HERMES PROJECT

SECOND PART

FINAL REPORT ON THE DEVELOPMENT OF THE HERMES III MODEL

prepared for the

NATIONAL TELECOMMUNICATIONS BRANCH

DEPARTMENT OF COMMUNICATIONS

by

LE LABORATOIRE D'ECONOMETRIE
de L'UNIVERSITE LAVAL

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FORWARD

This report concerns the description of an Operations Research model designed to examine certain economic aspects of the planning of telecommunications networks expansion with particular reference to inter-toll switching and transmission facilities. It does not profess to be a comprehensive treatise on the technical engineering principles of telephone, particularly in an operational context.

This report replaces the Interim Report of November 1972. It should be noted that whereas the Interim Report's rôle was, to a large extent, to formulate the problem and explain the approach adopted, the present report is essentially a technical document addressing itself to a necessarily more restricted audience and assuming knowledge both of the erlier project developments and the characteristics of the Canadian Inter-toll telecommunications network. A good deal of viatl information is contained in the appendicies. A User's Manual will complete the Hermes III package, however such a manual is not scheduled until a later phase of the project.

ABSTRACT

This Report contains a description of the Hermes III Model. This is a planning model dealing with expansion of interurban telecommunications capacity. This model, designed for the Federal Department of Communications, is a substantially extended version of the Models Hermes I and Hermes II designed and developed previously. One of the original features of these earlier models was that they handled cost functions which were step functions.

The fundamental difference consists in that the Hermes III Model starts from an earlier stage than its predecessors: data concerning traffic. One is thus forced to handle the switching network as well as the facilities network of interurban telecommunications. One of the essential characteristics of the Hermes III Model is that it handles these two networks simultaneously and not in succession, as in the conventional approach which is still in general use.

The methodology is chiefly that of linear mixed-integer programming, of network theory, of certain simulation techniques and of the economic theory of investment decisions.

RESUME

Ce rapport décrit le modèle Hermes III. C'est un modèle de planification de l'expansion de la capacité des télécommunications interurbaines. Ce modèle, conçu pour le Ministère fédéral des Communications, est une extension substantielle des deux modèles Hermes I et Hermes II formulés et développés précédemment. Un des traits saillants originaux de ces trois modèles est leur prise en compte de fonctions de coûts qui sont des fonctions en escalier.

La différence essentielle entre le modèle Hermes III et ses deux prédécesseurs consiste en ce que ce dernier part d'une étape antérieure, c'est à dire, les données concernants le trafic. On est ainsi amené à traiter aussi bien le réseau de commutation que le réseau physique des télécommunications interurbaines. Une des caractéristiques originales importantes du modèle Hermes III est qu'il traite ces deux réseaux simultanément et non pas successivement comme cela se fait dans l'approche conventionnelle généralement employée.

La méthodologie employée est principalement la programmation linéaire partiellement en nombres entiers, la théorie des graphes, certaines techniques de simulation et la théorie des choix d'investissements.

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1. INTRODUCTION

The first part of the Hermes Project resulted in the development of a model named Hermes I, the Software and Users Manual for Hermes I, and the extension of the model to include some more realistic features. This latter, known as Hermes II, was more efficient and sophisticated than Hermes I upon which it was based.

The second part of the Hermes Project, from April 15, 1972 to March 31, 1973 had, as its objectives:

a) completion of the work begun on Hermes II in order to obtain a realistic and totally operational model, without increasing the number of geographic nodes which comprised the model as of March 31, 1972

b) the development from Hermes II of a network model of transmission and switching, named Hermes III, capable of satisfying a given demand at minimum cost and taking into account :

   i) The trade-off existing between the costs of transmission and the costs of switching using a simulation approach.

   ii) The optimal allocation of circuits by assigned quality of service (PO1, PO2, PO3, ... Etc.); or in other words, of the optimal breakdown of circuits with respect to first choice circuits and to last choice circuits.

   iii) The reliability of the network.

The completion of the work on Hermes II was the subject of an earlier report and a Hermes II Users' Manual. The purpose of this report then is to present the Hermes III model as described in sub-section "b" above.

The development of the Hermes III model was carried out by a project team consisting of T. Matuszewski, C. Autin and B. Paquet from le Laboratoire d'économétrie de l'Université Laval and R. Riendeau, D. Geller and M. Hupé from Sorès Inc. The Department of Communications was represented primarily by J. Cline and J. Guerin.

1.1 Relationship with the preceding phases

The first phase of the Hermes project resulted in the development of a transmission facilities expansion model called Hermes I and its development to include some more realistic fratures and greater computational efficiencies in Hermes II.

In essence, the capabilities of the Hermes I and II models lay in the development of the least cost facilities expansion program for a given transmission facilities network. That is, problems were posed by specifying one or more pairs of nodes in the facilities network between which one or more additional broad band channels were required. The model would then choose the least cost means of providing these additional facilities.

In the development of Hermes I and II, a new approach was taken to the solution of such problems based on the use of mixed-integer linear programming.

The approach proved to be very useful in the treatment of some aspects of the problems which more traditional approaches were incapable of handling.

While the formulation of Hermes III must go beyond that of the earlier models and consider as well the routing of traffic in the switching network, our understanding remains that the primary concern is with an optimal capacity expansion program for the facilities network. Accordingly, the work of the first phase and the formulations of Hermes I and II provide valuable background and a base upon which to build the Hermes III Model. A complete description of the formulations of Hermes I and II and their various components are the subject of a lengthy series of reports and working papers on the Hermes project. In preparing this report, frequent reference is made to the reports and working papers of earlier phases and some familiarity with the concepts presented in these reports is expected on the part of the reader.

1.2 Objectives of the Hermes Project

The terms of reference prepared by the Department of Communication, Network Development Group, specify the following requirements :

The development of a network model of transmission and switching capable of satisfying a given demand at minimum cost and taking into account :

- The trade-off between transmission and switching costs.
- The optimal allocation of circuits by assigned grade of service.
- The reliability of the network.

The main objective of the study was to develop a model of a hypothetical telecommunications network consisting of less than sixty nodes for a given network hierarchical structure, this model would be capable of determining the number of circuits in high usage groups, full groups, and alternate groups which would satisfy a defined grade of service at minimum total annual costs While the network used to develop the model is hypothetical, it is a representative abstraction of the Canadian interurban telecommunications network of the Atlantic provinces and displays as many of its characteristics as possible.

Again, as was the case with Hermes I and II, a new approach to the modelling of a telecommunications network was necessary to produce a tool which is capable of addressing questions of policy as opposed to the operational type of problems faced by the utilities. In the Hermes III Model, for example, switching and transmission facilities are treated simultaneously. As well, in this model the marginal cost ratio between high usage and final/full groups is not accepted a priori, as is the current practice in the traditional approach.

1.3 Contents of the report

The specifications of the final report as laid down in the Statement of Work appended to the contract call for:

- an exhaustive description of the formulation of Hermes III, by then operational
- a set of recommendations concerning the perfection of Hermes III

The report is organized accordingly. Sections 2 and 3 of the report give an exhaustive description of the Hermes III formulation. Section 2 deals primarily with the theory of the overall methodology. Section 3 deals with each of the major components of Hermes III in turn.

While the model uses rigorous optimization techniques in developing solutions, it is clear that because of certain important non-convexities which result in combinatorial problems affecting problem size, some aspects of the problem cannot be so treated. Section 4 of the report deals with the uses of model and the methodology whereby some of these problems can be avoided.

Section 5 of the report deals with possible extensions of the methodology that is a set of recommendations concerning the perfecting of Hermes III. It will be noted that although the handling of "enlarged netowrks" (a concept allowing to take account of the coexistence of different carriers and/or of different types of facilities, such as micro-waves and the coaxial cable) had been originally considered as a possible extension and given only a summary treatment (see the terms of the reference of the phase April 1972 - March 1973.) it was decided to incorporate fully this feature into the Hermes III model. As the work proceeded it became clear to us that leaving this major refinement to a future stage would have involved a duplication of effort and hence obviously a higher overall cost and would have of course resulted in Hermes III so much less realistic.

2. FORMULATION OF HERMES III

The formulation contained herein represents a new approach to the solution of telecommunications network problems. This approach was adapted in response to the need to examine certain aspects of telecommunications network associated with policy and regulatory functions. It is based on the use of mixed-integer linear programming and differs from the conventional approach to network analysis in several important areas. One of the more important of these is in the handling of non-linear cost functions. To describe the investments in facilities, step cost functions are used and these functions show a tendency to decreasing average costs. Another important difference is in the simultaneous handling of the switching network as a whole rather than suboptimization by treating successive triangles of the network. A third difference is in the simultaneous handling of the switching and transimssion networks. The model thus contains several important breakthroughs in the existing methodology. It is laso, to our knowledge, the first model of this broad category and this size designed expressly to serve the needs of a regulatory agency and not those of the carriers.

2.1 General remarks on the nature of the problem

The formulation of Hermes III uses as a base, the approcah and methodology developed for Hermes I and II which are basically models to compute facilities expansion cost given demand increases from point to point, these demands increases being expressed in number of channels. However, the starting point of Hermes III is, now, at the level of the increased charges from point to point with the possibility of creating high usage (H.U.) and full groups (F.G.). The ways in which traffic could flow under various hypothetical conditions of existence for the H.U. and the F.G. and given the grade of service must be established and translated into a set of alternative switching and transmission facilities increases. The least cost facilities expansion program must then be found, given a set of constraints on such things as authorized paths in the physical network, survivability and total cost. The optimization problem just mentioned can be solved again with a different set of parameters and networks initial states, therefore Hermes III can be viewed as a simulation model.

2.2 Description of the model

We will first clarify the concepts of switching and transmission facilities networks. Then we will describe the functions of the modules CHARGE and CADUCEE III and finally we will describe the module TRANCHE III.

2.2.1 Switching network

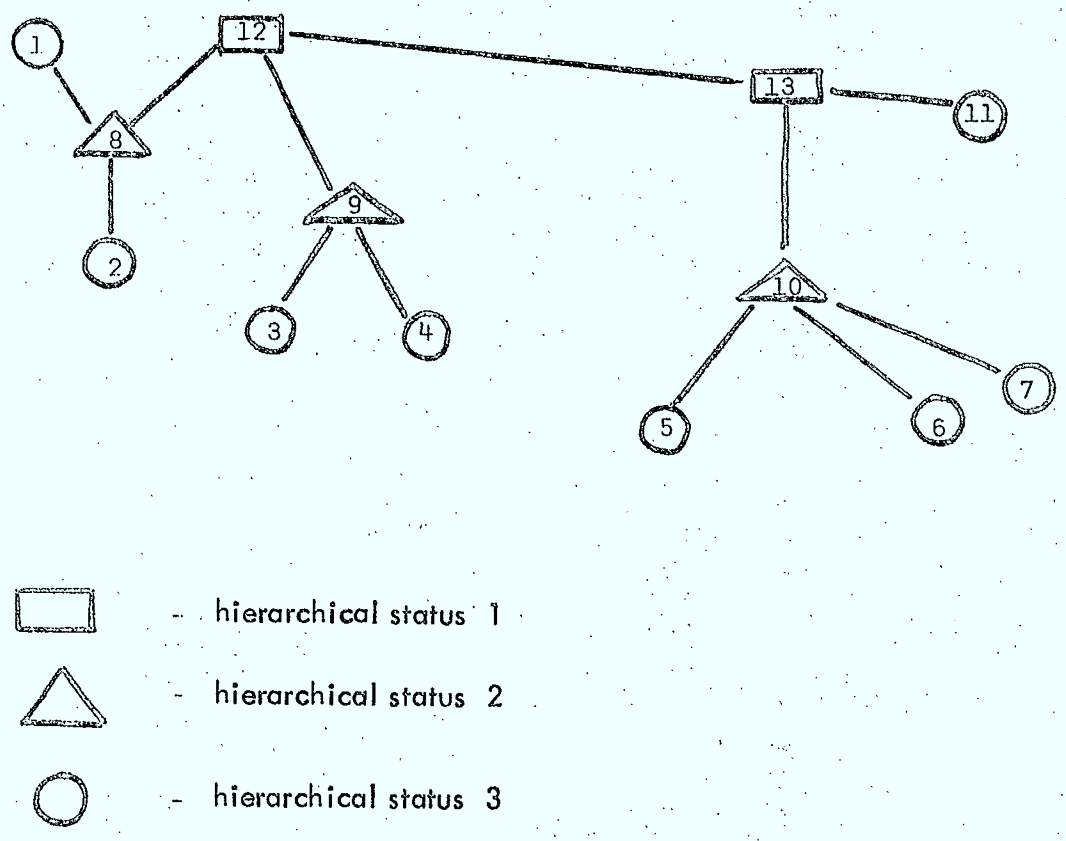
For purposes of the Hermes III model, the term "switching network" means a graph used to describe the paths along which calls may be routed between any two points. This is an artificial "network" not having necessarily any direct physical counterpart.

In the model, local switching is not included. It is to be noted that in drawing this graph, one is concerned with only those points where switching is required. Let us consider a hypothetical telecommunications network containing thirteen demand points. Figure 1 illustrates a basic final tree corresponding to the thirteen demand points. It must be noted that, if there are more than two Status 1 switching nodes, a cycle inevitably appears and the graph is no longer strictly speaking a tree.

This fact should be borne in mind wherever we refer to a basic final tree in this report. A further assumption is that switching machines are installed in demand points only. (In other words, in our hypothetical network, there are no pure switching nodes but such a node amounts to zero original point to point demand and thus can be readily handled by Hermes III without any modification of its formulation or of the corresponding software.)

