Topic 7

Identifying Optimal Routes

7.1 Identifying the Most Preferred Route

Suppose you needed to locate the best route for a proposed highway, or pipeline or electric transmission line. What factors ought to be considered? How would the criteria be evaluated? Which factors would be more important than others? How would you be able to determine the most preferred route considering the myriad of complex spatial interactions?

GIS data can set the stage by displaying individual maps of decision criteria but visual assessment of a bunch of maps taped to the wall is overwhelming. Swiveling your head back and forth rarely provides the detailed coincidence information needed to locate the best route. Map overlay can be used to combine the maps for viewing but manual delineation of the route still lacks the objective, quantitative and exhaustive approach provided by map analysis.

For example, you might be interested identifying the most preferred route for a powerline that minimizes its visual exposure to houses. The first step, as shown in figure 7-1, involves deriving an exposure map that indicates how many houses are visually connected to each map location. Recall from previous discussion that visual exposure is calculated by evaluating a series of "tangent waves" that emanate from a viewer location over an elevation surface.

This process is analogous to a searchlight rotating on top of a house and marking the map locations that are illuminated. When all of the viewer locations have been evaluated a map of Visual Exposure to houses is generated like the one depicted in the left inset. The specific command (see author's note) for generating the exposure map is *RADIATE Houses over Elevation completely For VisualExposure*.

In turn, the exposure map is calibrated into relative preference for siting a powerline— from a cost of 1 = low exposure (0 -8 times seen) = most preferred to a cost of 9 = high exposure (>20 times seen) = least preferred. The specific command to derive the Discrete Cost map is *RENUMBER VisualExposure assigning1 to 0 through 8 assigning 3 to 8 through 12 assigning 6 to 12 through 20 assigning 9 to 20 through 1000 for DiscreteCost.*
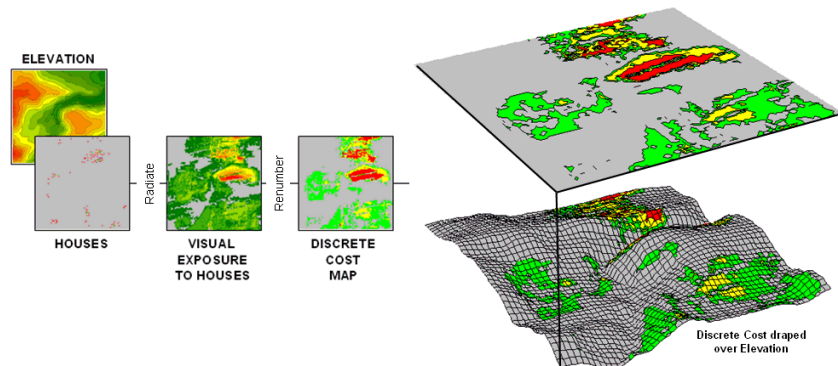

Figure 7-1. (Step 1) Visual Exposure levels (0-40 times seen) are translated into values indicating relative cost (1=low as grey to 9=high as red) for siting a transmission line at every location in the project area.

The right-side of figure 7-1 shows the visual exposure cost map draped on the elevation surface. The light grey areas indicate minimal cost for locating a powerline with green, yellow and red identifying areas of increasing preference to avoid. Manual delineation of a preferred route might simply stay within the light grey areas. However a meandering grey route could result in a greater total visual exposure than a more direct one that crosses higher exposure for a short stretch.

The Accumulative Cost procedure depicted in figure 7-2, on the other hand, uses effective distance to quantitatively evaluate all possible paths from a starting location (existing powerline tap in this case) to all other locations in a project area. Recall from previous discussion that effective distance generates a series of increasing cost zones that respond to the unique spatial pattern of preferences on the discrete cost map.
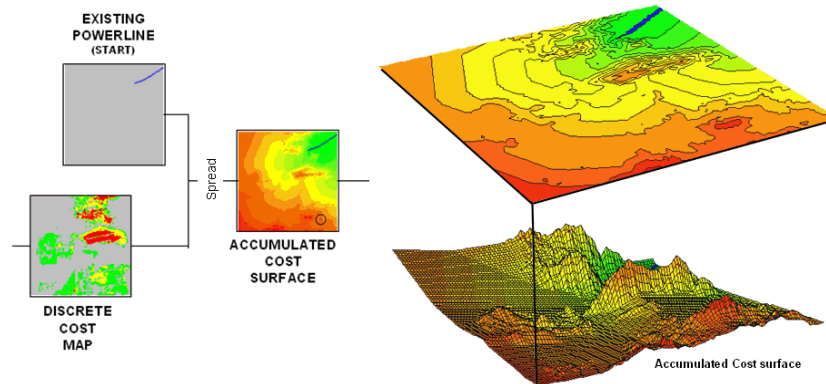

Figure 7-2. (Step 2) Accumulated Cost from the existing powerline to all other locations is generated based on the Discrete Cost map.

This process is analogous to tossing a rock into a still pond—one away, two away, etc. With simple "as the crow flies" distance the result is a series of equally spaced rings with constantly increasing cost. However, in this instance, the distance waves interact with the pattern of visual exposure costs to form an Accumulation Cost surface indicating the total cost of routing a powerline from the powerline tap to all other locations—from green tones of relatively low total cost through red tones of higher total cost. The specific command to derive the accumulation cost surface is *SPREAD Powerline through DiscreteCost for AccumulatedCost.*

Note the shape of the zoomed 3D display of the accumulation surface in figure 7-3. The lowest area on the surface is the existing powerline—zero away from itself. The "valleys" of minimally increasing cost correspond to the most preferred corridors for sighting the new powerline on the discrete cost map. The "mountains" of accumulated cost on the surface correspond to areas high discrete cost (definitely not preferred).

