A MODEL FOR PLANNING HIGHWAY INVESTMENTS IN RURAL AREAS: A CASE STUDY FOR A REGION OF SOUTHERN ITALY

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ABSTRACT

We focus on the accessibility of rural areas, in which the need to spend in highway projects is dictated not by the intensity of traffic flows, but by the purpose to pursue a policy of general development of these regions.

In this field the usual criteria for evaluation of highway projects, which are based on construction and maintenance costs, as well as produced internal benefits (reduction in time and cost of travel) are ineffective. We examined many experiences in developing countries, but we verified that, besides some conceptual and theoretical formulations, the idea which underlies the usual methodology is the search of maximum economy.

This principle does not apply to rural areas of developped States. In this case, the pre- existence of a road network, which is sometimes extensive and diffused, as well as inadequate and obsolete, the social and economical environment, the type of vehicles used, require the adoption of construction standards similar to those used in the whole national road system. On this basis, we suggest to pursue the objective of maximizing the accessibility of existing, as well as planned activity locations, by the rehabilitation and the integration of the existing network, effected by the optimal utilization of the available resources. So the identification of priority schemes for investments in the road network is pursued by an optimization technique, in which the objective function is given by an accessibility function. This function has the advantage to include the spatial allocation of activities, and the functional characteristics of the road network, and does not include the traffic flows: and it is well known that the estimation of traffic flows on the links of a network is highly indeterminate, in presence of important changes in the land use.

We formulate our problem in this way: given a network, in which some nodes are sources (sinks) of trips, given the set of existing links, and given the set of the new possible links, select among the new links the subset maximizing the objective function with the given budget constraint. In order to do this, we adopt

a branch and bound procedure, which utilizes the recent acquisitions in the field of network design.

The proposed procedure is applied for the identification of the optimal road network in the development plan of Sibaritide,a wide area in the Southern Italy, near the ancient city of Sybaris.

1. THE DECISION MODEL

1.1. STATEMENT OF THE PROBLEM

Current decisional techniques for roads with high traffic intensity rely essentially on the evaluation of internal benefits to transportation system (reduction of travel time and fuel consumption, increasing in comfort and safety); nevertheless they do not fit the case of rural areas of developped States, since actual flows are light and do not justify any investment by themselves; furthermore the estimates of future flows are affected by an high degree of uncertainty.

Then investment evaluation techniques should include indirect benefits in other sectors of economy (1), but indirect benefits estimations are always difficult, expecially when we are faced with the whole economic environment.

The idea which underlies experiences in underdevelopped countries is often the search for maximum economy, in the terms of construction and maintenance costs; sometimes external benefits, only in the agricoltural sector, are evaluated (2).

The minimum cost principle cannot be applied to our case, since construction and functional standards, similar to those adopted in the rest of the Country, are required; moreover the minimum cost principle would reduce to the statu quo maintenance, as villages in the area are already connected by the existing network.

So the general aim of investments in transportation field is to improve the accessibility of such regions, in order to support social and economical progress (3); we are forced to search the set of interventions in upgrading and integrating the existing infrastructures, in order to achieve the maximum accessibility, in presence of budget constraints.

1.2. THE MATHEMATICAL MODEL

Consider the study area R, which is divided in k subareas; denote by $E = \{e_1, e_2, \ldots e_k\}$ the set of centroids of such subareas; by $P = \{p_1, p_2, \ldots p_k\}$ the set of land use potentials. G(N,A) is the symmetric graph representing the road network; $N = \{1, 2, \ldots n\}$ is the set of network nodes; since we assume that zone centroids coincide with nodes of the graph, it is $E \subseteq N$; $A = A_1 \cup A_2$ is the set of arcs.

