 \).
areas having univocal numbering with an average extension of about 1300 km² and serving about 50000 subscribers.

During these studies some improvements at the computational tool level have been introduced. In order to test the validity of the algorithm and the computational tools two types of experiment have been carried out. They have been designed as simple as possible, to allow a trustworthy judgement.

The first experiment has been designed in order to show the power of the algorithm in determining the optimal evolution of the circuit routing (DRPE = Dynamic Routing Power Experiment). The second one has been designed to obtain the optimal investments/installations sequence to satisfy the demand (DIEP = Dynamic Investment Power Experiment).

For each test in both experiments the appropriate choice of the scenarios is crucial in order to evidence the syndromes of the planning study. In particular the characteristics of transmission systems, the years of their availability and the structure of their costs have been chosen with this aim, even if not too far from the real values. In the following we illustrate the results referring to a particular scenario, chosen among those considered in the extensive analysis so far carried out.

For both experiments the availability scenario of the carriers and of the systems in the considered period (20 years) is illustrated in Table 3.1. The upper part shows the carrier scenario: 5 carriers are available for all the links only during the study period and $Y_f$ is equal to n for all these carriers, but is not necessary for carriers A and B.

The second one has been designed to obtain the optimal evolution of the circuit routing (DRPE = Dynamic Routing Power Experiment). The experiment consists in finding the optimal investment/installation sequence corresponding to the scenario described in Table 3.1, for different values of the availability parameter n, the length of the link $\xi$ and of money cost $i_r$ and for different dynamics of demand. The results of the experiment are given by a sequence of tables (one for each year) which show the number of circuits assigned up to that year to each of the carriersystem pairs. In order to synthetize the results referring to specific values of n, $\xi$ and $i_r$, we have drawn maps such as that shown in fig. 3.7, which has to be read as follows: expressing the demand dynamic by an equivalent time-independent incremental demand $\Delta c$, the actual demand will be satisfied up to time $t_B$ by investments of type A, up to time $t_B$ by investments of type B etc.

Such maps put into evidence the dynamic thresholds between different types of investments, so that they are called Dynamic Threshold Maps (DTM).

References

(1) J.W. Forrester, "Industrial dynamics" M.I.T. Press 1961

(2) T. Basar, G. Oldser, Dynamic Non Cooperative Game Theory Academic Press 1982


### NETWORK SCENARIO

- **NETWORK STATE CONSTRAINTS**
  - Life cycle costs dependent from manufacturers' operating companies activities
  - Learning effect dependent etc.
  - Economies of scale effects

### SERVICE CONSTRAINTS

- Applied to Telecommunications System Design, Electrical Communication, Vol. 50, N. 1, 1975

### DECISION PROCESSES

- Production constraints: From Initiation to Implementation Business: From Initiation to Implementation

### IMPLEMENTATION PROCESSES

- Installation: From Initiation to Implementation Business: From Initiation to Implementation

### BUDGET CONSTRAINTS

- Production constraints: From Initiation to Implementation Business: From Initiation to Implementation

---

#### FIG. 1.1 POSSIBLE DECISION POWER SCENARIO

Legend:

- LCC M/OC = Life cycle costs dependent from manufacturers' operating companies activities
- LE M/OC = Learning effect dependent etc.
- TPE = Technology progress effects
- ESE = Economies of scale effects

---

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#### DEMAND SCENARIO

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#### NETWORK STATE CONSTRAINTS

| V | RV | V | V |

#### BUDGET CONSTRAINTS

| RV | V | RV | V |

#### PRODUCTION CONSTRAINTS

| V | P | RV | V |

#### SERVICE CONSTRAINTS

| RV | RV | V |

#### DECISION PROCESSES

| V | RV | P | V |

#### IMPLEMENTATION PROCESSES

| V | RV | P | V |

---

### REFERENCES

Fig. 1.2 Industrial Dynamic Model of Strategic Planning Process: manufacturers' point of view

Tab. 3.1 System scenario

<table>
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<tr>
<th>L</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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</table>

Legend:
- L Carrier/system label
- C Carrier/system capacity in systems/circuits
- YI First year of availability
- YF Last year of availability
- N An year 20

Fig. 2.1 Iterative process on which the algorithm is based

Session 2.1
Fig. 3.1 Network scenario: network topology
(length of the link)

Fig. 3.2 Network scenario: length of the links

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<tr>
<th>RELATION</th>
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Fig. 3.3 Network scenario: values of residual capacities and obsolescence for the carriers A and B

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<table>
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Fig. 3.4 Demand scenario

Fig. 3.5 Results of Dynamic Routing Power Experiment: circuits are routed on the link symbolized by
- during the entire period
- only till the 5th year
- only till the 10th year
- only till the 5th year and after the 10th year
Fig. 3.6 Results of Dynamic Routing Power Experiment: the symbol \( \square \) shows in the first column the year of investment; in the second the carrier installed; in the third the system installed.

Fig. 3.7 Illustration of Dynamic Threshold Map concepts.

Table 3.3 Results for Dynamic Investment Power Experiments for the model of demand growth, link length, interest rate and system availability parameter \( n \) are shown in Dynamic Threshold Map of corresponding figures.
### Errata Session 2.1 Paper #6

#### Section 9

<table>
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The figures on the left refer to part of the cost only viz. $\sum q_i n_i$ (see 10) whereas the total cost is given on the right.
Summary of Questions/Answers

Date: 10 June 1983
Session: 2.1
Paper: 5

Q.1 (J. Lee)

Your use of the dynamic threshold map is most interesting. The results so presented seem to be independent of current installed capacity and current installed technology. How does this impact investment decisions.

A.1 (Camerini et al.)

The dynamic threshold maps presented in the paper are all related to the same network state constraints scenario (i.e., same initial installed capacities and same initial installed technologies).

We have also DTM for different network state constraint scenarios, that shows an influence of constraints as strong as the values of residual capacities are little and the obsolescence year is distant.

In a certain way this can be seen confronting fig. 3.8 and 3.9 that shows the influence of 2 years delay in the system availability.