The path draped on the surface identifies the most preferred route. It is generated by choosing the steepest downhill path from the substation over the accumulated cost surface using the command *STREAM Substation over AccumulatedCost for MostPreferred_Route.* Any other route connecting the substation and the existing powerline would incur more visual exposure to houses.

The three step process (*step 1* Discrete Costà *step 2* Accumulated Costà *step 3* Steepest Path) can be used to help locate the best route in a variety of applications. The next section will expand the criteria from just visual exposure to other factors such as housing density, proximity to roads and sensitive areas. The discussion focuses on considerations in combining and weighting multiple criteria that is used to generate alternate routes.
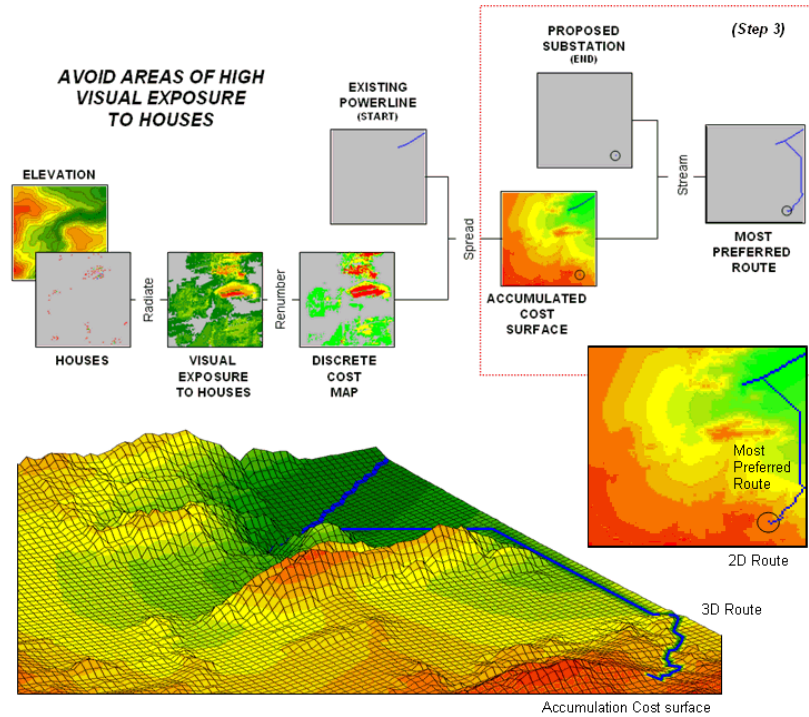
Figure 7-3.   (Step 3) The steepest downhill path from the Substation over the Accumulated Cost surface identifies the Most Preferred Route minimizing visual exposure to houses.

7.2 Considering Multi-Criteria in Routing

Last month's column described a procedure for identifying the most preferred route for an electric transmission line that minimizes visual exposure to houses. The process involves three generalized steps— discrete costà accumulated costà steepest path.

A map of relative visual exposure is calibrated in terms preference for powerline siting (*discrete cost*) then used to simulate siting a power line from an existing tap line to everywhere in the project area (*accumulated cost*). The final step identifies the desired terminus of the proposed powerline then retraces its optimal route (*steepest path*) over the accumulated surface.

While the procedure might initially seem unfamiliar and conceptually difficult, the mechanics of its solution is a piece of cake and has been successfully applied for decades. The art of the science is in the identification, calibration and weighting of appropriate routing criteria. Rarely is one factor, such as visual exposure alone, sufficient to identify an overall preferred route.

Figure 7-4 shows the extension of last month's discussion to include additional decision criteria. The bottom row of maps characterizes the original objective of avoiding Visual Exposure. The three extra rows in the flowchart identify additional decision criteria of avoiding locations in or near Sensitive Areas, far from Roads or having high Housing Density.

