Introduction

Dickert [7] has observed that in addition to identifying a set of anticipated impacts and specifying their ranges, environmental impact assessment must evaluate and communicate the relative trade-offs possible between various alternatives. Minimum environmental impact utility routing is a most difficult spatial resource allocation problem. Multiple sources and destinations may have to be joined by continuous routes over long distances. Points and regions or "Control Points" that must be passed through or avoided for system integrity reasons must be accommodated. Impact discontinuities over space are the dominant feature in the utility routing problem. The size of study areas in which to locate alternate routings further complicates the problem. Study areas may range from 2,000 to 200,000 square miles in extent. A major difficulty is to analyze with sufficient local accuracy the discontinuous impacts over these large tracts of land.

It may not be possible to locate a route of any length which avoids all regions of major impact. In the event that a certain amount of impact is to be tolerated at isolated points along the route, a methodology is required which will help determine which impact should be accepted.

Current Methods and Theories

Few attempts have been made to combine environmental impact assessment with path or route finding. Notable exceptions are the GCARS system by Turner [33;34] and the work by Krauskopf and Bunde [17]. Established environmental impact assessment methods on the whole provide only summary assessment at the regional level and do not facilitate alternate route development and assessment. A brief outline of their characteristics follows.

Expert Committee Assessment

This is a form of Delphi technique where various experts are assembled to write a report on selected alternate routings. Areas or routes of minimum impact are developed by consensus. The conclusion of this kind of study is strongly influenced by the subject area backgrounds of the study team, relative dominance of the investigators and their inclusiveness in conducting their individual research.

Checklist Assessment

Lists of environmental conditions or factors which should be reported upon are defined by various agencies [7;30]. A review team examines selected alternate routings and completes a checklist study for each route. However, the lists provide no methods to identify and rank impacts per se or to select
potential routes for consideration.

Assessment by Matrices

In its simplest form, this approach can be viewed as applying multi-dimensional checklists \[7\] where functional inter-relationships may be identified. A summary matrix is developed for each alternate routing. In the matrix, the assessors assign an Impact ranking and weight for each association between project functions and potential impacts. The most well-known matrix is described by Leopold et al. \[18\]. More advanced use of matrix summaries are possible; Hill and Tzamir \[14\], combining scaleogram analysis with matrix summaries claim improved results over benefit cost studies. However, similar to checklist assessment, the approach does not guarantee that the complete set of alternate solutions will be considered.

Benefit Cost Analysis

This is a regional summary method which explicitly compares anticipated project benefits with both construction and environmental discounted costs of project development \[2\]. The study area level analysis is usually based on gross national income (GNI) effects. The major difficulty is in establishing monetary values and weights associated with impacts. A method is very sensitive to the actual values used \[2\;3\]. A common problem is correctly evaluating secondary and interrelated side effects.

Descriptive Land Unit Analysis

This approach differs from the first four in its attempt to identify spatially areas tolerant and intolerant to project development. Extensive field work is used to identify and locate significant biotic communities and land uses. Physical terrain parameters are utilized to examine and locate major landscape types. The two taxonomies are combined to identify and locate land unit associations, thus establishing a series of subregions. Each of these regions is ranked according to its ability to tolerate the project \[15\;11\]. Routes are developed which attempt to traverse only tolerant areas. The method has attractiveness since it provides some local assessment of impact. However, the extensive field work and cartographic effort has tended to restrict this approach to smaller studies.

Input-Output Analysis

Environmental input-output analysis is an extension of the basic input-output method developed in the 1950s by economists and regional scientists who wished to study the interdependence of macro economic phenomena on a regional basis \[22\]. Hoornkamp and Paelinck \[25\] show how environmental side effects (specifically contaminants) can be included as inputs and outputs. This can be very helpful in examining the effects associated with alternate technologies or standards. However, the approach does not facilitate locating potential alternate routes in space.