$A_1 = \{a_1, a_2, \ldots a_l\}$ is the set of already existing arcs, i.e. existing roads; $A_2 = \{a_{l+1}, \ldots a_m\}$ is the set of design arcs; in particular, we define design arc a new link to be realized, as well as an existing one to be upgraded. Let then $C = \{c_{l+1}, c_{l+2}, \ldots c_m\}$ the set of construction or upgrading costs for the arcs in A_2. We can choose to realize or not each arc in A_2; we denote by $y(i)$ the related decision variable; it is a binary variable, and takes the value 1 in the first case, 0 in the second one; decision variables are arranged in the vector $\overline{y}$. If we denote A'_2 the set of realized design arcs, the set of arcs in $A_1 \cup A'_2$ must connect all the zone centroids.

Introduce then $T = \{t_1, t_2, \ldots t_m\}$, the set of link travel time; since we are dealing with roads in low density areas, which are charged only by local traffic, we presume that travel times are not affected by traffic intensity, i.e. there are no congestion effects. We introduce at last the function:

$$f = \sum_{i=1,k} \sum_{\substack{j=1,k \\ j \neq i}} P_i \cdot P_j \cdot t^{*}_{i,j} ,$$

where $t^{*}_{i,j}$ is the shortest route time between centroids i and j. As $t^{*}_{i,j}$ varies with the y choice, then: $f = f(E, P, G, C, \overline{y})$.

Call b the available budget, the problem may be formulated as follows:

$$\begin{aligned} &\text{minimize} && f(E, P, G, C, \overline{y}) \\ &\text{subject to} && \sum_{j=l+1,m} c_j \cdot y_j \leqslant b. \end{aligned} \qquad (1)$$

The problem (1) belongs to the wide class of network design problems, which encompasse a variety of applications. A general review of these problems is in the references (4, 5).
Peculiar characteristics of our problem are:
a) decision variables are binary;
b) land use potentials, not link flows, are included in the objective function.

1.3. THE SOLUTION ALGORITHM

Problem (1) is a hard combinatorial optimization problem. For its solution we follow to a certain extent a branch and bound procedure developped by G. Gallo (6), which improves that one proposed by Dionne and Florian (7).

The procedure proposed in this paper differs from the mentioned above since the objective function is computed for the set $E \subseteq N$ only, and the existence of already realized arcs is allowed.

The first peculiarity involves that, at each step k of the Branch and Bound procedure, the search for a feasible solution, and hence an upper bound, reduces to find the minimum cost tree spanning the set E; since it often includes only existing arcs, design arcs, being in the subset of feasible solution A_{2k} for the subproblem k, are added to it in decreasing order of the ratios v_j/c_j, where v_j is the penalty function
$f(E, P, N, A_1 \cup A_{2k} - a_j, y) - f(E, P, N, A_1 \cup A_{2k})$
until the budget is filled up.

The minimum spanning tree is found by Prim algoritm (8), adapted to our particular case. At each step i of the algorithm the set E is partitioned in two subsets:
E'_i is the subset of connected centroids, by minimum cost routes, plus the nodes in $N - E'_i$ belonging to these routes;
E''_i is the subset $E - E'_i$.
At step i we compute the minimum construction cost chains between each pair of nodes in E'_i and E''_i, then we include in E'_{i+1} the centroid e_i with minimum connection cost, as well as the nodes in $N - E'_i - e_i$ belonging to the related chain. The minimum spanning tree is found when the subset E''_i is empty.

The second peculiarity involves that, to represent the upgrading of an existing arc, we use dummy nodes and links, as shown in figure 1; dummy links have null lenght and null cost.

Fig. 1. Improvement of an existing link.

2. THE CASE STUDY

2.1. CHARACTERISTICS OF THE STUDY AREA

In this chapter we show an application of the proposed methodology for the Sibaritide, an area for which the Department of Country Planning of the University of Calabria is carring on a scheme of development plan.