Recall that *Base Maps* are field collected data such as elevation, sensitive areas, roads and houses. *Derived Maps* use computer processing to calculate information that is too difficult or even impossible to collect, such as visual exposure, proximity and density. The *Cost/Avoidance Maps* translate this information into decision criteria. The calibration forms maps that are scaled from 1 (most preferred—favor siting, grey areas) to 9 (least preferred—avoid siting, red areas) for each of the decision criteria.
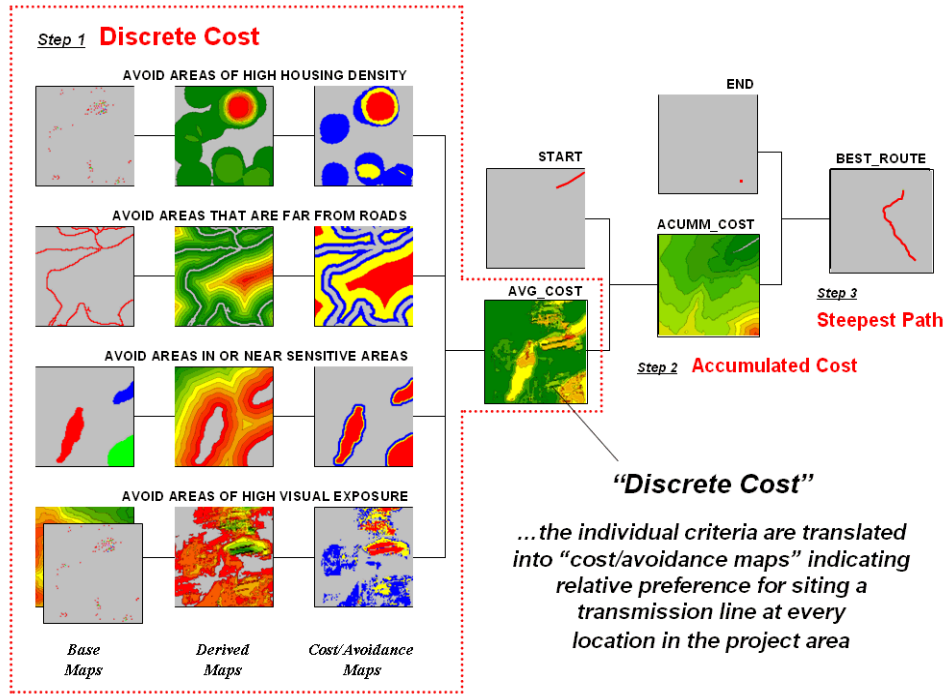
Figure 7-4. Discrete cost maps identify the relative preference to avoid certain conditions within a project area.

The individual cost maps are combined into a single map by averaging the individual layers. For example, if a grid location is rated 1 in each of the four cost maps, its average is 1 indicating an area strongly preferred for siting. As the average increases for other locations it increasingly encourages routing away from them. If there are areas that are impossible or illegal to cross these locations are identified with a "null value" that instructs the computer to never traverse these locations under any circumstances.

The calibration of the individual cost maps is an important and sensitive step in the siting process. Since the computer has no idea of the relative preferences this step requires human judgment. Some individuals might feel that visual exposure to one house constitutes strong avoidance (9), particularly if it is their house. Others, recognizing the necessity of a new power line, might rate "0 houses seen" as 1 (most preferred), 1 to 2 houses seen as 2 (less preferred), ... through more than 15 houses seen as 9 (least preferred).

In practice, the calibration of the individual criteria is developed through group discussion and consensus building. The Delphi process (see author's note) is a structured method for developing consensus that helps eliminate bias. It involves iterative use of anonymous questionnaires and controlled feedback with statistical aggregation of group responses. The result is an established and fairly objective approach for setting preference ratings used in deriving the individual discrete cost maps.

Once an overall *Discrete Cost* map (step 1) is calculated, the *Accumulated Cost* (step 2) and *Steepest Path* (step 3) processing are performed to identify the most preferred route for the powerline (see figure 1). Figure 7-5 depicts a related procedure that identifies a preferred route corridor.

The technique generates accumulation surfaces from both the Start and End locations of the proposed powerline. For any given location in the project area one surface identifies the best route to the start and the other surface identifies the best route to the end. Adding the two surfaces together identifies the total cost of forcing a route through every location in the project area.

The series of lowest values on the total accumulation surface (valley bottom) identifies the best route. The valley walls depict increasingly less optimal routes. The red areas in figure 2 identify all of locations that within five percent of the optimal path. The green areas indicate ten percent sub-optimality.
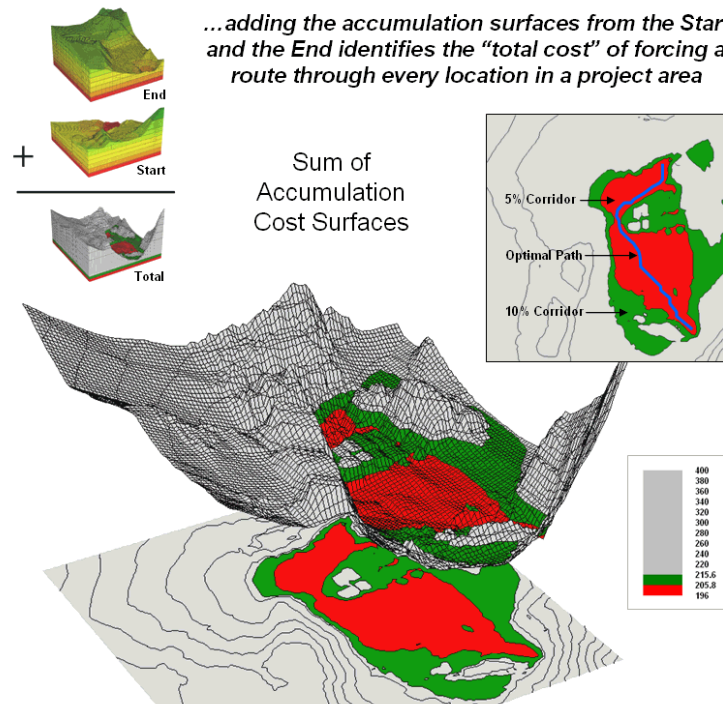

Figure 7-5. The sum of accumulated surfaces is used to identify siting corridors as low points on the total accumulated surface.

The corridors are useful in delineating boundaries for detailed data collection, such as high resolution aerial photography and ownership records. The detailed data within the macro-corridor is helpful in making slight adjustments in centerline design, or as we will see next month in generating and assessing alternative routes.

