POWER TRANSMISSION LINE ROUTE OPTIMIZATION

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1. Introduction

In this study we present an optimization model for routing of "High Voltage Power Transmission Cables" (Hence forth called Power Lines). We present a solution approach to this problem from a consultant point of view using Geographic Information System (GIS) techniques and conventional Operations Research (OR) techniques.

2. Problem Definition

The objective of the Power line Routing Problem is to seek locations of towers over the terrain such that the overall cost of tower construction and cable laying will be minimum. Figure-1 shows a schematic diagram.

Parameters influencing cost can be classified into two categories: Topography related such as land elevation, vegetation distribution, urbanization, road & rail network, etc., and tower related are tower height, tower foundation requirements due to route curvature, etc.

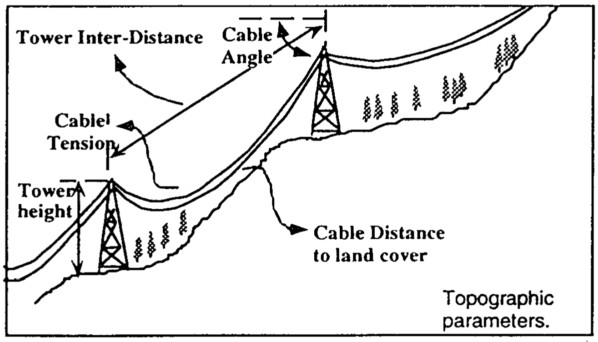

Figure -- 1 High voltage power transmission towers and cables.

Diameter, length and density of the cable determine the weight which acts downwards and is countered by tensioning of cable. Tower foundation must be made strong to counter the weight and tension of cable. Assuming that tower foundation can be made sufficiently strong, two important constraints restrict tower locations namely, Cable tension (t) and cable height from land cover(h). These constraints can be expressed as

$$t = f(X_i - X_{i-1},\ d, \rho, g, z_{i-1} + th_{i-1}, z_i + th_i) \quad \leq TS \qquad (1)$$

$$h = g(X_i - X_{i-1}, z_{i-1} + th_{i-1}, z_i + th_i) \quad \geq 10m \qquad (2)$$

Where $X_i - X_{i-1}$ = tower inter-distance, $X_i = (x_i, y_i, z_i)$, d = cable diameter, ρ = cable material density, g = gravity, z_i, z_{i-1} = elevation of location i,i-1; th_i, th_{i-1} = tower heights at i, i-1 and TS = tensile strength of cable. Minimum allowed cable distance to land cover is assumed as 10 m.

Considering tower height constant at 70.3m and cable tension and diameter at a fixed value, eqs - (1) and (2) can be simplified to

$$\text{tower inter-distance} \quad = | X_i - X_{i-1} | \quad \leq D_{max} \text{ and} \qquad (3)$$

$$\text{height difference} \quad = z_i - z_{i-1} \quad \leq H_{max} \qquad (4)$$

The problem specification we studied is summarized in table-1. D_{max} and H_{max} was assumed to be 700m and 70m respectively which are the values used in most of the transmission line routing formulations.

Table-1: Specification of the Power line routing problem.

Description	Value	Comments
Computation Domain	40x40 km^2	
Topograhic Parameters (Elevation, gradient, land-use, etc.,)		influences cost (Topography related)
Tower Height (other heights are 54.3, 66.3, 82.3m)	70.3m	influences cost (Tower related, constant)
Route Curvature		influences cost (Tower related, *not considered*)
Tower Inter-Distance	≤ 700 m	D_{max} constraint
Height Difference	≤ 70 m	H_{max} constraint

3. Optimization Model

General mathematical representation and description is summarized in figure-2.

4. GIS Data Preparation

GIS (Geographic Information System) Technology provides a convenient method of handling topographic data. By using GIS methodology it is possible to

(a) Handle many spatial data together in an automated and correlated fashion. Large volumes of data can be handled, visualized overlayed and manipulated.

(b) Spatial data can be easily converted to matrix form at different spatial units (greater than initial input resolution). Thus it is easy to make a 50x50m^2 cell matrix or 500x500m^2 cell matrix from the input data using various methods of aggregation.

(c) GIS systems can identify spatial adjacency. Spatial queries such as maximum in the neighborhood, minimum in the neighborhood and path length are easy to evaluate.

Cost matrix and elevation matrix required for the optimization model was calculated using the GIS tools by the following procedure:

1. Primary topographic data of the target region -- contour (elevation) map and land-use map

Minimize				***Minimize*** sum of
$\sum_{i=1}^{n} L(X_i) + \sum_{i=1}^{n} C(X_i)$				Cost Due to Land + Cost Due to Towers
Subject to				***Constraints***
$\lvert X_i - X_{i-1} \rvert$	$\leq$	700	i=2,3,... n	Tower Inter-Distance ≤ 700 m
$\lvert X_i - X_{i-1} \rvert$	$\geq$	0	i=2,3,... n	Tower Inter-Distance ≥ 0 m
$z_i - z_{i-1}$	$\leq$	70	i=2,3,... n	Cable height above 100m
X_1	=	A		Starting Point
X_n	=	B		Destination point
n	$\geq$	2		Number of towers ≥ 2
$X_i = (x_i, y_i, z_i) \in$		R^3	i=1,2,...n	Distance vectors

Figure-2: Mathematical representation of Power Line routing.

were digitized into computer at 10m surface resolution. Road, river and existing power line network were also digitized and made into separate coverages.

2. From the contour map data, surface gradient and surface aspect were derived mathematically.
3. After previewing the input data and derived data, relative cost index was developed for each. Raw data was graded into corresponding relative cost index matrix using this index.
4. Final relative cost matrix was derived by adding each graded relative cost index matrix after multiplying with the weight proportional to the relative importance of the variable. A sample of the relative cost index and importance is illustrated in table-2

Table-2 : Relative cost and relative importance of each variable in the model.

Ground variable	Relative cost index			Relative importance
	Low	Medium	High	
Gradient (%)	0~15	15~25	>25	Very important It affects feasibility.
Elevation (Mts.)	0~200	200~600	>600	Important. It affects cost
Urban Zone	Open, industrial land,	Low density residential land.	Prime land, high density land.	Very important. It affects feasibility.
Aspect (Direction)	direction against route direction		other directions	Fairly important. It affects feasibility at micro scale.

5. Solution Procedure

Step-1 Using appropriate (100m) spatial unit, construct intermediate cost matrix (400x400) C and feasible locations matrix (F). Calculate F using following rules:

$F_{i,j}$ = 0 Infeasible location; $z_{i,j}$ is a local maximum and $z_{i,j} > k' +$ local minimum of the neighboring cells. k' is a constant

= 1 feasible location; otherwise

Step-2 Calculate Least cost path from $X_1 = A$ to $X_n = B$ using F and C.

Step-3 A feasible solution for the overall problem derived as follows

n = 2 + Route length/700

X_1 = A

X_2 = A+700 along the route

$X_{i+1} = X_i +$ 700 along the route ...

Step-4 Using this feasible solution as starting point, calculate better solutions for the overall model using non-linear programming methodologies.

This procedure was applied to an test site in Saitama prefecture. The area of the test site was 35kmx45km. Elevation & roads network details were obtained from "Kokudo GSIJ". Land cover data was obtained through Remote Sensing.

6. Conclusion

Many large-scale terrain based combinatorial optimization problems can be modeled and solved more effectively using a combined approach of GIS and Operations Research. This study was undertaken mainly to establish feasibility of the approach and can be applied to real problems.

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