The study area, located in the North - East of the Region Calabria, has a surface of approximately 2600 square kilometres (Fig. 2). The altimetry is varied: the Crati valley, narrow in the West, widens in the middle (Sibari plain) and along the East coast; foothill zones of incresing altitude are located all

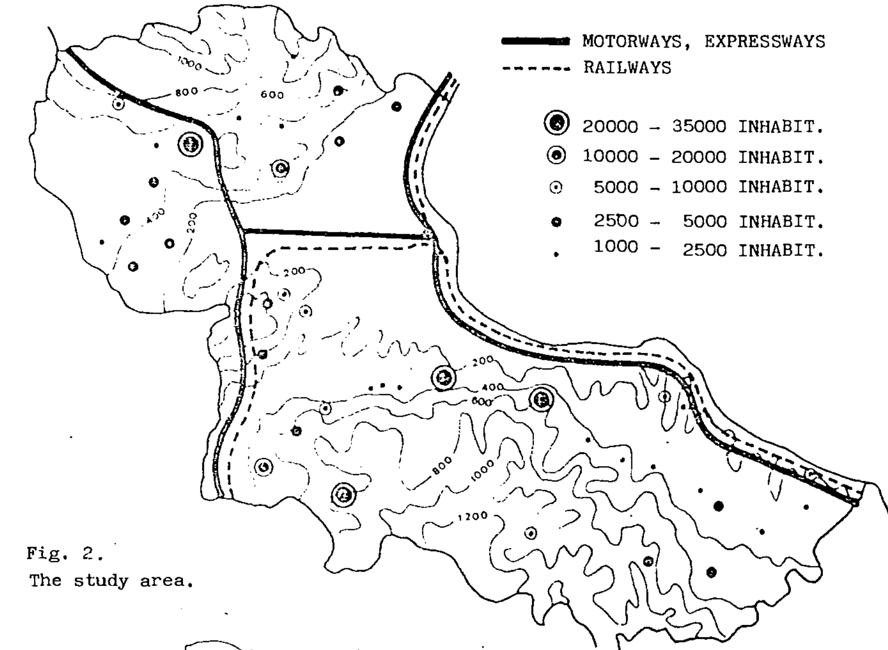

Fig. 2.
The study area.

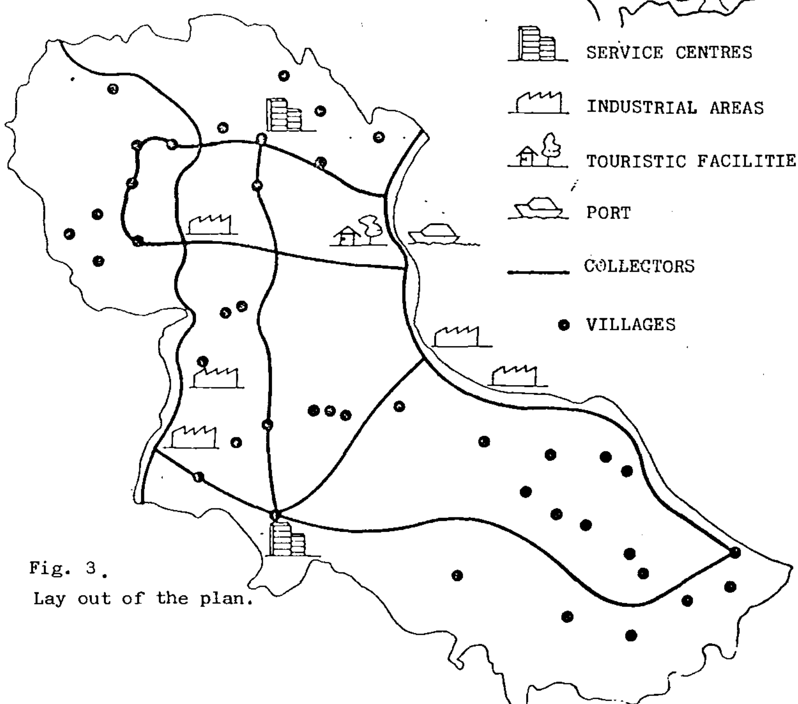

Fig. 3.
Lay out of the plan.

around the plains, and afterwards ridges of greater altitude.