FIGURE 1

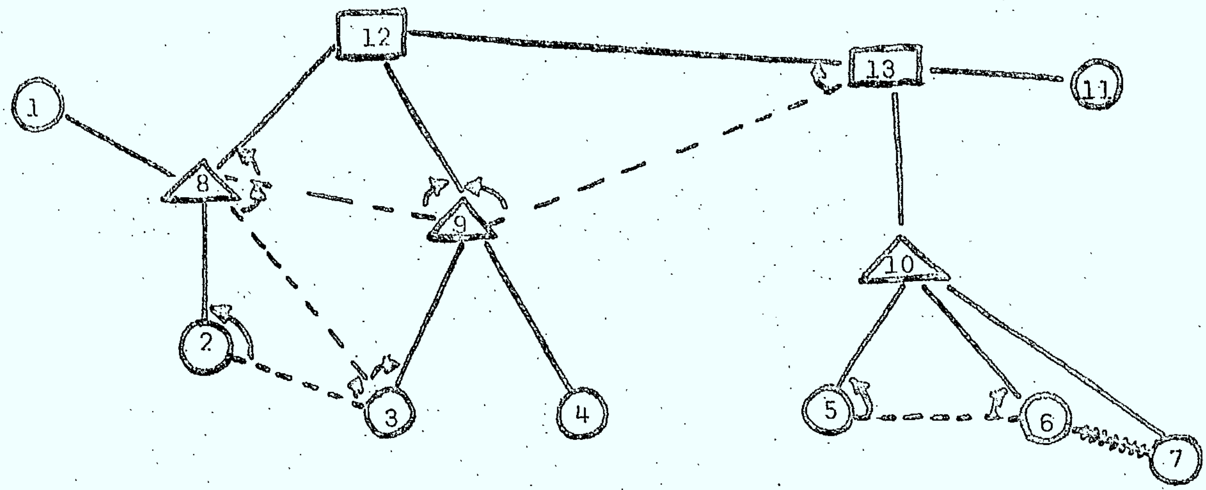
Basic final tree



Therefore the switching network shown in Figure 2 is made up of a basic final tree with the accompanying hierarchical status of each node, the final group connecting these nodes, the full groups and the H.U. groups. It is to be remembered that a given set of nodes with hierarchical status assigned may correspond to several different basic trees because homing rules could vary.

FIGURE 2

Switching network



final groups

H.U. groups

full groups

Let us identify the path followed by a given call by a sequence of nodes through which it passes.

According to the switching network and to the usual overflow and routing rules, a call from node 3 to node 4 can only follow the path 3-9-4. (The numbers underlined indicate that switching takes place at these nodes).

On the contrary, for a call from node 2 to node 3, the switching arrangements will try the following paths, in the order indicated.

2-3
2-8-3
2-8-9-3
2-8-12-9-3

For a call from node 6 to node 7, the only path possible is 6-7, which is a full group.

2.2.2 Facilities network

For purposes of the Hermes III Model, this is a "physical" network representing transmission link and nodal transmission and switching facilities in their geographic setting. Cost functions are defined on the elements of the facilities network. This is the type of network handled in the first part of the Hermes project. In the second part of the project, concerned with the Model Hermes III, we shall have to use the concept of the enlarged network to take account of the coexistence or potential coexistence of different transmission systems on a link and/or of different carriers. (See Report on the Second Phase, March 1972).

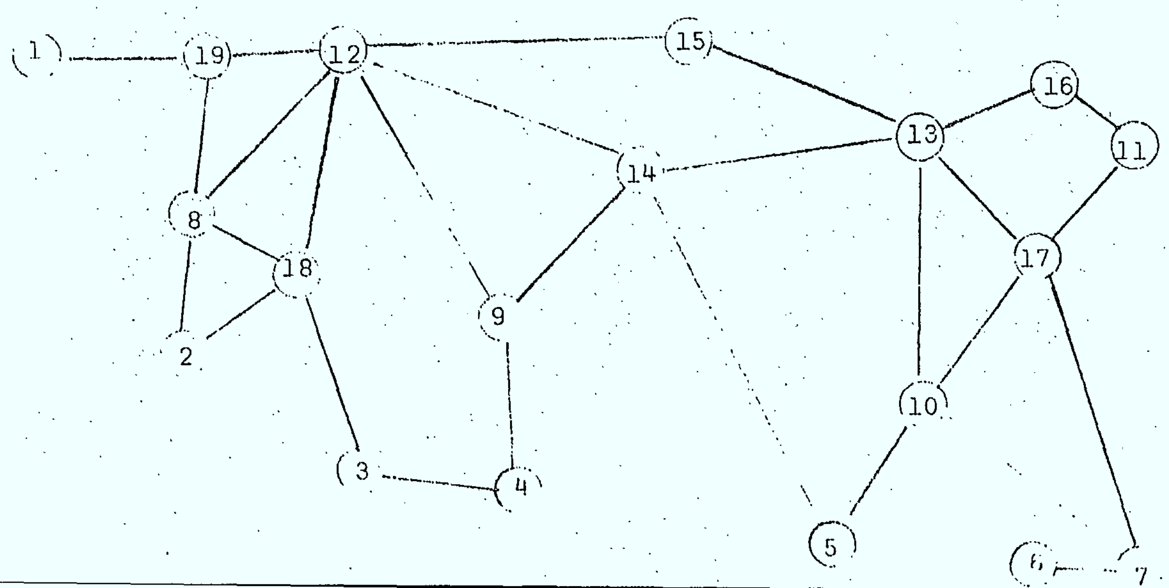
In the facilities network, one finds switching nodes and transmission nodes. Transmission nodes are transparent in the facilities network.

To each link of the switching network there corresponds a set of transmission facility assignment chains, which obviously are defined with reference to the facilities network. These chains indicate the physical "pipes" which may be followed by the circuits corresponding to links of the switching network. The number of facility assignment chains may be quite large, even if the number of pairs of demand points under investigation is small. The sum of the circuits finally allocated to these chains must be equal to the number of circuits allocated to the switching network link to which they correspond. In the model the circuits are two way circuits.

Figure 3 illustrates a transmission facilities network supporting the switching network shown in Figure 2.

FIGURE 3

Transmission facilities network



In the facilities network, all the links consist of sets of circuits. The nodes numbered 14 through 19 are transparent and do not appear in the corresponding switching network shown in Figure 2.

It should be noted that in the facilities network, there is no link between nodes 8 and 3, while there exists a high usage group between these two nodes in the switching network. Let us suppose that this high usage group contains 100 circuits. To sustain this group, one can have, for instance, 75 circuits going through the nodes 8-12-9-4-3 and 25 circuits going through the nodes 8-2-18-3 (with respect to these two chains the nodes 12-9-4-18-2 play the role of transparent nodes).

Let us now suppose that the link 5-10 of the facilities network contains 50 circuits. It may happen that 25 of these circuits support the final group 5-10 of the switching network and the 25 remaining circuits support the high usage group 5-6 (we assume here that the chains going through the link 5-10 of the facilities network and which are associated with the link 5-6 of the switching network contain in total 25 circuits).

Dedicated lines and television do not correspond to any concept of the switching network and have to be handled separately. The task is, however, simplified by the fact that the demand for dedicated lines and for television is expressed in number of circuits. Furthermore, the circuits serving that type of demand cannot give rise to switching in the sense covered herein. In this case, the demand constraints are formulated directly in the facilities network (as in the models Hermes I and Hermes II). However, where services requiring transmission band width greater than one circuit (4khz) are involved all circuits serving to transmit such a service must pass through the same facility assignment chain. Moreover, it is essential that the transmission path for broad band data, television, picture phone, etc. be made available as one band width. This refinement will not be treated in the model.

2.2.3 Functions of CHARGE

Suppose we are given an initial state on the switching network; that is we know :

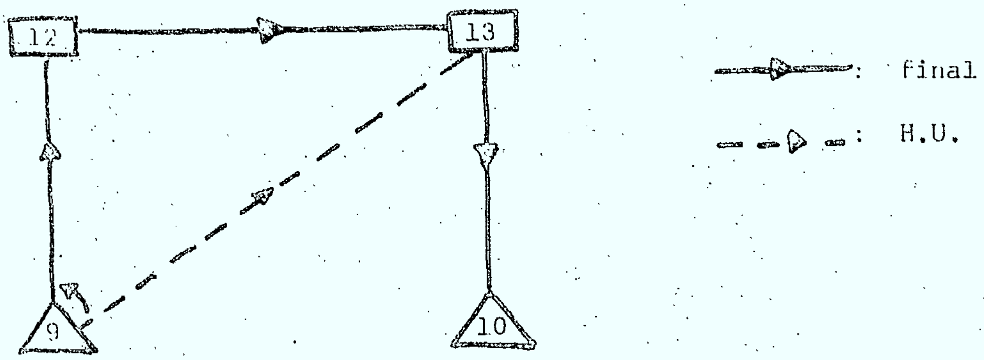
- The number, location and identification of the switching network nodes;
- The node hierarchy and the homing arrangement; that is to say, the basic tree of the last choice (final) structure;
- The loss probabilities on the final groups;
- The set of already installed H.U. and Full groups ;
- The overflow rules for the H.U. groups ;
- The set of overflow probabilities for the H.U. groups;
- The initial origin-destination offered traffic matrix for switched traffic in Erlangs (note that traffic is directed).

With the above information, the graph of the switching network is completely defined. The module CHARGE can compute the offered traffic generated on each arc by each origin-destination.

Take for instance the switching network on Figure 2. For an offered traffic of $a_{9\ 10}$ directed from the node 9 to the node 10, the relevant partial sub-graph becomes (given the homing arrangement and the overflow rules) the sub-network described in Figure 4 below. Note the existence of two possible paths from 9 to 10: the paths 9-13-10 and 0-12-13-10.

FIGURE 4

Sub-Network: Nodes 9 and 10



The charge generated by $a_{9,10}$ on the arc (13,10) for example, can be computed once the blocking probabilities $P_{9,12}$, $P_{12,13}$ on the final route and the overflow probability $P_{9,13}$ are known. That charge is :

$$a_{9,10}\,(1-P_{9,13}) + a_{9,10}\,P_{9,13}(1-P_{9,12})\,(1-P_{12,13}).$$

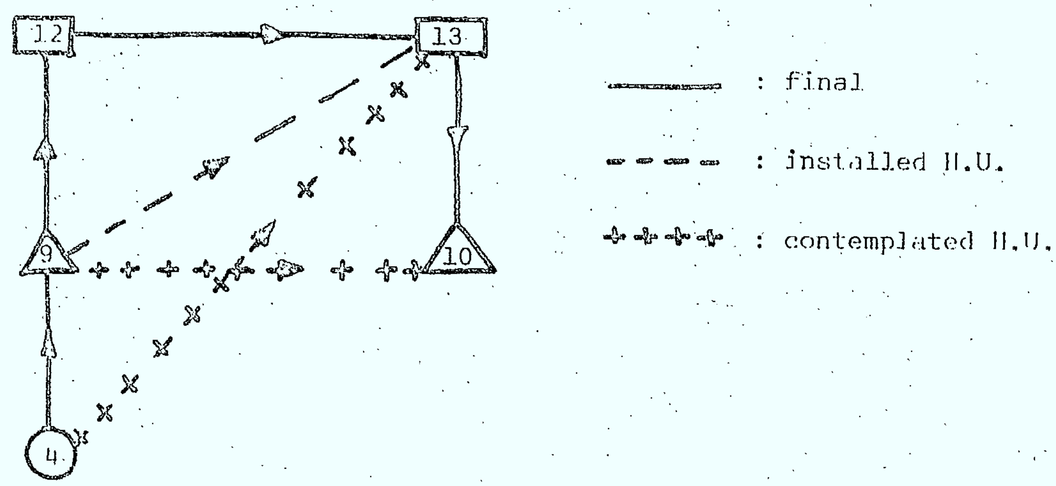
Therefore, for any initial state, CHARGE can compute the generated traffic on each arc of the switching network. Since we postulate two way circuits, CHARGE give the generated traffic on each link of the switching network by adding the generated traffic in both directions from all pairs of demand points.

The charge on each link having being obtained, CHARGE computes the necessary number of circuits given the blocking or overflow probabilities. The Erlang-B formula was used for this version of the software but with a little more software development, the Poisson formula can be substituted for Erlang-B where final links are concerned.