7.3 Calibrating and Weighting Criteria

The past two columns have described procedures for constructing a simple GIS model that determines a preferred route for a proposed electric transmission line. The discussion focused on the spatial logic inherent in the solution and its expression as a flowchart and processing code. The model's structure is representative of most suitability models and is composed of a series of processing steps that are analogous to a cooking recipe—do this, and this, then that, and that, etc.—except the result is a prescriptive map instead of a chocolate cake.

As in cooking, the implementation of a spatial recipe provides able room for interpretation and varying tastes. For example, one of the criteria in the routing model seeks to avoid locations having high visual exposure to houses. But what constitutes "high" …5 or 50 houses visually impacted? Are there various levels of increasing "high" that correspond to decreasing preference? Is "avoiding high visual exposure" more or less important than "avoiding locations near sensitive areas." How much more (or less) important?

The answers to these questions are what tailor a model to the specific circumstances of its application and the understanding and values of the decision participants. The tailoring involves two related categories of parameterization—calibration and weighting.
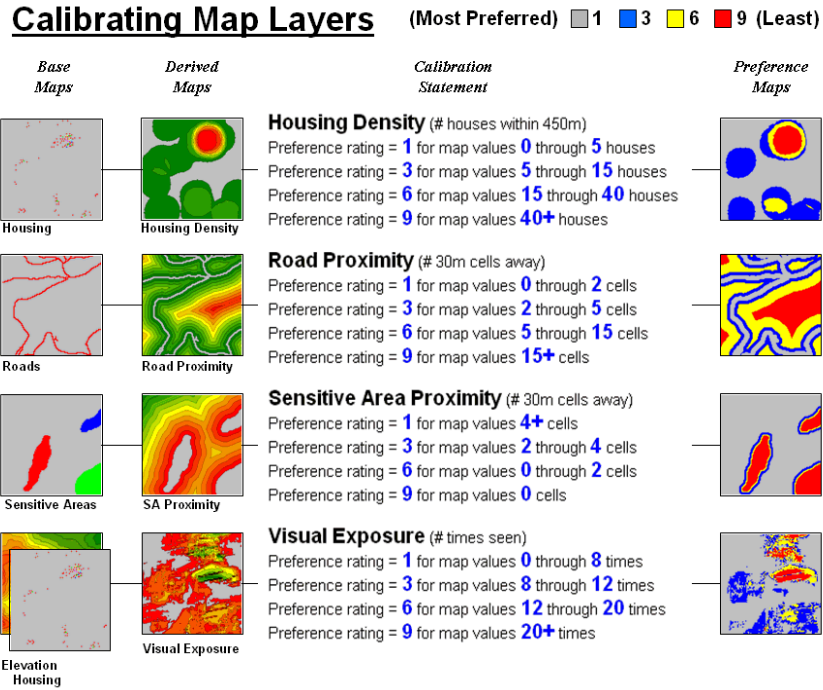
Figure 7-6. The Delphi Process uses structured group interaction to establish a consistent rating for each map layer.

Calibration refers to establishing a consistent scale from 1 (most preferred) to 9 (least preferred) for rating each map layer used in the solution. Figure 7-6 shows the result for the four decision criteria used in the powerline routing example.

The *Delphi Process*, developed in the 1950s by the Rand Corporation, is designed to achieve consensus among a group of experts. It involves directed group interaction consisting of at least three rounds. The first round is completely unstructured, asking participants to express any opinions they have on calibrating the map layers in question. In the next round the participants complete a questionnaire designed to rank the criteria from 1 to 9. In the third round participants re-rank the criteria based on a statistical summary of the questionnaires. "Outlier" opinions are discussed and consensus sought.
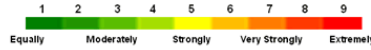
The development and summary of the questionnaire is critical to Delphi. In the case of continuous maps, participants are asked to indicate cut-off values for the nine rating steps. For example, a cutoff of 4 (implying 0-4 houses) might be recorded by a respondent for Housing Density preference level 1 (most preferred); a cut-off of 12 (implying 4-12) for preference level 2; and so forth. For discrete maps, responses from 1 to 9 are assigned to each category value. The same preference value can be assigned to more than one category, however there has to be at least one condition rated 1 and another rated 9. In both continuous and discrete map calibration, the median, mean, standard deviation and coefficient of variation for group responses are computed for each question and used to assess group consensus and guide follow-up discussion.

Weighting of the map layers is achieved using a portion of the *Analytical Hierarchy Process* developed in the early 1980s as a systematic method for comparing decision criteria. The procedure involves mathematically summarizing paired comparisons of the relative importance of the map layers. The result is a set map layer weights that serves as input to a GIS model.

In the routing example, there are four map layers that define the six direct comparison statements identified in figure 7-7 (#pairs= (N * (N – 1) / 2)= 4 * 3 / 2= 6 statements). The members of the group independently

order the statements so they are true, then record the relative level of importance implied in each statement. The importance scale is from 1 (equally important) to 9 (extremely more important).

Figure 7-7. The Analytical Hierarchy Process uses pairwise comparison of map layers to derive their relative importance.

This information is entered into the importance table a row at a time. For example, the first statement views avoiding locations of high Visual Exposure (VE) as extremely more important (importance level= 9) than avoiding locations close to Sensitive Areas (SA).   The response is entered into table position row 2, column 3 as shown. The reciprocal of the statement is entered into its mirrored position at row 3, column 2. Note that the last weighting statement is reversed so its importance value is recorded at row 5, column 4 and its reciprocal recorded at row 4, column 5.