The geological features include limestone in the North (Massif of Pollino), with conglomerates and breccias in the foothill zones; in the South (Plateau of Sila) there are alternations of granite, gneiss and limestone; the piedmont hills are often clayey, and subject to landslides.

The population amounts about 250000 residents; in the past villages were located on the tops of the hills, far from the coast and the plains, to escape Saracen pirates and malaria. In the last years the smaller villages, expecially in the inner area, showed a trend to decrease; on the other side the biggest ones had an increase in population and activities; now touristic facilities are getting up along the coast.

Active population is employed mainly in agricolture and in tertiary activities.

2.2. THE TRANSPORT SYSTEM

The actual road network amounts to about 1000 route kilometres; there are 65 kilometres of motorways and 84 kilometres of expressways.

The network includes two main North - South axes, with a cross axis connecting them; these roads, of recent construction, have good design standards, light traffics, and, on the whole, a good level of service.

The rest of the network embraces obsolete roads, with very poor design standards; the design speed, in the hilly and mountainous zones, frequently does not exceed 30 km/h.

The railway network includes two single track lines, which run parallel to road axes; since plants are obsolete, station far from villages, trains supply poor, railways have only a modest function in the transport system.

2.3. THE PROPOSED PLAN

The general development plan provides a distribution ipothesis for population and activities, referring to the increases in the target year (2000).

The figure 3 shows the general lay-out of the plan; it consists in a loop connecting activity centres (industrial areas, service centres, et c.), located in the plain and foothill areas, and a set of feeders connecting villages. All demographic and activity development is located along this loop.

ZONE N°	AREA SQ.KM.	POPULATION	WORKERS AGRICOLTURE	INDUSTRIES	SERVICES	LAND USE POTENTIAL
1	248.6	55000	1600	2100	7000	139286
2	325.5	31000	1900	3400	2900	80582
3	134.6	11500	1400	1200	700	25667
4	94.0	19000	1800	1500	1100	39026
5	99.3	15500	1900	1700	800	33595
6	49.4	3000	400	5850	150	38451
7	142.3	12000	1800	1250	800	27487
8	196.0	33000	2650	10000	2000	111564
9	85.3	10000	500	9000	250	64740
10	198.5	42000	1400	3600	7000	134980
11	193.2	39000	1650	900	2350	68426
12	310.1	12000	1300	1050	600	24267
13	405.0	24500	1350	2500	1200	51352
14	50.0	-	-	9000	-	52164
15	60.4	-	-	-	3000	30906
TOTAL	2592.2	307500	19650	53050	29850	922483

Table 1. Planned zone characteristics

The study area has been divided in 15 zones, of which planned populations and workers for sector of activity are referred in the table 1; we define for each zone the land-use potential:

$$LUP(I) = POP(I) + K1 \cdot WI(I) + K2 \cdot WS(I),$$

where POP(I), WI(I), WS(I) are respectively the population, the workers in industries and in tertiary activities of the zone I; the constants K1 and K2 are scale factors to equalize the relative wheights of population and workers, and are given by:

$$K1 = \sum_{I=1,k} POP(I) \;/\; \sum_{I=1,k} WI(I)$$

$$K2 = \sum_{I=1,k} POP(I) \;/\; \sum_{I=1,k} WS(I)$$

The zone centroids coincide with the equal nodes of the route network graph.