We must now hypothesize increases in origin-destination offered traffic combined with the possibility of creating new H.U.'s. For instance, again referring to Figure 2 suppose 3 new H.U.'s are contemplated : one between 9 and 10, one between 4 and 13 and one between 10 and 11. Since the H.U. may or may not be created, building on the initial switching network, we have $2^3=8$ possible switching networks on which to consider increased traffic. When there are n contemplated H.U. the number 2^n can be very high and it is not efficient to envisage the use of 2^n zero-one variables in our problem. Rather, we use the concept of relevant sub-graph as described above. Continuing our example, we find that the relevant sub-graphs for the new offered traffic from 4 to 10 is as shown in Figure 5. We are left with 2^2 sub-graphs according to the creation

FIGURE 5

Sub-Network : Nodes 4 and 10



or non creation of the 2 contemplated H.U. If we call δ_{ij} a zero-one variable which takes the value one when the H.U. between i and j is created and zero otherwise, we get the 4 following configurations :

	1	2	3	4
$\delta_{9\ 10}$	0	1	0	1
$\delta_{4\ 13}$	0	0	1	1

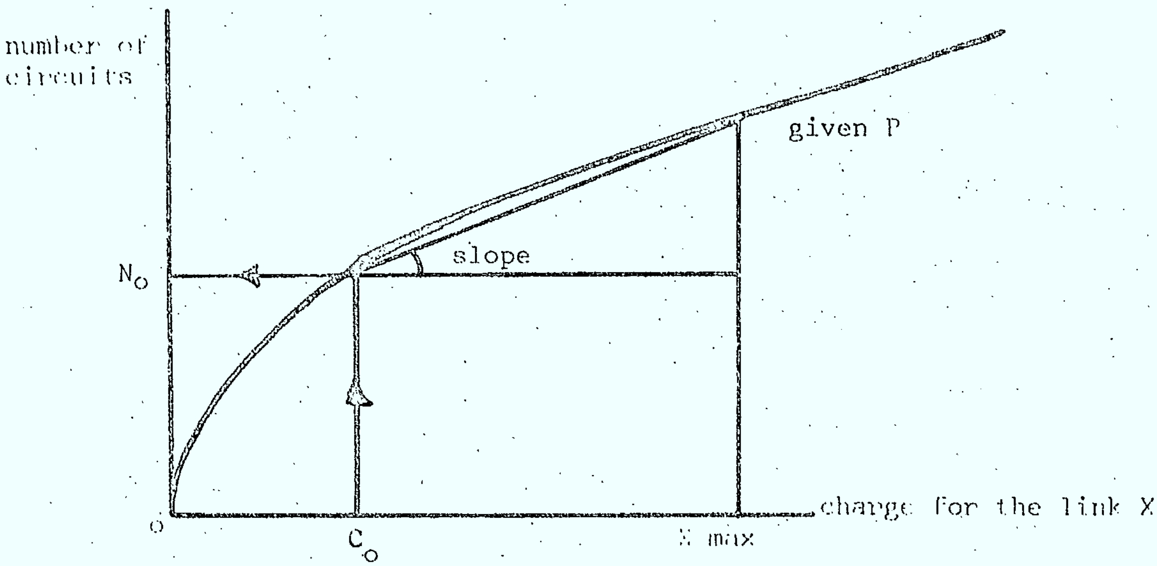
For each switching network configuration relevant to 4-10 the charge generated by the new offered traffic from 4 to 10 on each arc of the graph can be computed. All pairs of origin-destination offered traffic can be so treated. It is to be noted that the configurations are not independent in general. For instance, the configurations (9 10, 4 13) for the demand pair (4, 10) are not independent of the configurations 9,10 for demand pair (9, 10) This interdependencey will be handled in the TRANCHE III module.

The problem we must solve is : knowing the charge generated on a given link by a set of initial offered traffic and knowing the charge generated on the same link under different configurations after increases of the offered traffic, what demand, in term of circuits, will be submitted to the optimization problem in TRANCHE III?

If the transformation from charge to circuit were a simple straight line through the origin, there would be no problem. Unfortunately the transformation for a given blocking or overflow probability has the shape shown in Figure 6.

FIGURE 6

Charge to circuits conversion curve



For the initial state (given the switching network and the offered traffic) there is only one resulting charge for a given link. This charge is called C_0 and N_0 the corresponding number of circuits. It must be emphasized that C_0 results from all the origin-destination pairs of demand points, whereas the resulting charge for a given relevant configuration is for one pair of demand points only. Even with reasonable large demand increases, it is quite possible that the resulting charges will be less than C_0 for links which are part of the initial switching network. For contemplated H.U.'s the initial charges are zero. Therefore, whatever the configuration, the new charges are to the right of the initial charge as on Figure 6. It is clear from the data available on the facilities network that we will not be able to decrease the number of circuits allocated to a given link of the switching network since we do not know where the initial number of circuits are installed in the facilities network. Moreover precise economic criteria are not available to make the adjustment. If, for a given combination of configurations, a decrease should occur, it will be interpreted as a zero variation for TRANCHE III and will be noted in the output of CHARGE. Since the model is to simulate medium term demand increases, it is foreseen that there will be high enough increases on all pairs of demand points to offset decreases in charges due to traffic being taken over by new H.U.'s.

The proposed solution, which could be improved in subsequent phases of the project, is the following :

We assume we are on the very flat portion of the transformation curve (Figure 6)

For each link and each pair of demand points, for the unique initial state configuration, the initial charge is computed.

For each link, summing on the number of demand points, the total initial charge is computed.

For each link, each pair of demand points and each relevant configuration, the new charge is computed.

For each link, the maximum charge is found with respect to all the relevant configurations associated to a given demand pair. This is done for all demand pairs.

For each link, the preceding maxima are summed even though the configurations from which they are issued are not necessarily compatible. Therefore, there is a risk of overshooting but the flatness of the curve attenuates the consequences of that risk.

For each link the number of circuits is computed, first for the initial total charge, second for the summation of maxima just mentioned. The difference is calculated and the slope :

$$\frac{\text{numbers of circuits difference}}{\text{charges difference}} = s$$

is the coefficient which is used in the computation of the number of new circuits required by the increased charges as follows :

number of new circuits for a given configuration = s (new charge - total initial charge).

These required numbers of new circuits will be used in the optimization problem in TRANCHE III.

For links whose initial charge was zero (contemplated H.U. for instance), to avoid poor linear approximation, we substitute for the zero initial state, the summation of all minimum non zero charges generated by the demand pairs : that is the total minimum charge when the H.U. is in fact created. If we had to design a completely new network, such as approximation would be used as well.

Note: The reader must be careful in interpreting the s coefficient described above. This coefficient is not a pure marginal coefficient as it seems to be. It has been computed under the hypothesis that one configuration is chosen for each pair of demand points and that the resulting total charge increase generates a circuit requirement. The s coefficient is a kind of compromise since we do not know what will be the total charge increase before TRANCHE III chooses among the configurations.

The last function attributed to CHARGE is to determine the coefficients associated which each configurations in order to compute the required capacity at the switching machine level. Given a switching node, the choice of a given configuration associated with a know demand increase generates charge variations for all the arcs adjacents to that node. The summation for all those charge variations is done and it is converted in number of lines according to the formula given by the D.O.C. :

Required number of lines = Total charge variation in Erlangs x $\frac{36}{21}$.

If the total charge variation is negative, the required number of lines is negative. It seems highly improbable that, for a node, the grand total charge variation for all demands will be negative in TRANCHE III. If this is the case, the solution will show an increase in unused capacity for that switching node.

The sum up, CHARGE determines :

1. For each pair of demand points, the several configurations of switching networks which are relevant.

2. For each pair of demand points, the requirement in terms of new circuits for each relevant configuration and each link of the switching network involved in that configuration.

3. For each pair of demand points, the requiremenr for new lines for each relevant configuration and each switching node involved in that configuration,

The section describing the software will describe the algorithm used in CHARGE.

2.2.4 Function of CADUCEE III

As CADUCEE I and II were indispensable in earlier versions, CADUCEE III is a necessary module in Hermes III. Without it, no reasonable sized problems can be solved.

CADUCEE I and II provided the set of admissible physical transmission chains for each considered demand pair in order to reduce the number of activities in the linear programming module. CADUCEE III is designed to provide the set of admissible physical transmission chains as well but in this case for each pair of adjacent nodes in the switching network as described in section 2.2.2.

Therefore, even if we considerer only a few pairs of demand points, there will be many more pairs of adjacent nodes in the relevant switching networks associated with these pairs of demand points. Moreover, the "enlarged network" concept multiplies the number of possible chains between two points of the transmission network. For all these reasons, CADUCEE had to be rewritten to improve its efficiency. The detailed algorithm is described in the software section of this report.

It suffices here to mention that for each link of the switching network the module CHARGE computes the maximum charge increase generated by each pair of demand points, then, the summation of all these maximum charges increases is made and the number of new circuits wanted at that maximum level is computed. This maximum requirement for new circuits is used in CADUCEE III to find the admissible chains which would be able to support the new circuits connecting the extremal nodes of the considered link. We recall that the concept of "admissible chain" is one which may intervene in the optimal solution in TRANCHE (see the report on the second phase, March 1972). If a chain is found nonadmissible for the sum of the maximum new circuits requirements, it is also nonadmissible for lesser requirements.

Briefly, the module CADUCEE III furnishes TRANCHE III with one set of transmission activities (chains) for each link oflthe switching network since the original increases between paired demand points have been translated in requirements for new circuits between adjacent nodes of the switching network.

2.2.5 Function of TRANCHE III

As its predecessors, TRANCHE III is the optimization module. It solves a mixed linear programming problem which minimizes the expansion cost required by a given demand increase.

2.2.5.1 The cost functions

The general form of the cost functions used in Hermes I and II have been retained. Step cost functions are the only functions accepted, for the moment, in the module. The new elements are the following :

1. The unit of measurement for the arguments of the functions is the circuit instead of the channel. Capacity is installed by circuits blocks of any technically desired sizes.

2. The assumption of no unused capacity has been elimated and it is possible to start with a certain number of unused circuits on a physical link. As soon as one wants to use these circuits to satisfy the new requirements, one has to incur a small fixed cost (a kind of connecting cost). This feature has been included to avoid unrealistic allocation all around the network. Otherwise, if the existence of unused capacities was the rule "no cost" criteria could lead to the allocation of circuits to very long routes for close demand nodes. Moreover, the screening of CADUCEE III could in this case be less efficient in terms of admissible chains.

3. In TRANCHE III, nodes of the switching network can have switching capacities and therefore step cost functions can also be defined in order toincrease the capacities of these nodes.

More detail on the cost functions is contained in preceding reports. It should be noted that the cost functions deal with total expansion cost.

2.2.5.2.1 The circuits assignment activities

For each link of the switching network, there is a set of admissible chains in the facilities network. Each chain can receive a certain number of circuits that pertain to the group of circuits assuring communications between the extremal nodes of the above link. It is understood that the assigned circuits form a group, from the accessibility point of view, even if certain circuits are physically separated on several chains. This divisibility potentially obtained without adding special constraints is obviously a first step toward meeting survivability requirements. For computational considerations, a level of activity (assigned number of circuits to a chain) is a real non-negative variable, except for non-divisible groups of circuits as, for example, television in which case a level is a zero-one variable mutually exclusive of the other zero-one variables associated to the chains in the same set. In that later case, each zero-one variable is multiplied into the same coefficient which gives the required number of circuits for the indivisible demand (see CHARGE).

2.2.5.2.2 The relevant switching network configuration creation activities.

For each pair of demand points of the switching network as we explained in 2.2.5, a set of relevant switching network configurations is established by CHARGE. A zero-one variable creates, when it has the value one, an associated configuration. The other configurations in the same set do not come into existence. In other words, for each pair of demand points there is a set of mutually exclusive zero-one variables. These creation activities generate circuit requirements and line requirements by multiplying the zero-one variables into the right coefficients established by CHARGE.

2.2.5.2.3 The investment activities

For each link and node of the facility network, a sequence of investment activities will express the new transmission capacity to be installed, as in the previous Hermes models. As well, for each switching node, a sequence of investment activities will express the new switching capacity to be installed. All the investment activity levels will be integer variables. If there is unused capacity for a link, the first activity is not properly an investment activity but a a "filling up" activity.

2.2.5.3 The constraints

The constraints mathematically force the model to respect the proper relationships between :

1. The circuit assignments and the demand for circuits ;

2. The circuit assignments and the capacities of links and nodes;

3. The sequencing of investment variables: a facility has to be put in place before any addition to it can be made.

4. The compatibility of the configuration creation activities;

5. The variables and their value range.

2.2.5.3.1 Assignment of a sufficient number of circuits to satisfy the demand

For each link of the switching network one configuration must be chosen in each set of configurations associated with each pair of demand points. As we have seen each zero-one variable so chosen has for coefficient a required number of new circuits. The total of these required circuits must be equal to the total number of circuits assigned through the circuit assignment activities.

2.2.5.3.2 Limitation of circuit assignments and augmentation of the installed capacities

For each link of the facility network a constraint exist which limits the number or circuits assigned to the link. The limit on any link is the number of circuits already installed as specified in the initial state plus the investment activities for that link. This constraint is the same type of capacity constraint that was used in the Hermes I and II models.

For each node with switching facilities, a constraint of the same type limits the lines entering and leaving the node. The limit in this case as well is the capacity available from the initial state plus the investment activities for that node.

2.2.5.3.3 Sequencing of investment activities

The method of ordering the entry of investment variables in the solution has been thoroughly discussed in the reports prepared in the first part of the Hermes project. In the model, a set of precedence relationships is established which require that full capacity, associated with a given level of investment activity, is utilized before the next level is considered.

2.2.5.3.4 Compatibility constraints

For each set of configuration creation variables associated with a pair of demand points, a constraint secures mutual exclusiveness.

For all the sets of configuration creation variables, constraints insure that, if an HU or FG exists for one configuration, it also exists for all other configurations in which it appears.

2.2.5.4 The objective function

In TRANCHE III, only the investment and "filling up" activities have non zero coefficients. The value of the linear form we which to minimize is thus the total expansion cost of an investment program.

3. THE SOFTWARE OF HERMES III

In Chapter 2, the overall structure and the formulation of HERMES III was discussed in detail The purpose of this chapter is to describe the software of each of the major modules of Hermes III as they relate in the overall structure and individually.

3.1 The overall structure

Chapter II of the report on the preliminary Phase of the Hermes project, issued in December 1971, discusses in detail the nature of the problems faced in developing Hermes software and the reasons for adopting the modular approach, The model discussed in that report was Hermes I. Hermes II followed and built upon the experience gained in developing Hermes I.

As was the case for Hermes I and II, the Hermes III version of the model takes the form of a set of modules. These modules are represented in Figure 7 The modular approach has proved to be of significant value in the development of the Hermes series of models as it has allowed that major portions of the software remain "active" during development of a more advanced Hermes package. The modules which are shown in the figure and which will be discussed in the course of this chapter are CHARGE, CADUCEE III and TRANCHE III.