Once the importance table is completed, the map layer weights are calculated. The procedure first calculates the sum of the columns in the matrix, and then divides each entry by its column sum to normalize the responses. The row sum of the normalized responses derives the relative weights that, in turn, are divided by minimum weight to express them as a multiplicative scale (see author's note for an online example of the calculations). The relative weights for a group of participants are translated to a common scale then averaged before expressing them as a multiplicative scale.

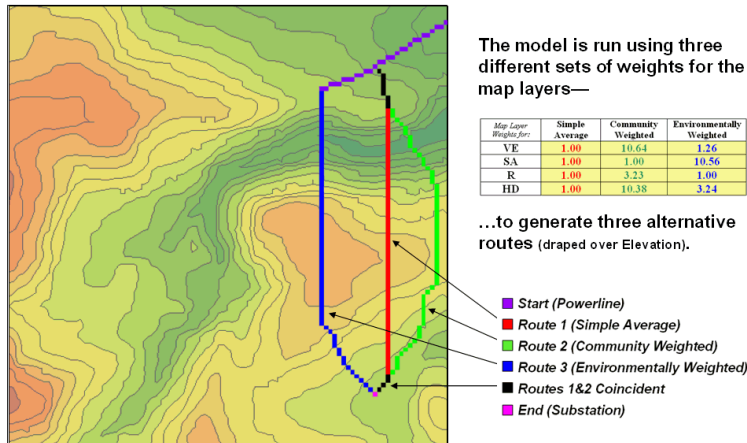### Generating Alternative Routes

Figure 7-8. Alternate routes are generated by evaluating the model using weights derived from different group perspectives.

Figure 7-8 identifies alternative routes generated by evaluating different sets of map layer weights. The center route (red) was derived by equally weighting all four criteria. The route on the right (green) was generated using a weight set that is extremely sensitive to "Community" interests of avoiding areas of high Visual Exposure (VE) and high Housing Density (HD). The route on the left (blue) reflects an "Environmental" perspective to primarily avoid areas close to Sensitive Areas (SA) yet having only minimal regard for VE and HD. Next month's column will investigate qualitative procedures for comparing alternative routes.

7.4 Evaluating Alternative Routes

The past several columns (July-September, 2003) have focused on the considerations involved in siting an electric transmission line as representative of most routing models. The initial discussion described a basic three step process (*step 1* Discrete Costà *step 2* Accumulated Costà *step 3* Steepest Path) used to delineate the optimal path. The following column focused on using multiple criteria and the delineation of an optimal path corridor. Last month's discussion shifted to methodology for calibrating and weighting GIS model criteria used for determining preferred areas for siting.
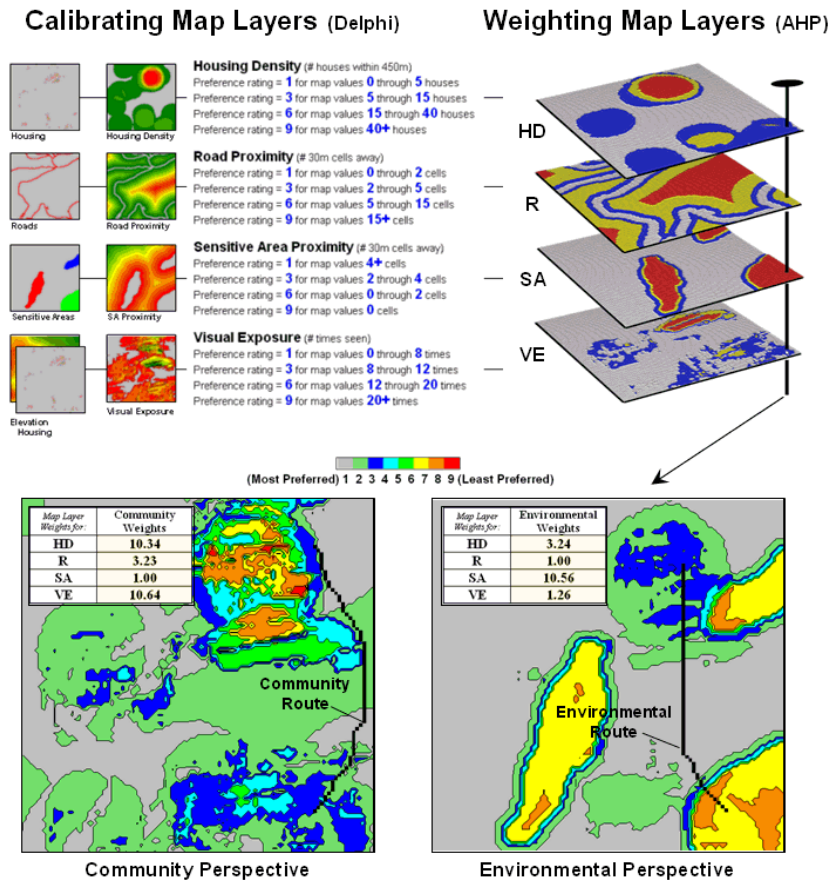

Figure 7-9. Incorporating different perspectives (model weights) generate alternative preference surfaces for transmission line routing.