2.4. THE DECISION NETWORK

One of the focus problem of the plan is the road network, which plays an essential role in the functional linkage of the system;

LINK N°	NODES		LENGHT KM	OVERALL SPEED KM/H	TRAVEL TIME MINUTES	COST IT.LIRES BILLIONS
1	1	2	11.70	40	17.55	0.00
2	1	4	16.70	40	25.05	0.00
3	1	14	18.50	77	16.25	0.00
4	1	17	19.60	50	23.52	0.00
5	2	3	23.00	30	46.00	0.00
6	2	14	20.70	73	19.70	0.00
7	3	14	8.00	40	12.00	0.00
8	4	14	11.50	80	8.63	0.00
9	4	15	9.70	80	7.27	0.00
10	5	6	16.40	40	24.60	0.00
11	5	14	20.10	44	28.65	0.00
12	6	9	5.00	100	3.00	0.00
13	6	14	17.60	100	10.56	0.00
14	7	8	23.80	34	42.00	0.00
15	7	9	22.30	30	44.60	0.00
16	7	10	16.60	30	33.20	0.00
17	8	10	48.00	30	96.00	0.00
18	8	11	22.70	80	17.03	0.00
19	8	15	10.50	80	7.88	0.00
20	9	10	23.90	30	47.80	0.00
21	10	12	61.20	30	122.40	0.00
22	11	12	10.80	40	16.20	0.00
23	11	16	20.00	80	15.00	0.00
24	12	13	22.00	30	44.00	0.00
25	13	16	28.00	30	56.00	0.00
26	15	17	7.80	80	5.85	0.00
27	1	2	9.28	80	6.96	4.52
28	1	4	12.80	80	9.60	14.85
29	1	17	17.18	80	12.89	13.77
30	2	3	17.18	60	17.18	17.46
31	3	14	6.35	60	6.35	4.84
32	4	5	7.95	80	5.96	8.19
33	5	7	15.15	80	11.36	17.26
34	7	10	11.39	80	8.54	12.10
35	8	10	21.52	60	21.42	34.14
36	9	10	15.44	80	11.58	28.45
37	10	12	39.83	60	39.83	45.52
38	11	12	10.75	60	10.75	6.68
39	12	13	19.18	60	19.18	29.54
40	13	16	17.14	60	17.14	26.82

Table 2. Link characteristics

the actual road network can supply only a part of planned linkages; upgrading of existing links and construction of new ones are so required. The graph in figure 4 shows a scheme of the actual network, and the new links, required to realize all the

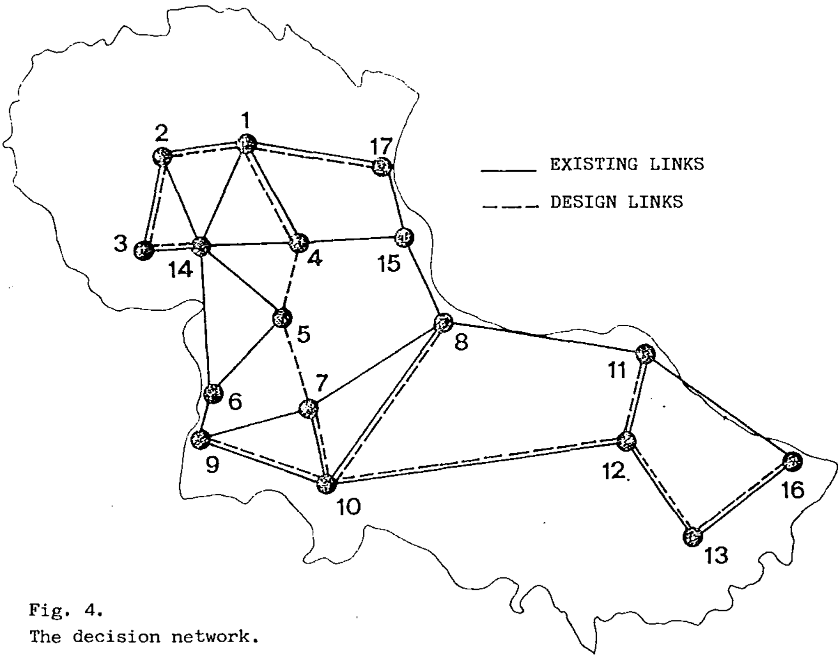

Fig. 4.
The decision network.