The charge module did not appear in the preceding versions of the model. Its principal objective is to calculate the loads on the links of the switching network, given a set or paired demand points on this network. The module calculates the different loads (in terms of Erlangs) on each link of the network, and for each possible alternative profile of the switching network, i.e. each alternative sub-set of the overall of potential H.U. groups.

Hence, for each link of the switching network, the module CHARGE gives a load vector. Each component of the vector corresponds to a load (in Erlangs) on the link in question, this load being associated with a particular profile of the switching network. To reduce the number of chains given to TRANCHE III, the module chooses the maximum component of this vector and transforms this load in terms of circuits : these values are then used as inputs to CADUCEE III, and TRANCHE III. CHARGE is described fully later in this chapter.

Each of the values transmitted to CADUCEE III represents a demand in terms of circuits between paired demand points of the physical network : the nodes of each pair are the end nodes of the link of the switching networks to which this demand applies. At the level of CADUCEE III, we may have a large number of demand pairs for each demand pair in the switching network. This has necessitated some major changes in the software which are described in a later section of this chapter.

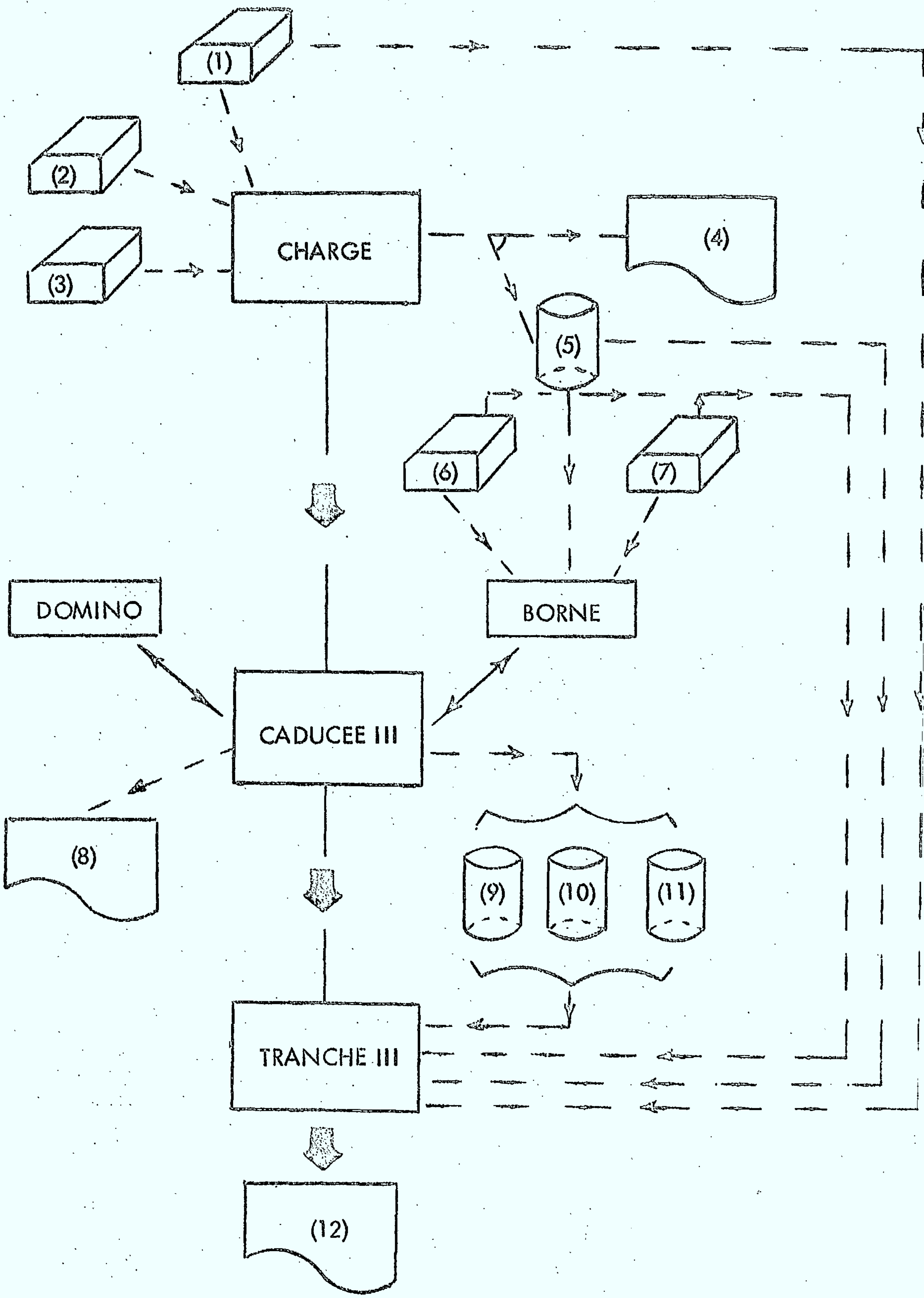


FIGURE 7

GENERAL FLOW CHART: HERMES III

FIGURE 7 (con't)

Légende

(1) Description du réseau de commutation y compris l'ensemble des HU ou FG potentiels.

(2) Matrice de trafic initial entre tous les sommets du réseau de commutation.

(3) Matrice de trafic total (y compris les accroissements de demande)

(4) Tableaux des charges sur le réseau de commutation, par paire de points de demande et pour chaque profil pertinent. Ces charges découlent de (3) et tiennent compte de l'état initial défini en (2). Ce sont donc des accroissements de demande.

(5) Cette filière continent toute l'information définie en (4) ainsi qu'un vecteur d'accroissement maximum de demande par arête du réseau de commutation.

(6) Définition des accroissements de demande entre les paires de points de demande du réseau physique pour lesquels au moins un des sommets d'extrémités n'appartient pas au réseau de commutation. Cet ensemble comprend également les paires de points de demande où l'accroissement de demande est indivisible.

(7) Description du réseau physique

(8) Tableaux des statistiques sur les chaînes admissibles

(9) Chaînes admissibles pour les paires de points de demandes su réseau de commutation.

(10) Chaînes admissibles pour les paires de joints de demande du réseau physique.

(11) Chaînes admissibles pour les paires de points de demande où l'accroissement spécifié est indivisible.

(12) Programme optimal d'accroissement de capacité. Au niveau de réseau physique nous parlerons d'accroissements des capacités de transmission tandis qu'au niveau du réseau de commutation, il s'agira des accroissements de capacité de commutation aux sommets.

The TRANCHE III module will work at two levels : at the level of the facilities network and at that of the switching network. Its objective, however, is not changed from that of TRANCHE I or II, and because of the introduction of additional activities to deal wi th the switching network, the optimal solution covers both networks.

TRANCHE III is described later.

3.2 CHARGE

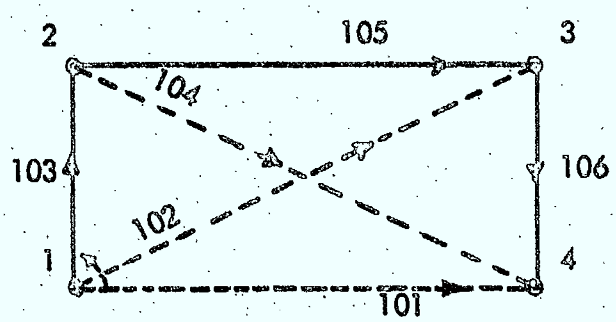
This module did not appear in the preceding versions of the model. Its principal objective is to calculate the loads on the links of the switching network, given a set of paired demand points on this network.

For a given pair of demand points, this module calculates as many load vectors as there are relevant profiles for this pair of demand points. We recall that this set of profiles is defined from the switching network, the set of potential HU or FG groups and the set of homing rules and that all calculations are performed according to the theory of "multiple overflow". From this set of vectors, CHARGE calculates an "upper-bound load vector" for that pair of demand points. When all paired demand points have been processed, CHARGE adds up the set of "upper-bound load vectors" to obtain a vector of "demand increase" in terms of circuits. This vector will then be used as input to CADUCEE III.

3.2.1 L'algorithme

Le texte qui suit décrit de façon assez formelle l'algorithme permettant l'évaluation des charges sur les arcs d'un réseau de commutation.

Soit le réseau de commutation suivant:



Les règles de débordements multiples sont contenues dans la matrice des débordements D suivante:

101		
102	101	
103	101	102
104		
105	104	
106		

Une ligne de la matrice D, notée $D_{M=(I,J)}$, définit les origines possibles des débordements sur l'arc M=(I,J).

Finalement, nous avons la matrice de trafic T suivante, contenant les données de trafic entre les couples de points de demande qui nous intéressent pour un problème donné.

	1	2	3	4
1		a_{12}	a_{13}	a_{14}
2			a_{23}	a_{24}
3				a_{34}
4				

3.2.1.1 Principe de l'algorithme

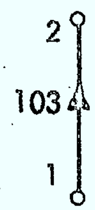
Le principe de l'algorithmen est simple et consiste, pour un arc donné M=(I,J) du réseau de commutation, à calculer la charge sur cet arc générée par un couple de points de demande. En itérant cette procédure pour tous les points de demande et en cumulant les charges obtenues, on obtient finalement la charge totale sur l'arc M=(I,J) découlant de la matrice T.

Cette façon de procéder nous permet de réduire considérablement le volume des calculs puisqu'on ne travaille plus au niveau de réseau de commutation tout entier mais seulement sur un sous-réseau, nommément le sous-réseau pertinent au couple de points de demande considéré à ce moment.

Pour chacun des couples de points de demande considérés, on définit le sous-réseau qui lui est pertinent, le matrice A^*_{IJ}. Pour l'exemple discuté ici, nous aurons:

Couple de points de demande

a) $a_{12} > 0$ (1,2)

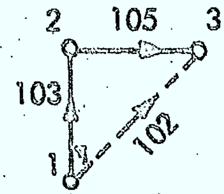


A^*_{12}

	1	2	3	4
1		103		
2				
3				
4				

Note: Nous appelerons cet sous-réseau, le "profil."

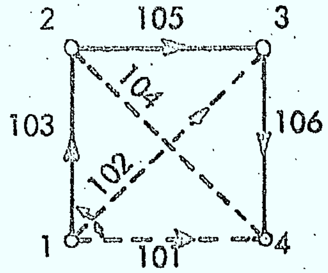
b) $a_{13} > 0$ (1,3)



	1	2	3	4
1				
2				
3				
4				

A^*_{13}

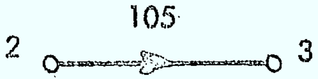
c) $a_{14} > 0$ (1,4)



	1	2	3	4
1		103	102	101
2			105	104
3				106
4				

A^*_{14}

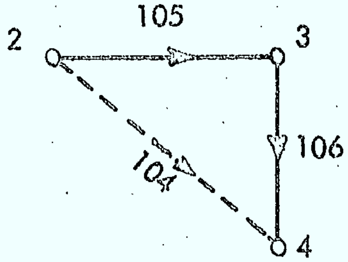
d) $a_{23} > 0$ (2,3)



	1	2	3	4
1				
2			105	
3				
4				

A^*_{23}

e) $a_{24} > 0$ (2,4)



	1	2	3	4
1				
2			105	104
3				106
4				

A^*_{24}

f) $a_{34} > 0$ (3,4)

A^*_{34}

	1	2	3	4
1				
2				
3				106
4				

Dans l'exemple considéré ici, nous aurons $2^3 = 8$ profils possibles.
Si nous posons simplement:

K =	1	2	3	4	5	6	7	8
13	0	0	0	0	1	1	1	1
14	0	0	1	1	0	0	1	1
24	0	1	0	1	0	1	0	1

L'objectif est maintenant d'évaluer les charges sur les arcs du réseau de commutation pour chacun de ces profils. Or, grâce aux calculs effectués précédemment, le calcul des charges générées par un couple donné n'est pas nécessaire pour tous ces profils.

Dans l'exemple discuté ici, nous avons:

Couple de points de demande	Profils pertinents (K)		
(1,2)	1	et	(K=2,3,4,5,6,7,8) = 1
(1,3)	1,5	et	(K=2,3,4) = 1; (K=6,7,8) = 5
(1,4)	1 à 8	et	
(2,3)	1	et	(K=2,3,4,5,6,7,8) = 1
(2,4)	1,2	et	(K=3,5,7) = 1; (K=4,6,8) = 2
(3,4)	1	et	(K=2,3,4,5,6,7,8) = 1

Par exemple, le calcul de la charge sur l'arc M = (I,J) générée par la demande entre (2,4) sera calculée uniquement pour les profils K = 1,2 et les charges pour les profils K = 3,5,7 seront égales à la charge obtenue pour le profil K = 1 et celles pour les profils K = 4,6,8 égales à celle obtenue pour le profil K = 2.

3.2.1.2 Notations utilisées

$A^{K}_{L,N}$ sous-réseau pertinent au couple (L,N) pour le profil (K). Par exemple, pour (L,N) = (1,4) et K = 3

$A^{3}_{1,4}$

	1	2	3	4
1		103		101
2			105	
3				106
4				

$M = (I,J)$ l'arc (I,J) du réseau de commutation. (Ex: 103 = (1,2))

$C^{(L,N)}_{M=(I,J)}(K)$ charge sur l'arc M = (I,J) générée par la demande pour le couple (L,N) étant donné le profil (K)

$a_{L,N}$ demande entre le couple (L,N)

$CH^{(L,N)}(K)$ L'ensemble des chemins entre (L,N) pour le profil (K).