The top portion of Figure 7-9 identifies the calibration ratings assigned to the four siting criteria that avoid locations of high housing density (HD), far from roads (R), near sensitive areas (SA) and high visual exposure (VE).

The bottom portion of the figure identifies weighted preference surfaces reflecting Community and Environmental concerns for siting the powerline. The community perspective strongly avoids locations

with high housing density (weight= 10.23) and high visual exposure to houses (10.64). The environmental perspective strongly avoids locations near sensitive areas (10.56) but has minimal concern for high housing density and visual exposure (3.24 and 1.26, respectively).

The routing solution based on the different perspectives delineates two alternative routes. Note that the routes bend around areas that are less-preferred (higher map values; warmer tones) as identified on their respective preference surfaces. The optimal path considering one perspective, however, is likely far from optimal considering the other.

One way to compare the two routes is through differences in their preference surfaces. Simple subtraction of the Environmental perspective from the Community perspective results in a difference map (figure 7-10). For example, if a map location has a 3.50 on the community surface and a 5.17 rating on the environmental surface, the difference is -1.67 indicating a location that is less preferred from an environmental perspective.
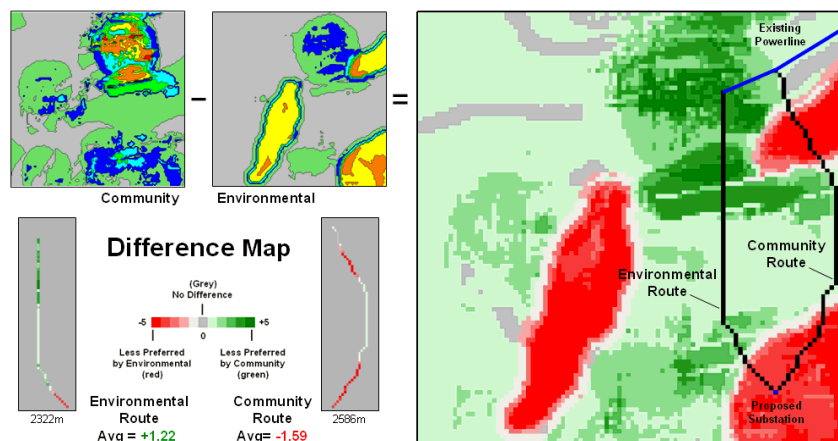

Figure 7-10. Alternative routes can be compared by their incremental and overall differences in routing preferences.

The values on the difference map on the right side of the figure identify the relative preference at each map location. The sign of the value tells you which perspective dominates—negative means less preferred by environmental (red tones); positive means less preferred by community (green tones). The magnitude of the value tells you the strength of the difference in perspective—zero indicates no difference (grey); -1.67 indicates a fairly strong difference in opinion.

Alignment of the alternative routes on the difference map provides a visual evaluation. Where a route traverses grey or light tones there isn't much difference in the siting preferences. However, where dark tones are crossed significant differences exist. The two small insets in the lower left portion mask the differences along the two routes. Note the relative amounts of dark red and green in the two graphics. Nearly half of the Community route is red meaning there is considerable conflict with the environmental perspective. Similarly, the Environmental route contains a lot of green indicating locations in conflict with the community perspective.

The average difference is calculated by region-wide (zonal) summary of values along the entire length of the routes. The +1.22 average for the Environmental route says it is a fairly unfriendly community alternative. Likewise, the -1.59 average for the Community route means it is environmentally unfriendly.
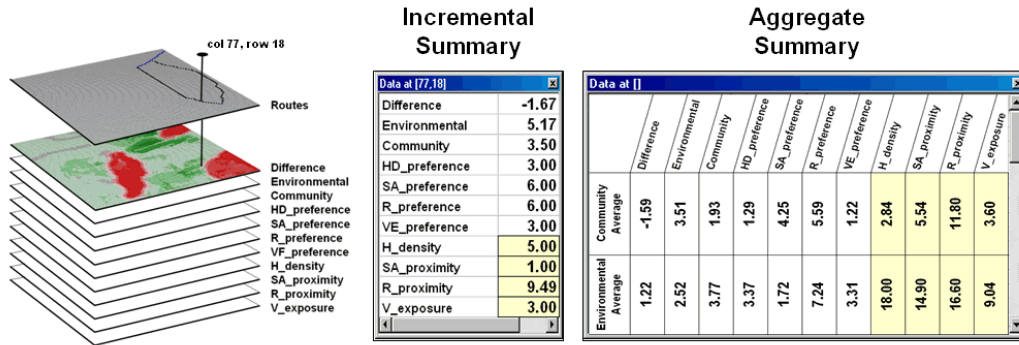
Figure 7-11. Tabular statistics are used to assess differences in siting preferences along a route (incremental) or an overall average for a route (aggregate).

The schematic in figure 7-11 depicts a "map stack" of the routing data. Mouse-clicking anywhere along a route pops-up a listing of the values for all of map layers (drill-down). In the example, the difference at location column 77, row 18 is -1.67 that means the location is environmentally unfriendly although it is part of the Environmental route. This is caused by the 1.00 *SA_proximity* map value indicating that the location is just 30 meters from a sensitive area.

In addition to the direct query at a location (incremental summary), a table of the average values for the map layers along the route can be generated (aggregate summary). Note the large difference in average housing density (only 2.84 houses within 450m for the Community route but 18.0 for the Environmental route) and visual exposure (3.60 houses visually connected vs. 9.04).