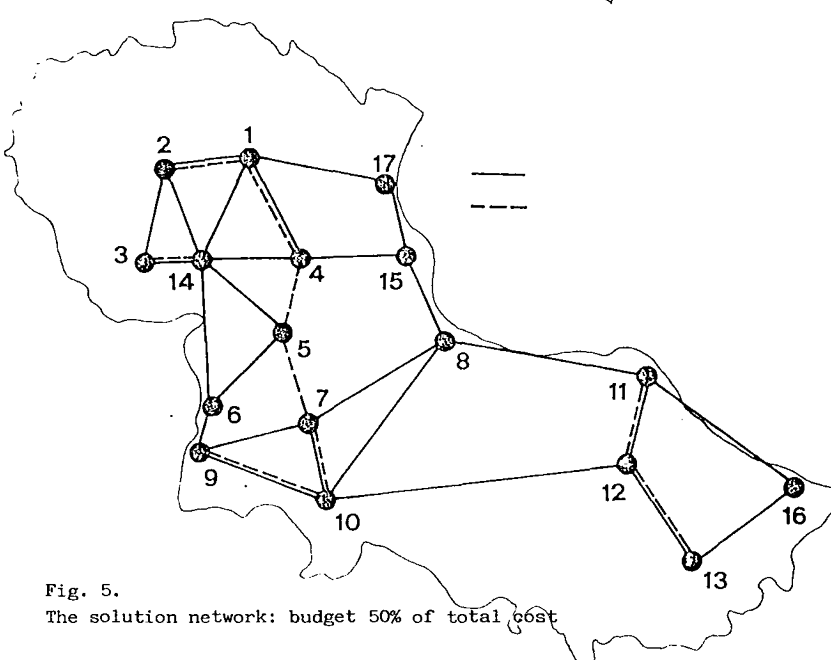

Fig. 5.
The solution network: budget 50% of total cost

planned connections. We call decision network this one.

Considering the different functions of links (main collectors and feeders) and the ground morphology, we assign these design standards:

main collectors:	interval of design speed	80 - 100	KM/H
	maximum gradient	5 - 6	%
	minimum radius	260	m
feeders:	Interval of design speed	60 - 80	KM/H
	maximum gradient	8	%
	minimum radius	120	m

The construction and upgrading costs were computed, at a preliminary stage, by a computer program developped in the Department Computer Centre.The financial amount, required to realize all planned links, is 264.14 billions of It. Lires.

Table 2 shows characteristics of the decision network links; for sake of simplicity, we omitted the dummy arcs. We assumed as overall speed the actual one for existing links and the lower value of the design speed interval for the new ones.

2.5. OBTAINED RESULTS

The proposed road investment model was adopted to select the optimal networks related to budget amounts of 50%, 75% and 100% of the total construction cost. Table 3 resumes obtained results for the above mentioned budgets, as well as for the statu quo network; figures 5, 6 and 7 representes the obtained networks.

AVAILABLE BUDGET	FILLED UP BUDGET	OBJECTIVE FUNCTION	f(B)/f(O)	NEW LINKS KM
0.00 TC	0.000 TC	$41349 \cdot 10^9$	1.000	0.00
0.50 TC	0.478 TC	$25694 \cdot 10^9$	0.621	108.29
0.75 TC	0.669 TC	$23959 \cdot 10^9$	0.579	146.99
1.00 TC	0.846 TC	$23728 \cdot 10^9$	0.573	186.82

Table 3. Results

We observe that the available budget is never filled up completely, but it is expecially remarkable that, when the available budget is the total construction cost, only the 84.6% is filled up, meaning that there are some links (29 and 40) of which construction or upgrading does not improve the objective function.

We can furthermore observe that a budget greater than 75% of the total cost does not improve meaningfully the solution.