3.2.1.3 Calcul de $C^{(L,N)}_{M=(I,J)}(K)$

a) Construire la matrice $A^{K}_{L,N}$

b) Construire l'emsemble $CH^{(L,N)}K$ en respectant les règles d'acheminement

c) Poser $C^{(L,N)}_{M=(I,J)}(K) = 0$ (Initialisation)

d) Considérer un chemin de l'ensemble trouvé en b). Si tous les chemins ont été considérés, conserver $C^{(L,N)}_{M=(I,J)}(K)$ et passer à h).

e) Si le chemin ne passe pas par M = (I,J), passer à d).

f) Si le HU installé vient après M = (I, J), passer à d). Sinon définir:

1) $W^* = \left\{ \text{arcs qui précèdent } M = (I,J) \right\} = \left\{ W^*_j \right\}_{j=1,n}$

2) $W^{**} = \Big\{ HU \in A^{K}_{L,N}$ qui débordent sur au moins un des arcs du chemin jusqu'à $M = (I,J)$ compris$\Big\} = \left\{ W^{**}_i \right\}_{i=1,m}$

3)

$$P = \begin{cases} \displaystyle\prod_{\left\{(K_1,K_2) \;\middle|\; (K_1,K_2) \in W^{**}_i\right\}} P_{K_1,K_2}^{\;\delta_{K_1,K_2}} & \text{si } \left\{W^{**}_i\right\} \neq \emptyset \\ 1 & \text{si } \left\{W^{**}_i\right\} = \emptyset \end{cases}$$

g) Utiliser l'expression

$$C^{(L,N)}_{M=(I,J)}(K) \begin{cases} C^{(L,N)}_{M=(I,J)}(K) + Pa_{L,N} \displaystyle\prod_{\left\{(K_1,K_2) \;\middle|\; (K_1,K_2)\; W^*_i\right\}} (1 - P_{K_1,K_2}) & \text{si } \left\{W^*_i\right\} \neq \emptyset \\ C^{(L,N)}_{M=(I,J)}(K) + Pa_{L,N} & \text{si } \left\{W^*_i\right\} = \emptyset \end{cases}$$

et passer à d).

h) Si tous les profils pertinents ont été considérés passer à i).
Sinon, définir le prochain profil et passer à a).

i) Si tous les arcs ont été traités, passer à j).
Sinon, définir le prochain arc M = (I, J) et passer à c).

j) Si tous les couples de points ont été considérés passer à k).
Sinon, définir le prochain couple (L, N) et passer à a).

3.2.2 Exemple d'application du module CHARGE

Soit le réseau de commutation représenté à la matrice de trafic T (dont certains éléments sont nuls afin de simplifier l'exposé) associée à ce réseau (figure 9).

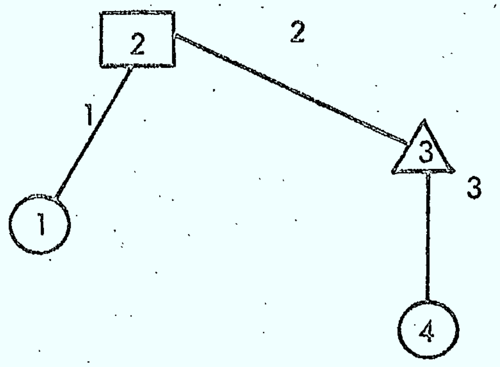


FIGURE 8

	1	2	3	4
1		400		300
2			300	200
3				100
4				

T

FIGURE 9

Les données de trafics sont en erlangs mais les résultats obtenus par le module CHARGE demeurent invariants par rapport à une matrice de trafic en ccs puisque la transformation de ccs à erlangs est linéaire (1 erlang = 36 ccs). Cette matrice de trafic nous servira d'état initial du réseau de commutation.

A partir de ces éléments, nous désirons évaluer les charges sur les arêtes du réseau de la figure 1, tout en admettant la possibilité d'installer un HU entre les sommets 1 et 4, soit parce que la qualité de service entre ces sommets n'est plus acceptable ou encore parce que le volume de traffic entre ces sommets est suffisant pour en justifier la mise en place. Le réseau obtenu est celui de la figure 10. En plus de considérer la possibilité d'installer un HU entre les sommets 1 et 4, nous supposons également des accroissements de demande tels que spécifiés dans la matrice ΔT (figure 11).

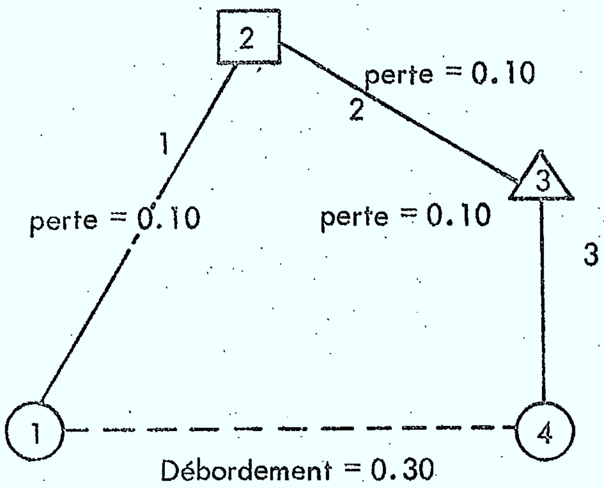


FIGURE 10

	1	2	3	4
1		100		200
2			100	150
3				100
4				

ΔT

FIGURE 11

Le problème peut maintenant s'énoncer comme suit: à partir des charges initiales sur les arcs du réseau de commutation de la figure 1 , charges générées par la matrice T, déterminer le nouvelles répartitions de charges suite aux accroissements de demande contenus dans la matrice ΔT et la possibilité supplémentaire l' d'installer un HU entre les sommets 1 et 4.

L'algorithme utilisé dans CHARGE consiste à diviser ce problème en sous-problème complémentaires à l'aide des étapes suivantes.

Etape (a)

Calcul des charges générées par la matrice T sur le réseau de la figure 8.

couple / arc	(1-2)	(1-4)	(2-3)	(2-4)	(3-4)	Etat initial
1	400	300	0	0	0	700
2	0	270	300	200	0	770
3	0	243	0	180	100	423
4	-	-	-	-	-	-

TABLEAU 1

La dernière colonne de ce tableau nous donne l'état initial sur les arcs de réseau de commutation.

Etape (b)

Calcul des charges générés par la matrice T + ΔT sur les arcs du réseau de la figure 10.

couple / arc	(1-2)	(1-4)		(2-3)	(2-4)	(3-4)
		0	1			
1	500	500	150	0	0	0
2	0	450	135	400	350	0
3	0	395	121	0	315	200
4	0	0	500	0	0	0

TABLEAU 2

Etape (c)

Calcul des modifications de charges suite au passage de la figure 8 à la figure 10 et de la matrice T à une matrice T + $\triangle$T. (Tableau 3 : Tableau 2 - Tableau 1)

	(1-2)	(1-4)		(2-3)	(2-4)	(3-4)	Demandes	
		0	1				0	1
1	100	200	-150	0	0	0	300	- 50
2	0	180	-135	100	150	0	430	115
3	0	152	-122	0	135	100	387	113
4	0	0	500	0	0	0	0	500

TABLEAU 3

Les deux dernières colonnes du Tableau 3 représentent les accroissements de demandes sur les arêtes correspondantes du réseau de la figure 3 générées par la matrices $\triangle$T. Jusqu'à maintenant, tous les calculs ont été effectués en erlangs. La prochaine étape concerne le passage d'erlangs au nombre de circuits.

Etape (d)

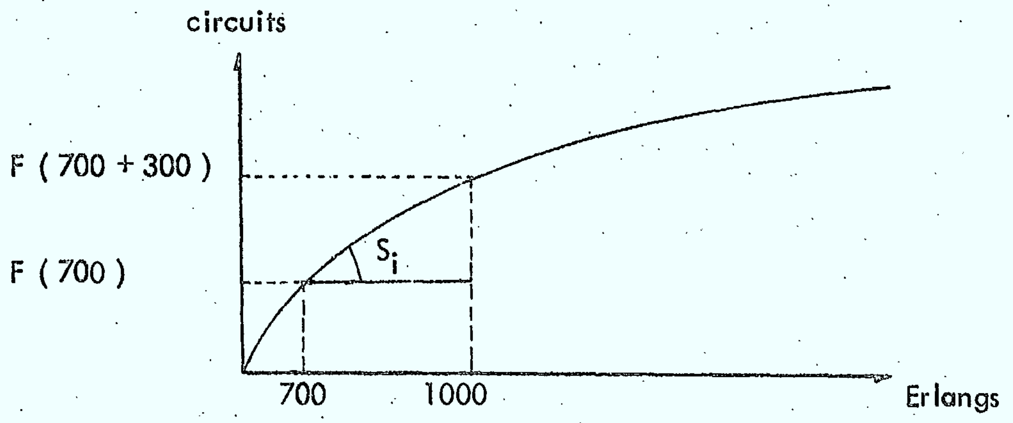
Si nous désignons par C_l^o, la charge initiale sur l'arc l et par D_l, l'élément correspondant à l'arête l dans l'avant-dernière colonne du Tableau 3, nous aurons:

$$S_l + = \frac{F(C_l^o + D_l) - F(C_l^o)}{D_l}, \text{ où}$$

S_l désigne le coefficients de transformation d'erlangs à circuits et F, la fonction de transformation d'erlangs à circuits. Par exemple, pour l'arc 1, nous aurons:

$$S_1 = \frac{F(700 + 300) - F(700)}{300}, \text{ où}$$

encore, graphiquement,



Finalement, il suffit de multiplier chaque élément du Tableau 3 par le coefficient S_i qui lui est associé.

Etape (e)

Parallèlement aux calculs effectués à l'étape (c), le modèle évalue les variations des charges commutées aux sommets du réseau de commutation. Ces calculs s'effectuent à partir du Tableau 3 et, dans l'exemple ci-dessus, nous obtenons le tableau suivant:

couple / sommets	(1-2)	(1-4) 0	(1-4) 1	(2-3)	(2-4)	(3-4)
1	0	0	0	0	0	0
2	0	180	-135	0	0	0
3	0	152	-122	0	135	0
4	0	0	0	0	0	0

TABLEAU 4

Ainsi, pour l'ensemble des accroissements spécifiés, la capacité des équipements de commutation au sommet 3 devra être augmentée de 287 (=152 + 135) unité lorsque le HU entre 1 et 4 n'est pas installé. Cependant, se le HU est installé, la capacité supplémentaire requise n'est plus que de 13 (+ -122 + 135) unités.

Les résultats de chacune des étapes sont stockés sur fichier pour être utilisés au niveau de module TRANCHE III. Le contrôle est ensuite passé au module CADUCEE.

3.3 CADUCEE III

Each of the values transmitted to this module represents a demand in terms of circuits between paired demand points of the physical network: the nodes of each pair are the end nodes of the link of the switching networks to which this demand applies.

As was pointed out before, at the level of CADUCEE III, we will have to treat as many pairs of demand points as we have links in the switching network. Since the formulation of CADUCEE II could not handle the problem of simultaneously treating a very large number of demand pairs, our primary concern was to increase the performance of this module. This has been achieved through implementation of some of the improvements discussed in Working Paper No. 6. . The CADUCEE III module uses the framework of CADUCEE II except that the original network has been reduced to a set of admissible nodes through the use of CADUCEE I. When convergence is obtained (at the level of admissible nodes), a "Maximum Relevant Demand Vector" is obtained and then CADUCEE II takes control.

We recall that the identification of admissible nodes with CADUCEE I is very fast so that the cpu (central processing unit) time required for these calculations is much less than the corresponding cpu time reduction at the CADUCEE II level.

Finally, as was the case with CADUCEE I and II, this module will provide the set of admissible physical chains for each paired points of demand considered. These sets are then transmitted ot the TRANCHE III module.

3.4 TRANCHE III: Identification of minimum cost capacity expansion programs

The TRANCHE III module identifies the minimum cost expansion program in terms of activity analysis. The added features in Hermes III of Switching networks and the concept of Enlarged Networks (parallel routes, distinct carriers, indivisible demand) necessitated the reformulation of the TRANCHE module. The software described under the general title TRANCHE consists of two parts. These can be described as the problem matrix generator (SETUP) and the mixed integer linear programming package.

3.4.1 Formulation of the TRANCHE III module

For purposes of clarity in outlining the processes and operation of the setting up of a problem, a simple switching and transmission facilities network is employed. The switching network is the same as described in section 3.2.

Figures 12 and 13 respectively show the switching and transmission facilities network.

FIGURE 12

Switching network

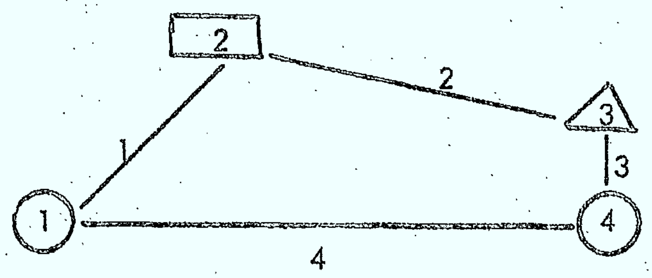
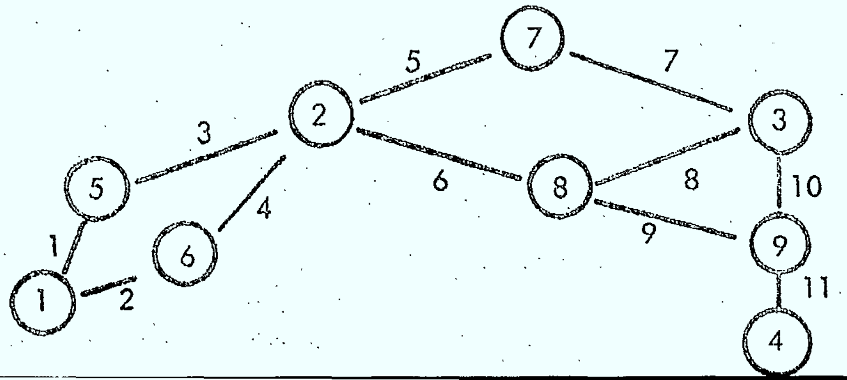


FIGURE 13

Transmission facilities network



It is to be noted that the nodes of the switching network must be a subset of the transmission facilities network. The link numbers in the two networks are for identification purposes only and do not have any other signifigance. Furthermore, the network shown and problem posed is trivial and is in no way intended to show the power and versatility of the software developed.