In practice, several alternative perspectives are modeled and their routes compared. The evaluation phase isn't so much intended to choose one route over another, but to identify the best set of common segments or slight adjustments in routing that delineate a compromise. Rarely is GIS analysis used as a decision *making* system that dictates a solution. Most effective applications utilize the analysis as a decision *support* system that encourages "thinking with maps."

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Author's Note: *Supplemental discussion and an Excel worksheet demonstrating the calculations are posted at www.innovativegis.com/basis/, select "Column Supplements" for Beyond Mapping, September, 2003.*

- *Delphi and AHP Worksheet an Excel worksheet templates for applying the Delphi Process for calibrating and the Analytical Hierarchy Process (AHP) for weighting as discussed in this sub-topic (GeoWorld, September 2003)*
- *Delphi Supplemental Discussion describing the application of the Delphi Process for calibrating map layers in GIS suitability modeling*
- *AHP Supplemental Discussion describing the application of AHP for weighting map layers in GIS suitability modeling*

Author's Note: MapCalc Learner (www.redhensystems.com/mapcalc/) commands are used to illustrate the processing. The Least Cost Path procedure is available in most grid-based map analysis systems, such as ESRI's GRID, using RECLASS to calibrate the discrete cost map, COSTDISTANCE to generate the accumulation cost surface and PATHDISTANCE to identify the best path.

7.5 Exercises

Access *MapCalc* using the *Bighorn.rgs* by selecting **Start**à **Programs**à **MapCalc Learner**à **MapCalc Learner**à **Open existing map set**à **NR_MapCalc Data**à **Bighorn.rgs**. The following set of exercises utilizes this database.

7.5.1 Routing Model

√α From the Map Analysis menu, select **Scripts**à **Open** and select the script …\Scrips**Transmission.scr**. Execute it a command line at a time top to bottom by double-clicking on each command sentence. Relate the map analysis operations to the logical flow identified in the flowchart below and in figure 7-4.
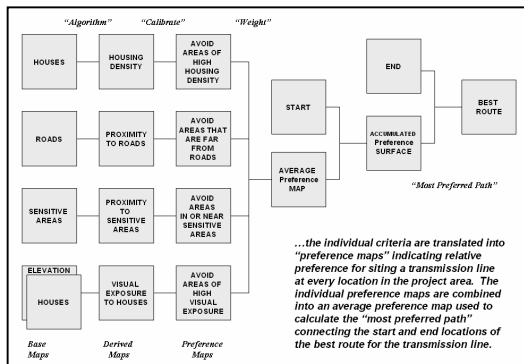
The first series of commands establish the *Derived Maps* of the criteria for routing…

Transmission_line	
Operation	Operation Detail
NOTE	TRANSMISSION LINE SITING MODEL -- uses Bighorn.rgs database
NOTE	1) Calculate Derived Maps
NOTE	…housing density (within 15 cells * 30m/cell= 450m radius)
SCAN	SCAN Houses Total IGNORE 0.0 WITHIN 15 CIRCLE FOR Housing_density
NOTE	…proximity to roads
SPREAD	SPREAD Roads NULLVALUE PMAP_NULL TO 100 Simply FOR Road_proximity
NOTE	…proximity to sensitive areas
SPREAD	SPREAD Sensitive_areas NULLVALUE PMAP_NULL TO 100 Simply FOR SensitiveAreas_proximity
NOTE	…visual exposure to houses within one-half mile (27 cells)
RADIATE	RADIATE Houses OVER Elevation TO 27 AT 1 NULLVALUE 0 Completely FOR Houses_ visualExposure
PAUSE	

The next set of commands establishes the *Cost/Avoidance Maps* that interpret the conditions in terms of relative preference for routing…

NOTE	2) Interpret Derived Maps for Individual Cost Maps (1= low cost through 9= high cost)
NOTE	…avoid areas of high housing density
RENUMBER	RENUMBER Housing_density ASSIGNING 1 TO 0 THRU 5 ASSIGNING 3 TO 5 THRU 15 ASSIGNING 6 TO 15 …
NOTE	…avoid areas that are far from roads
RENUMBER	RENUMBER Road_proximity ASSIGNING 1 TO 0 THRU 2 ASSIGNING 3 TO 2 THRU 5 ASSIGNING 6 TO 5 TH…
NOTE	…avoid areas in or near sensitive areas
RENUMBER	RENUMBER SensitiveAreas_proximity ASSIGNING 9 TO 0 ASSIGNING 6 TO .001 THRU 2 ASSIGNING 3 TO 2 …
NOTE	…avoid areas of high visual exposure to houses
RENUMBER	RENUMBER Houses_ visualExposure ASSIGNING 1 TO 0 THRU 8 ASSIGNING 3 TO 8 THRU 12 ASSIGNING…
PAUSE	

The next command establishes the overall *Discrete Cost Map* by calculating for each map location the average preference of the four individual cost maps …
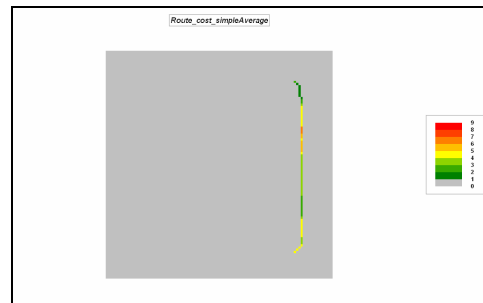
NOTE	3) Calculate Average Cost for siting a transmission line at each map location
ANALYZE	ANALYZE Cost_housingDensity TIMES 1 WITH Cost_roadProximity TIMES 1 WITH Cost_sensitiveAreas TIMES …
PAUSE	