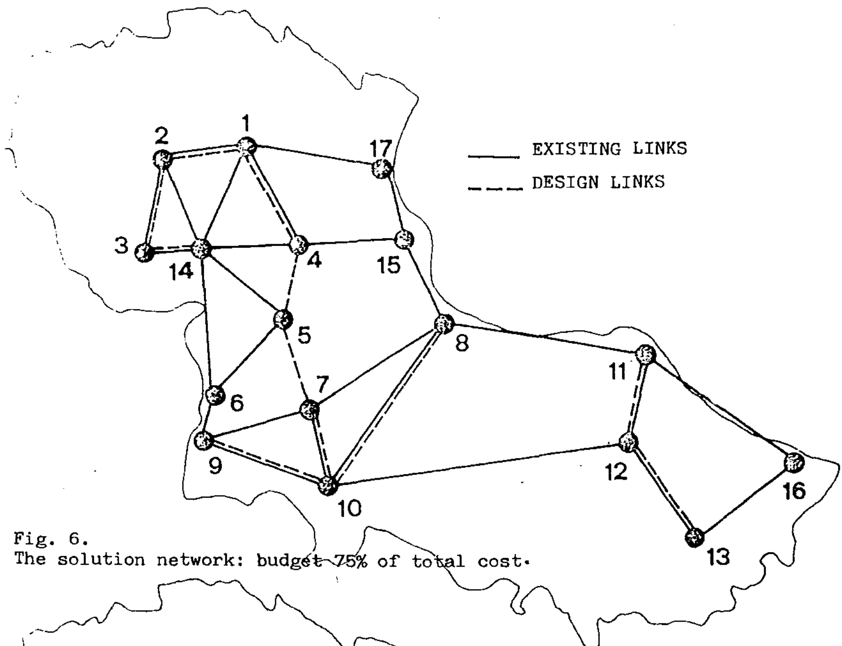

Fig. 6.
The solution network: budget 75% of total cost.

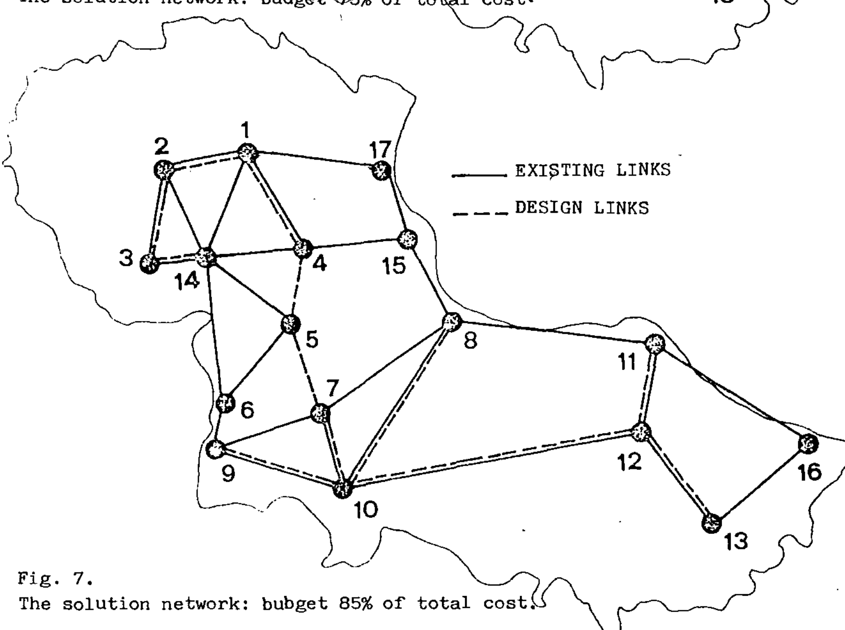

Fig. 7.
The solution network: bubget 85% of total cost.

Perhaps in the case study the assumed land use does suggest the optimal network design by itself; but in more complex cases the proposed methofology can prove better its utility.

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