In addition to the demand on the switching network we wish to satisfy the following demand increases (Table 5).

TABLE 5

Demand table

Node to node		Demand in voice circuits
5	9	200 V.C. divisible
6	3	100 V.C. divisible
8	4	240 V.C. television (non divisible)
6	9	900 V.C. television (non divisible)

Tables 6 and 7 show the Transmission Facilities and Switching Nodes data for the network shown in Figures 12 and 13.

TABLE 6

Transmission facilities data

	Node	to Node	Mileage	V.C. type	Total V.C. blocks available	Cost/V.C. block ($ 100) x miles				
						1	2	3	4	5
1	1	5	0	600	4	100	100	100	300	
2	1	6	65	600	1	100	300			
3	5	2	60	1,200	5	100	300	100	100	100
4	6	2	75	960	4	100	100	100	300	
5	2	7	20	600	3	150	150	450		
6	2	8	20	1,200	4	100	100	100	300	
7	7	3	10	600	4	100	100	100	300	
8	8	3	20	1,200	4	100	100	100	100	
9	8	9	65	1,200	4	150	450	150	150	
10	3	9	60	1,200	5	150	450	150	150	150
11	9	4	20	600	3	350	150	150		

TABLE 7

Switching nodes data

Nodes	Lines/step.	Total no. of steps	Cost/300 line step ($ 100)		
			1	2	3
1	300	2	1,900	580	
2	300	3	1,900	580	580
3	300	2	580	580	
4	300	3	580	580	580

Admissible chains:

Admissible chains are of three types (from CADUCEE III)

1. chains for demand from switching network (CHARGE)
2. chains for demand as in Hermes I and II
3. chains for indivisible demand (i.e. T.V.)

Tables 8, 9 and 10 list the admissible chains for the three demand types respectively.

TABLE 8

Admissible chains for divisible demand generated by CHARGE

Node	to Node	Chain no.	Chains, nodes and links
1	2	1	(1) —1— (5) —3— (2)
		2	(1) —2— (6) —4— (2)
2	3	3	(2) —6— (8) —8— (3)
		4	(2) —6— (8) —9— (9) —10— (3)
		5	(2) —5— (7) —7— (3)
3	4	6	(3) —8— (8) —9— (9) —11— (4)
		7	(3) —10— (9) —11— (4)
1	4	8	(1) —2— (6) —4— (2) —6— (8) —9— (9) —11— (4)
		9	(1) —1— (5) —3— (2) —5— (7) —7— (3) —10— (9) —11— (4)
		10	(1) —1— (5) —3— (2) —5— (7) —7— (3) —8— (8) —9— (9) —11— (4)

TABLE 9

Admissible chains for divisible demand as in Hermes I & II

Node	to Node	Chain No.	Chains, nodes, and links
5	9	1	(5) -3- (2) -6- (8) -9- (9)
		2	(5) -3- (2) -5- (7) -7- (3) -10- (9)
6	3	3	(6) -4- (2) -6- (8) -8- (3)
		4	(6) -4- (2) -5- (7) -8- (3)

Node	to Node	Chain No.	Chains, nodes, and links
8	4	1	(8) -9- (9) -11- (4)
		2	(8) -8- (3) -10- (9) -11- (4)
6	9	3	(6) -4- (2) -6- (8) -9- (9)
		4	(6) -4- (2) -6- (8) -8- (3) -10- (9)

TABLE 10

Admissible chains for non-divisible demand

The Problem Matrix Generator (SETUP) converts the information from Tables 5,6 and 7, the sets of admissible chains, and the profiles from CHARGE into a "Basic Problem Matrix" as shown in figure 14. All rows, columns, bounds, costs, righthand sides, are generated in the SETUP module.

Demand Rows and Columns

There are three types of demand rows and columns that we must consider.

1. Demand generated by CHARGE

2. Demand as in Hermes I and II

3. Indivisible demand

Type 1: Demand Rows and Columns

The demand on any link in the switching network is not constant but is a function of the profile chosen from CHARGE. In the previous Hermes phases, demand was given as a righthand side constraint and was assumed to be a constant value.

Sub-blocks 1 and 2 in figure 14, along with their corresponding righthand side constraints define the variable demand required on the switching network. Row names beginning with the letters SN identify the pertinent links in the switching network, i.e. SN12 refers to the switching network link joining the nodes 1 and 2 of the switching network.

Columns beginning with the letter S identify the admissible transmission facility chains fjoining the nodes of the switching network, i.e. S0101 refers to the first chain made available to satisfy a demand or link SN12 of the switching network. Similarily, S0102 refers to the second chain which can be used to meet a demand or link SN12 of the switching network.

Sub-block 3 identifies the links of the facilities network making up the associated chains, i.e. matrix element M(LN01, S0101) = M(LN03, S0101) = 1 identifies a chain made up of the transmission facility links 1 and 3 that join the switching network nodes 1 and 2 or link SN12 of the switching network.

M (SN12, S0101) = M (SN12, S0101) = -1 identifies two chains that can be used to fulfull the variable demand as chosen from sub-block 2.

Sub-block 2 contains the values as generated by CHARGE. The columns of sub-block 2 of gigure 4 (beginning with the letter c) define the profiles of the switching network i.e. C0100 refers to the first demand pair of the switching network. The last two digits (00) indicate that only one profile for the first demand pair of the switching network is available. Columns C0201, C0202 refer to two profiles of the second demand pair of the switching network.

Row	S0101	S0102	S0201	S0202	S0203	S0301	S0302	S0401	S0402	S0403	R0101	R0201	R0102	R0202	D0101	D0201	D0102	D0202
SH12	-1.	-1.								①								
SH23			-1.	-1.	-1.													
SH34						-1.	-1.											
SH14								-1.	-1.	-1.								
RT59											1.	1.		④				
RT63													1.	1.				
DD64															240.	240.		⑦
DD69																	900.	900.
LH01	1.								1.	1.				⑤				⑧
LH02		1.						1.										
LH03	1.								1.	1.	1.	1.						
LH04		1.						1.					1.	1.			900.	900.
LH05					1.				1.	1.		1.		1.				
LH06			1.	1.				1.			1.		1.				900.	900.
LH07					1.				1.	1.		1.		1.				
LH08			1.			1.				1.			1.			240.		900.
LH09				1.		1.		1.		1.	1.				240.		900.	
LH10				1.			1.		1.			1.				240.		900.
LH11	③					1.	1.	1.	1.	1.					240.	240.		
Y1001																		
Y1002																		
Y1003																		
Y2003																		
Y1004																		
Y1005																		
Y1006																		
Y1007																		
Y1008																		
Y1009																		
Y2009																		
Y1010																		
Y2010																		
Y1011																		
SU001																		
SU002																		
SU003																		
SU004																		
Z1001																		
Z2001																		
P0001																		
0 0 UHDUP															1.	1.	1.	1.
0 0 UHOLO															0	0	0	0
COST																		

Row	C0100	C0201	C0202	C0000	C0400	C0500	H1001	H2001	H1002	H2002	H1003	H1004	RHS
SH12	200.	200.	-150.	0	0	⑫							≤ 0
SH23	0	100.	-135.	100.	150.	0							≤ 0
SH34	0	152.	-112.	0	135.	100.							≤ 0
SH14	0	0	500.	0	0	0							≤ 0
RT59													≥ 200. ⑥
RT63													≥ 100.
DD64													≥ 240. ⑨
DD69													≥ 900.
LH01													≤ 0
LH02													≤ 0
LH03													≤ 0
LH04													≤ 0
LH05													≤ 0
LH06													≤ 0
LH07													≤ 0
LH08													≤ 0
LH09													≤ 0
LH10													≤ 0
LH11													≤ 0
Y1001													≥ 0 ⑬
Y1002													≥ 0
Y1003													≥ 0
Y2003													≥ 0
Y1004													≥ 0
Y1005													≥ 0
Y1006													≥ 0
Y1007													≥ 0
Y1008													≥ 0
Y1009													≥ 0
Y2009													≥ 0
Y1010													≥ 0
Y2010													≥ 0
Y1011													≥ 0
SU001	0	0	0	0	0	0 ⑫	[illegible]	[illegible]				⑮	≤ 0
SU002	0	[illegible]	[illegible]	0	0	0			[illegible]	[illegible]			≤ 0
SU003	0	152.	-122.	0	135.	0					[illegible]		≤ 0
SU004	0	0	0	0	0	0						[illegible]	≤ 0
Z1001							1.	-1.				⑯	≥ 0
Z2001									2.	-1.			≥ 0
P0001		1.	1.			⑰							= 1
0 0 UHDUP	1.	1.	1.	1.	1.	1.	1.	1.	1.	2.	2.	3.	
0 0 UHOLO	1.	0	0	1.	1.	1.	0	0	0	0	0	0	
COST							300.	500.	[illegible]	[illegible]	[illegible]	500.	

Row	X1001	X2001	X1002	X2002	X1003	X2003	X3003	X1004	X2004	X1005	X2005	X1006	X2006	X1007	X2007	X1008	X2008	X1009	X2009	X3009	X1010	X2010	X3010	X1011	X2011
SH12																									
SH23																									
SH34																									
SH14																									
RT59																									
RT63																									
DD64																									
DD69																									
LH01	-600.	-600.																							⑩
LH02			-600.	-600.																					
LH03					-1200.	-1200.	-1200.																		
LH04								-600.	-600.																
LH05										-600.	-600.														
LH06												-1200.	-1200.												
LH07														-600.	-600.										
LH08																-1200.	-1200.								
LH09																		-1200.	-1200.	-1200.					
LH10																					-1200.	-1200.	-1200.		
LH11																								-600.	-600.
Y1001	1.	-3.																							⑪
Y1002			1.	-1.																					
Y1003					1.	-1.																			
Y2003						3.	-1.																		
Y1004								1.	-3.																
Y1005										1.	-2.														
Y1006												1.	-3.												
Y1007														1.	-3.										
Y1008																1.	-2.								
Y1009																		1.	-1.						
Y2009																			2.	-1.					
Y1010																					1.	-1.			
Y2010																						3.	-1.		
Y1011																								2.	-1.
SU001																									
SU002																									
SU003																									
SU004																									
Z1001																									
Z2001																									
P0001																								⑱	
0 0 UHDUP	3.	1.	1.	1.	1.	1.	3.	3.	1.	2.	1.	3.	1.	3.	1.	3.	1.	1.	1.	2.	1.	1.	3.	1.	2.
0 0 UHOLO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COST	100.	300.	100.	300.	100.	300.	100.	100.	300.	150.	450.	100.	300.	100.	300.	150.	300.	150.	450.	150.	150.	450.	150.	350.	150.

FIG. 14 - BASIC PROBLEM MATRIX

M (SN12, C0101) = 100 infers that for the first demand pair of the switching network; the switching network link joining nodes 1 and 2 (SN12) is used and the demand on this link is 100 voice circuits.

M (SN12, C0201) =M (SN12, S0101) = -1 refer to the second demand pair of the switching network. Two profiles are possible. The first profile, if chosen, places a demand for 200 voice circuits on the switching network link SN12. If on the other hand the second profile is chosen, 150 voice circuits are released from SN12. It should be noted that when a demand on the switching network results in more than one profile, the profiles for that demand pair are mutually exclusive and only one profile may be used at a time.

The demand on link SN12 can, therefore, vary as a function of profiles chosen. In this example the demand on SN12 can be either 300 voice circuits (100 + 200) or -50 voice circuits (100 + (-150)) depending on the profile chosen by the branch and bound algorithm of TRANCHE III.

Type 2: Demand Rows and Columns

In Hermes I and II demand was defined in blocks of channels. The Hermes III model has the capability of accepting demand in units of voice circuits (or 4 Kg circuits).

Rows beginning with the letters RT identify a demand found in sub-block 6 (right side sides) i.e. RT59 refers to a demand on the transmission facilities network between nodes 5 and 9. The demand required must be greater than or equal to 200 voice circuits (sub-block 6 $\gtrsim$ 200)

The admissible chains that can possibly satisfy this demand are the columns beginning with the letter R. Column R0101 identifies the first admissible chain for the first demand pair. Similarily R0201 refers to the second admissible chain for the first demand pair.

M (RT 59, R0101) = M (RT 59, R0201) = 1 (in sub-block 4) sets the corresponding for the chains R0101, R0201 which may possibly satisfy the demand of 200 voice circuits for demand pair RT 50.

Sub-block 5 identifies the transmission facility links making up a specific chain (activity levels for chains).

Type 3: Demand Rows and Columns

The new formulation of Hermes III permits the specification of row divisible demands (i.e. Satellite Television).