The next set of commands identifies the *Least Cost Path* (optimal path) by first creating an *Accumulation Cost Map* from the starting location and then streaming downhill over the surface from the ending location…

NOTE	4) Identify Least Cost Path for the transmission line
NOTE	…accumulated cost surface from starting location
SPREAD	SPREAD Powerline NULLVALUE PMAP_NULL TO 500 THRU Cost_simpleAverage Simply FOR AccumulatedCo…
NOTE	…identify least cost path over accumulated cost surface (steepest downhill path)
STREAM	STREAM Power_substation OVER AccumulatedCost_simpleAverage Simply Steepest Downhill Only FOR Route_…
NOTE	…characterize cost along route
COMPUTE	COMPUTE Route_simpleAverage Times Cost_simpleAverage FOR Route_cost_simpleAverage
PAUSE	
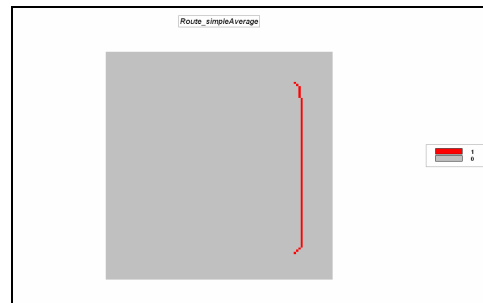
*Least Cost Path using default display*

Least Cost Path with discrete cost displayed using User Defined ranges, # ranges = 9 and color locks at intervals 0 to 1 = light grey, 1 to 2 = green, 4 to 5 = yellow, 8 to 9 = red

7.5.2 Extending the Routing Model

The final set of commands repeats the process using a weighted average of the individual cost layers favoring avoiding sensitive areas and visual exposure…

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NOTE	5) Identify best route assuming avoiding sensitive areas and high visual exposure factors are ten times more import...
NOTE	...calculate weighted average of individual cost maps
ANALYZE	ANALYZE Cost_housingDensity TIMES 1 WITH Cost_roadProximity TIMES 1 WITH Cost_sensitiveAreas TIMES ...
NOTE	...accumulated cost surface from starting point
SPREAD	SPREAD Powerline NULLVALUE PMAP_NULL TO 500 THRU Cost_weightedAverage Simply FOR Accumulated...
NOTE	...identify least cost path over accumulated cost surface (steepest downhill path)
STREAM	STREAM Power_substation OVER AccumulatedCost_weightedAverage Simply Steepest Downhill Only FOR Rout...
NOTE	...characterize cost along route
COMPUTE	COMPUTE Route_weightedAverage Times Cost_weightedAverage FOR Route_cost_weightedAverage
NOTE	...end of script

Route_cost_weightedAverage
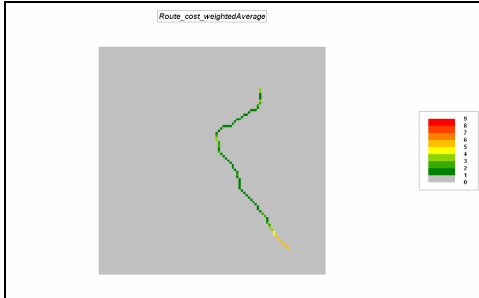
On your own, repeat the process to identify another route where consideration of avoiding high housing density factors and areas far from roads are ten times more important than sensitive areas and visual exposure.

ANALYZE Cost_housingDensity TIMES 10 WITH Cost_roadProximity TIMES 10 WITH Cost_sensitiveAreas TIMES 1 WITH Cost_visualExposure TIMES 1 IGNORING PMAP_NULL Mean FOR Cost_weightedAverage2

SPREAD Powerline NULLVALUE PMAP_NULL TO 500 THRU Cost_weightedAverage2 Simply FOR AccumulatedCost_weightedAverage2

STREAM Power_substation OVER AccumulatedCost_weightedAverage2 Simply Steepest Downhill Only FOR Route_weightedAverage2

COMPUTE Route_weightedAverage2 Times Cost_weightedAverage FOR Route_cost_weightedAverage2

Route_cost_weightedAverage2
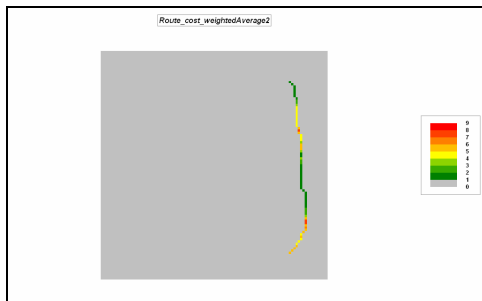
Totally on your own, repeat the process using simple average of all the individual cost layers

except now include a new consideration of avoiding steep slopes—
0 to 5% = 1 (favor)
5 to 10% = 2
10 to 15% = 5
15 to 30% = 7
30 to 65% = 9 (avoid)

Hint: use **Reclassify**à **Renumber** command to create a new interpreted cost/avoidance map reflecting the above preferences then include it in the calculation of the simple average with the other four criteria map layers.

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