Rows beginning with the letters DD identify non-divisible demand found in sub-block 7 (right hand sides) i.e. DD 84 refers to a non divisible demand on the transmission facilities network between nodes 8 and 4. The demand required (as in the sample problem) must be greater or equal to 240 voice circuits. (sub-block 7 $\gtrsim$240).

Columns commencing with the letter D idenrify the associated admissible chains i.e. D 0101 is the first chain made up of links (sub-block 8) LN 09 and LN 11 which may be capable of satisfying indivisible demand DD84 $\gtrsim$ 240 voice circuits. The matrix element M(DD 84, D0101) = 240 along with the right hand side constraint $\gtrsim$ 240 ensures that only one chain can be chosen to satisfy this indivisible demand.

In the preceeding discussion we have used the phrase "admissible chains that can possibly satisfy this demand". It should be noted that the admissible chains are not tested for capacity requirements in CADUCEE III. The link capacities are only tested for TRANCHE III. If, for example, there exists only one chain for a particular demand and furthermore a specific link on the chain does not have sufficient capacity to fullfill this demand, then a feasible solution does not exist.

Facility Rows and Columns

There are two types of facilities which need to be considered.

1) Transmission facilities

2) Switching facilities

Transmission facilities

The transmission facility links are identified by rows beginning with the letters LN. Link 1 of the transmission facilities network is named LN01.

The investment activities on the links LN are associated by the columns beginning with the letter X.

The matrix element M (LN01, X1001) = -600 (sub-block 10) infers that the first set of investment activities on link LN01 is measured in a unit block of 600 voice circuits. The maximum number of these 600 voice circuit blocks that can be used to satisfy a specific demand has an upper bound of three (sub-block 12) and a lower bound of zero. Furthermore the installation of each 600 voice circuit block costs $ 10,000.00.

A demand of 300 voice circuits on link LN 01 would require the installation of the first 600 voice circuit block at a cost of $ 10,000.00. Extending this analysis, a demand increase from 1 to 600 voice circuits would cost $ 10,000.00. Table 11 shows the range of circuits and associated costs for link LN 01.

TABLE 11

Ranges of demand and associated costs of link LN01

Demand	Cost
0 $\geq$ voice circuits $\leq$ 1	$ 0 000
1 $\leq$ voice circuits $\leq$ 600	$ 10 000
600 $\leq$ voice circuits $\leq$ 1200	$ 20 000
1200 $\leq$ voice circuits $\leq$ 1800	$ 30 000
1800 $\leq$ voice circuits $\leq$ 2400	$ 60 000

To ensure that the requirring of facility installations are met, ordering constraints are required.

The rows beginning with the letter y and sub-block 11 and 13 are employed for this purpose.

	x1001	x2001	x1003	x2003	x3003	
Y1001	1	-3				0
Y1003			1	-1		0
Y2003				3	-1	0
Bound up	3	1	1	1	3	
Bound lo	0	0	0	0	0	

TABLE 12

Sequencing constraints

Referring to table 12, it is shown that in order to install the second set of facilities on link LN 01 (i.e. X 2001) the constraints force the first set of facilities X 1001 to be installed up to the maximum of 3 blocks of 600 voice circuits or 1800 voice circuits. If X 1001 is set to zero by the lower bound, and x 2001 is set to 1 by the upper bound, than y 1001 equals -3 which does not satisfy the constraint that y1001 must be greater than or equal to zero.

Tables 13 and 14 depict whether the constraints are met for all possible values of X1003, X1003, X1003 for link LN 03 respectively.

x_{1001}	x_{2001}	Y 1001 takes the value	Is the constraint met?
0	0	0	yes
1	0	1	yes
0	1	-3	no
2	0	2	yes
2	1	-1	no
3	0	3	yes
3	1	0	yes

TABLE 13

Test of ordering constraints on LN01

x_{1003}	x_{2003}	x_{3003}	Value of Y 1003	Value of Y 2003	Is the constraint met?
0	0	0	0	0	yes
1	0	0	1		yes
0	1	0	-1	3	no
1	1	0	0	3	yes
0	0	1	0	-1	no
1	1	1	0	2	yes
1	1	2	0	1	yes
1	1	3	0	0	yes

TABLE 14

Test of ordering constraints on LN03

Switching facilities

The Hermes III model permits the utilization of investment activities at switching nodes. The CHARGE module generates the number of lines required to be switched at the switching nodes in the switching network.

The switching nodes are identified by the rows beginning with the letters SW. Row SW 001 refers to node 1 of the switching network. The profiles of the switching nodes (sub-block 14) and the corresponding number of lines therein are generated by CHARGE.

Matrix element M (SW 002, C 0201) = 180 infers that for a demand between nodes 1 and 4 in the switching network and the choice of profile C0201 (contemplated HU group between nodes 1 and 4 not installed) there is a requirement to switch 180 lines at switching node 2 (SW 002). Also, node 3 requires switching capacity of 152 lines M (SW 003, C0 201) = 152).

Sub-block 15 is analogous to sub-block 10, and sub-block 16 is analogous to sub-block 11.

The investment activities of switching facilities are identified by columns beginning with the letter N. These columns are analogous to the investment activities of columns beginning with the letter X. Also the rows starting with the letter Z are for the purpose of sequencing constraints on switching activities and are similar to the Y rows.

Rows beginning the the letter P are compatability constraints on the profiles chosen from CHARGE. Columns C 0201, C 0202 are two profiles created by the non-inclusion or inclusion of the HU group between switching nodes 1 and 4. As previously mentioned, these profiles are mutually exclusive and only one may be chosen.

When matrix element M (P0001, C0201) = 1, the righthand side constraint = 1 (sub-block 18) must be met. This constraint faces the element M (P0001, C0202) to zero. Similarly, if M (P0001, C0202) = 1, then the constraint faces M (P0001, C0201) to equal 0.

4. THE USES OF HERMES III

The original purpose of the Hermes project was to develop methodology for planning interregional telecommunications network capacity expansion from an initial state at minimum capital cost, given certain hypothetical configurations of demand changes and other constraints. The result of the Hermes project to date has been the series of models Hermes I, II and III.

This chapter describes the possible range of uses of the Hermes III software. In the course of developing Hermes III, considerable improvement has been made to the original software developed for Hermes I. However although the formulation of Hermes III goes beyond that of the earlier models, the fundamental purpose remains the same. Therefore the primary use of the Hermes III model must be as a tool for determining the least cost capacity expansion program for the interregional, or more properly, inter-toll facilities network.

As well as the primary use of the software, this chapter describes the possible uses of Hermes III as a simulator. In addition, the uses which can be made of certain modules of the software independently to solve certain types of problems are described.

4.1 Determining the capacity expansion program

The determination of a least cost capacity expansion program is the basic purpose of Hermes III. The basis of determining this program is a mixed-integer lineas programing formulation. The description of the whole of the software of Hermes III and its use in determining the least cost facilities expansion program is the subject of the rest of this report and will not be dealt with at length here. A full description of mathematical programming and its application to telecommunications networks is contained in the reports produced during the earlier phases of the Hermes project.

The outputs which describe the minimum cost facilities expansion program are as follows:

1. A facility network represented by:
   - a link capacity matrix (indicating the number of trunks by pairs of connected nodes)
   - a node capacity matrix

2. A switching network identifying the final, HU and Full Groups and the number of circuits of each group.

3. The minimal total capital (on annual basis) and operating costs of the above proposed network divided into: total nodal cost, total transmission cost, additional cost occasioned by the survivability requirements.

4.2 Determining the effect of changes in predefined conditions

The Hermes III Model makes use of techniques which ensure that any capacity expansion program obtained is mathematically rigorously optimal. However, the optimal solution is obtained within the configuration of a set of predefined condition. These conditions are necessary due to the very large number of variables, non-convexity, and the combinatorial nature of the problem. In order to evaluate the wide range of possible alternatives which could be posed by the D.O.C., recourse to simulation becomes inevitable. This approach differs from the simulation approach using Monte Carlo methods whire sub-optimal solutions are aimed at.

Although the model proceeds by searching for an optimal solution among the feasible solutions it is practical to remember that the model's importance lies in the first place in sorting the feasible and non-feasible solutions. The non-existence of feasible solutions simply means that the predefined conditons contain contradictions.

In view of the above observation, it would be wasteful and virtually impossible to develop a software package capable of handling any possible situation that might be required. There is a trade-off between a large unwieldly software package versus repeated uses of a more compact package with user intervention between successive runs. This section of the report deals with the use of the Hermes software as a simulator. Table 15 shows those those preconditions or simulations which are considered suitable and useful for the initial Hermes III software.

4.2.1 Certain types of reliability conditions

The March 1972 report discussed the question of handling survivability in the Hermes family of models. It is to be remembered that survivability requirements refer to the facilities network and not to the switching and the facilities networks simultaneously. The principle of handling the survivability requirements remain essentially the same as those outlined in the 1972 report.

The main burden of dealing with the survivability requirement is likely to fall on the simulation approach. It must be stressed how important it will be to narrow the range of possible survivability requirements to be considered and to identify all the special features of any given problem which might reduce the number of simulations required.

An important by-produced of using the model to handle survivability requirements will be, of course, the estimation of the additional cost of satisfying them.

It is to be pointed out that the imposition of survivability requirements enhances the likelihood of the non-existence of feasible solutions. This is one of the reasons why provisions are being made for partial relaxation of these requirements.

TABLE 15: POSSIBLE SIMULATIONS WITH HERMES III

1. Certain types of reliability conditions (survivability)
2. Changes in hierarchical structure
   a) Changes in homing rules (Final basic trees with no changes in hierarchical status of any node)
   b) Changes in hierarchical status (changes in homing rules become inevitable)
3. Changes in blocking probabilities
4. Changes in overflow rules (single vs multiple overflows)
5. Changes in contemplated HU groups
6. Changes relating to the facilities network
   a) Changes in cost functions
   b) Changes in initial state (important for planning over a period of time)
   c) Adding financial constraints (important for planning over a period of time)
   d) Changes in the facilities network itself.

4.2.2 Consequences of changes in hierarchical structure

These are essentially of two types dealing respectively with changes in homing rules with the hierarchical status of every node remaining the same and changes in the hierarchical status of one or more nodes (the second type necessarily involves changes in homing rules). These would be handled by the simulation approach. In order words the implications in terms of costs of changes in the hierarchical structure would be determined by successive runs of the model.

4.2.3 Changes in blocking probabilities

In the formulation of Hermes III, the blocking probabilities on final groups and the overflow probabilities on HU groups must be given. In other words a single run of the model will not indicate what these probabilities ought to be.

On the other hand, questions dealing with the consequences of having alternative blocking probability requirements, consequences which effect the capacity expansion program and the associated cost, which are the main output of the model, are af obvious interest to the D.O.C.

Blocking probability on final groups determines a lower bound on the overall grade of service between pairs of demand points. In this case overall grade of service is defined in terms of "point-to-point" blocking probability. The blocking probability on final groups (and hence the lower bound on overall grade of service) can be changed from run to run and the resulting changes in cost calculated.

If the blocking probability on final groups is fixed, the overall grade of service associated with each solution depends on the overflow probability of the HU groups. Various levels of overflow probability could be assigned and the cost of the optimal solutions determined for these levels. The costs of these solutions could then be compared.

4.2.4 Changes in overflow rules

Overflow rules deal with diverting traffic load from HU groups to other groups.

As in the case of blocking probabilities, overflow rules are part of the input data of any given problem submitted to the model. The capacity of assigning different overflow probabilities to each link is essentially a question of making the model more sophisticated and more realistic. Changes to overflow rules would be handled by simulation.

4.2.5 Changes in the set of contemplated trunk groups

A switching network consists of a basic final tree and a set of HU and full groups. In any problem, this constitutes part of the data. The optimization problem considers a reasonable finite number of contemplated or potential HU and/or full groups with a clear identification of either category. The model then chooses the optimal capacity expansion program of the facilities network, deciding as it goes along which of the contemplated HU groups are to be installed and what their capacities are to be.

The model is restricted in choice to selecting from the specified list of contemplated HU and/or full groups. It is thus clear that the solution obtained is a sub-optimal solution of the more general problem, in which all possible HU and/or full groups are specified as contemplated. Solving a problem of such magnitude is clearly beyond the realm of practicality. Investigating the consequences of altering the set of contemplated trunk groups will be handled by simulation. It is stressed, however, that within the terms of any problem specified as above, the model will yield a mathematically rigorously optimal solution.

4.2.6 Changes relating to the facilities network

This simulation problem has been previously handled in Hermes I and II. Since we are incorporating every essential feature of Hermes I and II into the Hermes III Model, it is clear that Hermes III is capable of simulating changes in the physical network.

Several passages in earlier reports and working papers deal with this question.

4.2.7 Planning over a period of time

The definition of cost functions is annual operating and investment costs. This feature of Hermes III makes it more realistic in handling planning over time than Hermes I and II. However, this problem must be handled by simulation.

A small number of successive periods could be considered. Two to four periods would be reasonable. Demand increases over time are step functions of time and assumed to be deterministic. Demand for any period, actually specified, may exceed the minimal requirements for that period. It may include a margin of excess capacity which will not be used until some future period but which it may be advantageous to put in place already now because of the economics of scale. The The results of the simjlation could be used to adjust the intial capacities of the second second period and so on. This procedure would be continued until the final period period were reached. Of course, the state of the network at the end of the planning period must be specified. The arbitrariness of this specification is softened by the use of present discounted values.

The number of simulation runs could be quite considerable even for a small number of per periods.

The simulation methodology would not result in a global optimum for planning over time but will permit the comparison of alternative expansion programs, and the orders of magnitude of trade-offs between them over various planning horizons and hypotheses.

4.3 Utilisation partielle du modèle

La version actuelle de Hermes III permet à l'utilisateur de ne faire appel qu'à certains modules. Les options sont les suivantes:

(a) Module CHARGE seulement

(b) Modules CADUCEE III et TRANCHE III

(c) Modules CHARGE, CADUCEE III et TRANCHE III.

Lorsque l'utilisateur ne s'intéresse qu'aux accroissements de charges sur le réseau de commutation générées par des accroissements de demande entre paires de points de ce réseau, il utilise l'option (a). Par contre, s'il ne s'intéresse qu'au réseau physique, il utilise l'option (b), ce qui revient à utiliser le modèle Hermes II. S'il désire tenir compte et du réseau de commutation et du réseau physique, alors il utilise l'option (c), c'est-à-dire le modèle Hermes III.

Ainsi, nous pouvons voir que le modèle Hermes II correspond formellement à l'option (b) du présent modèle. Cependant, nous soulignons ici que le fait d'utiliser l'option (b) revient à utiliser une version améliorée du modèle Hermes II puisque le module CADUCEE qui sera utilisé est CADUCEE III et non CADUCEE II.

5. POSSIBLE EXTENSIONS OF HERMES III

The Hermes III software is an extension of software developed during the earlier phase of the Hermes project. While Hermes III represents a very large step forward both conceptually and in programming from the original model, there are several areas where improvements should be made. There are treated here at two levels: conceptual and software.

5.1 Conceptual extensions

5.1.1 Survivability

As describes in the interim report on Part 2 of the Hermes project, it would appear possible that certain aspects of survivability could be handled by incorporating them as constraints in the model. While survivability must now be treated as a simulation application of the software, it would be possible, if this method of handling survivability were developed, to reduce the volume of required simulation. It would of course mean increased complexily in the software and in the model formulation.

5.1.2 Planning over several periods of time

Optimizing on two simultaneously should be studied. The size of the problem with one period only is more than doubled when we considered 2 periods, for two reasons: 1) we need compatibility constraints for the configurations of the two periods; 2) in order to find the admissible chains for the second period we need high upper limit since we don't know what the results are for period 1 and we must content ourselves with the lower limit of the 1 period for the same reason.

5.1.3 Cost functions

It has been brought up in several earlier reports, that we could use piecewise linear cost functions with real arguments. The problem in using such type of functions is at the CADUCEE level. We would have to work with slopes and steps instead of slopes only. This amounts to increase the ratio between the upper and lower bounds and we don't know if CADUCEE will be efficient enough in screening the dominated chains. In any case, a new CADUCEE should be written and a new TRANCHE also.

5.2 Software extensions

The software of Hermes III is operational in that CHARGE, CADUCEE III and TRANCHE III are running and can produce acceptable results. However, the software is still largely experimental, and lacks the polish of earlier versions of Hermes. The improvements which should be made at the software level are described below.

5.2.1 Inter-module linkages

The output of one module acts as input to the next and therefore these linkages must exist or the software is not operational. However, at present, some manual intervention is required to effect this linkage. As a first improvent, the linkage should be made fully automatic and under the control of option selection inputs from the user. As described in the section on the usage of Hermes III, the selection of modules and their independant operation would be very desirable and practical if done in this manner.

5.2.2 Report writer and plotting routine

The output of Hermes III is still at the level required for the development of the software. While this is sufficient from the point of view of those who use the software regularily, the output is in fact difficult to read. A report writer, therefore, would lie a very usefull extension of the software. As an extension of the report writer, a routine which produced maps or plots of the solutions would be usefull from a legibility point of view.

5.2.3 Automation of simulation procedure

At present, if the software is to be used for simulation, requiring several passes of the model, each pass must be set up as a seperate run. Certain types of simulation runs, which might be required more frequently, might well be considered as cancidates for automation. Essentially, this would involue the development of a "front end" program which would specify the initial conditions and changes to these conditions to the Hermes software.

5.2.4 User's manual

While not strictly a software extension, the utility of a user's manual for the Hermes III software is obvious.

5.3 <u>An extension of the model's use as a planning tool</u>

The proposal outlined here describes in brief the type of study which could be carried out by D.O.C. using Hermes software to its fullest as a planning tool. This project is offered by way of an example.

The suggestion made here starts from the assumption that a large number of users, business, but mostly households would be prepared to wait a "reasonable" period (say, up to 10 minutes on the average) before having their long distance calls put through, if they get a reasonable price reduction. The idea is, of course, borrowed from that used by the airlines. There would be 2 types of direct-dialing long distance calls. The first would remain as it is. The second, which might start with the digit 2 instead of the digit 1 for instance, would be a stand by call. The user would dial the regional code and the number she wants to reach and will then hang up and wait. As soon as a connection is established the phones would ring in both places.

This would of course require appropriate arrangements including equipment to store the waiting calls. These should not be too complicated. One might note that no more than 26 digits will have to be stored: 10 digits for the call of origin, 10 digits for the destination call and 6 digits to record the time the call was placed. It is by no means necessary that this storage of the waiting calls be done at all the levels of the switching hierarchy. One might well imagine that this storage takes place only at some higher level of the hierarchy. It is to be noted that this arrangement could be introduced piecemeal on different parts of the system, starting even with a single pair of demand points.

It would probably be too complicated to search continuously for free circuits and to put throuth the waiting calls of the second type. Though this might perhaps be possible with Full Groups and perhaps even High Usage groups. It not, every, say, 1 or 2 minutes the system would try to put the waiting calls through. As with air freight (though not with "stand-by" passengers) one could envisage that calls that had been waiting, say, 10 minutes, are automatically put into the stream of regular long-distance calls.

It will be noted that this arrangement will inevitably lower the quality of service of the regular calls (the capacity of the facilities being kept constant, of course). A very important problem would be to find the appropriate price differential between the two types of long distance calls. We have absolutely no experience on which to base estimates of the responsiveness of consumers to the quality of service as it is understood in the sense used here, that is, in the sense of having to wait for a long distance call to go through.

The Model Hermes III is perfectly capable of handling the extension outlined above, given, of course, time and the resources necessary which it would be difficult to estimate at the present stage. In any case, any serious discussion of this proposal would involve very intense collaboration with the technical personnel of the D.O.C. The objective of the proposal is, of course, to reduce the facility expansion requirements in the coming years while giving the users a choice, compatible with the logic of the price system, between at least two different qualities of service.

APPENDIX 1

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APPENDIX 2

Mathematical formulation of TRANCHE III

APPENDIX 2

MATHEMATICAL FORMULATION OF THE MIXED LINEAR PROGRAM IN TRANCHE III

1 THE VARIABLES OR ACTIVITY LEVELS

1.1 For circuits assignment activities

- Sets of indices:

A: is the set of all pairs of adjacent nodes of the switching network for which CHARGE has found at least one configuration with nonzero new circuit requirements (demand).

R(i): is the set of admissible chains in the transmission network for i belonging to A.

- Variables:

x(i;j): is the activity level, a non-negative number, which is the number of new circuits assigned on chain $j \in R(i)$ to satisfy the whole or part of the requirements for new circuits for i belonging to A.

1.2 For relevant switching network configuration creation activities

- Sets of indices:

D: is the set of all pairs of demand points.

C(t): is the set of configurations for t belonging to D.

H(t): is the set of relevant contemplated links in the switching network for the configurations contained in C(t).

- Variables:

d(k;t): is equal to 1 if the configuration $k \in C(t)$ is created and is equal to zero otherwise.

1.3 For investment activities

- Sets of indices:

KL: is the set of links of the transmission network for which capacity expansion activities (or filling up activities) are possible.

TL(k): is the set of capacity expansion (investment or filling up) activities for k belonging to KL.

KS: is the set of switching nodes for which capacity expansion activities (or filling up activities) are possible.

TS(k): is the set of capacity expansion (investment of filling up) activities for k belonging to KS.

- Variables:

y(k;j): is the number, an integer, of blocks of circuits put into place to increase the capacity on link k belonging to KL or node i belonging to KS by means of investment activity j belonging to TL(k) in the case of a link or belonging to TS(k) in the other case.

Note we use the same symbolism for the level of a "filling up" activity and we will not mention this type of activity anymore.

2 THE CONSTRAINTS

2.1 Assignment of a sufficient number of circuits to satisfy the demand

$$\sum_{j \in R(i)} x(i;j) - \sum_{t \in D} \sum_{k \in C(t)} n(i;k;t) \,.\, d(k;t) \geq 0 \;,\; i \in A$$

Note that the coefficient n(i;k;t): number of new circuits required when configuration k for the pair of demand points t is chosen, has been computed by CHARGE.

2.2 Limitation of circuit assignments and augmentation of capacities

- For the transmission links:

$$\sum_{i \in A} \sum_{j \in R(i)} \delta(j;k) \,.\, x(i;j) - \sum_{j \in TL(k)} b(k;j) \,.\, y(k;j) \leq 0 \;,\; k \in KL,$$

where $\delta(j;k)$ takes the value 1 if the chain j uses the link k, and takes the value 0 otherwise; where b(k;j) is the number of circuits installed by one block of type (k;j) in transmission facility investments.

- For the switching nodes:

$$\sum_{t \in D} \sum_{k \in C(t)} s(i;k;t) \,.\, d(k;t) - \sum_{j \in TS(i)} b(i;j) \,.\, y(i;j) \leq 0 \;,\; i \in KS;$$

note that the coefficient s(i;k;t): number of new lines required when configuration k for the pair of demand points t is chosen, has been computed by CHARGE. The coefficient b(i;j) is the number of lines installed by one block of type (i;j) in switching facility investments.

2.3 Sequencing of investment activities

For a given k belonging to KL (or KS):

First case: all levels of investment activities take the values 0 or 1 only.

The sequencing constraints are

$$y(k;j) \geq y(k;j+1) \quad j \in TL \text{ (or TS)}$$

since the investment activities are ordinally ordered and we assume that the numerical indices are assigned in the same order.

Second case: the levels of investment activities alternate in the following sens:

the first activity has a 0,1 range of integer values,

the second activity has a 0,1,2,3,..., $\bar{y}(k;2)$ integer values,

the third activity has a 0,1 range again,

the fourth activity has a 0,1,2,3,..., $\bar{y}(k;4)$ range,

and so forth.

This kind of pattern is always possible to impose.

The sequencing constraints become

$$\bar{y}(k;2) \,.\, y(k;1) \geq y(k;2)$$
$$y(k;2) \geq \bar{y}(k;2) \,.\, y(k;3)$$
$$\bar{y}(k;4) \,.\, y(k;3) \geq y(k;4)$$

etc ...

2.4. Compatibility constraints

- Mutual exclusiveness for the configurations:

$$\sum_{k \in C(t)} d(k;t)=1 \;, \; t \in D.$$

- Compatibility of configurations:

A contemplated link i in the switching network belong to $H = \bigcup_t H(t)$. Call $t_{j_1}, t_{j_2}, \ldots, t_{j_n}$ a permutation of the n elements of D. If the link i belongs to only one H(t) there is no need of compatibility constraints, since the mutual exclusiveness constraint for the set C(t) will be sufficient.

If the link i belongs to more than one H(t), we will establish compatibility constraints, for each i, the following way.

Call $H(t_{j_1}), H(t_{j_2}), \ldots, H(t_{j_k}), (k \leq n)$, the sets which contain the link i.

Then, for each link i belonging to H, we have the set of constraints as follows:

$$\sum_{k \in C(t_{j_1})} \delta(i;k) \, . \, d(k;t_{j_1}) - \sum_{k \in C(t_{j_2})} \delta(i;k) \, . \, d(k;t_{j_2}) = 0$$

$$\sum_{k \in C(t_{j_{n-1}})} \delta(i;k) \, . \, d(k;t_{j_{n-1}}) - \sum_{k \in C(t_{j_n})} \delta(i;k) \, . \, d(k;t_{j_n}) = 0$$

where $\delta(i;k)$ takes the value 1 if the link i is involved in configuration k and 0 otherwise.

Since the mutual exclusiveness constraints secure us with only one d(k;t) in each set of configurations C(t), we will have a pattern as shown below:

1	-1			=	0
	1	-1		=	0
		1	-1	=	0

which implies the simultaneous existence of a given contemplated link in all the chosen combination of configurations that need it. In other words we have the following string of equivalent propositions:

(The configuration chosen for t_{j_1} has the link i) if and only if

(the configuration chosen for t_{j_2} has the link i) if and only if

... if and only if (the configuration chosen for t_{j_n} has the link i).

Note that this string of propositions is equivalent to the string of negations of the same propositions, so it is not necessary to impose compatibility constraints for the configurations which do not contain the link in question.

2.5 Bounding constraints on the activity levels

$x(i;j) \geq 0$, $i \in A$, $j \in R(i)$.

$d(k;t)$ is a zero-one variable , $t \in D$, $k \in C(t)$.

$y(k;j)$ is a non negative integer less than or equal to $\bar{y}(k;j)$, $k \in KL$, $j \in TL(k)$.

$y(k;j)$ is a non negative integer less than or equal to $\bar{y}(k;j)$, $k \in KS$, $j \in TS(k)$.

3 THE OBJECTIVE FUNCTION

Call z the total expansion cost. The investment activities only have nonzero marginal cost coefficients in the linear form we want to minimize, therefore the objective function is

$$z = \sum_{k \in KL} \sum_{j \in TL(k)} c(k;j) \cdot y(k;j) + \sum_{k \in KS} \sum_{j \in TS(k)} c(k;j) \cdot y(k;j).$$

This summation is the expansion cost for transmission facilities and for switching facilities. TRANCHE III chooses the best combination of variables subject to the above constraints.