Irard and Van Zele \[16\] propose urban-form environmental analysis by multiregional input-output. Essentially, an input-output model is developed for each region, extra entries are then added establishing the linkages between regions, and the input-output sub-tabulations are combined into one table. However, Miernyk \[22\] reports that a purely economic input-output study of the Colorado River Basin, divided into only six regions and without using substantial aggregation of firms into industry groups, required the development of a 3M x 3M matrix of 90,000 entries. This characteristic has led Irard and Van Zele \[16\] to conclude that environmental impact assessment by input-output analysis at the local or sub-regional level is impractical until sufficiently detailed data bases are available.

Cartographic Overlays

This approach has evolved out of the land classification techniques developed by British and American field workers in the 1920s and 1930s. The impetus for land classification systems was to inventory soil type and the value of land for agricultural purposes. The initial idea was to make separate field studies of specific phenomena (e.g., soil texture, soil reaction, soil drainage) map each phenomenon on a separate map series using some simple interval classification scheme, and cartographically overlay the different map series to produce a summary map series. The summary map was visually inspected and generalized into regions with similar characteristics. Assessment series are often interpretive and abstract. Statistical models (e.g., factor analysis and multiple regression analysis) have been used to establish a baseline for mapped components. Combining assessment tables have been used to arrive at partial or final assessments.

Alexander and Manheim \[1\] were among the first to apply an extension of basic land classification techniques to route selection. In this case, the application was to route part of Interstate Route 91 in Massachusetts. They identified twenty-six design requirements and for each requirement performed a land classification. By using grey scale shading these developed twenty-six maps which were then overlayed to provide a summary assessment of areas suitable for highway development. Effectiveness was increased by using "hierarchical categories" to group preliminary grouping of requirements, which were combined until there was a sub-composite map for each non-similarly structured group. The final composite map was examined visually. The choice of a dark [i.e., highly suitable] route could be located.

McIlharg \[21\] independently developed a similar graphical approach. He identifies numerous factors related to a problem, maps them and combines the maps into a composite. The factors tend to be interpretations based upon physical or natural phenomena and existing land uses. Similarly, Irard and Manheim, he uses colour in addition to shade intensity. This gives him the possibility of carrying both intensity and comparability assessment through the cartographic process.

Both of these manual approaches have the important property of providing a detailed localized assessment. However, they fail to take into account interrelationships between neighbouring areas, and they provide no effective and objective means of identifying alternate routings.
Information System Analysis

In the early 1960s Neiman and Miller [23] pioneered the use of computer based information systems for routing studies. A study area was broken into arbitrary one kilometer units or cells; a map series were analyzed, and a classification record of a number of variables was made in an information system for each one kilometer unit. The computer was used in a bookkeeping mode simply to store the data and draw maps on a cell-by-cell basis using a standard printer mapping program. Krauskopf and Bunde [17], Rattrey et al. [29], Robinette [31], Lyle and Von Nordke [20], and Coleman [5] used similar approaches for various routing and area assessment purposes.

In general, the information system studies appear to apply simple linear weighted models to data in cell based regional data banks. Little is documented regarding data collection and data base flexibility. To date, there has been little advance beyond the fundamental land classification approach.

Analysis by Mathematical Surfaces

Turner [33,34] has used surface analysis to develop the Generalized Computer-Aided Route Selection (GCARS) system, which is being used by the Ontario Ministry of Transportation and Communications for highway route selection studies. A number of sample points are fixed in space by geographic coordinates (X,Y); the data values at a point are referred to as Z, for each variable "i". Thus an arbitrary point "j" in space may have the information record

\[ X_j, Y_j, Z_{i1}, Z_{i2}, Z_{i3}, \ldots, Z_{im} \]

Each arbitrary ZI is considered as belonging to the surface described by the ZI values distributed over X, Y space. Then the functional relationship

\[ Z_l = f(X,Y) \]

is defined where the function f is a mapping from X,Y to ZI at some arbitrary order of f. The advantage of this approach is that only a sample of points is required to derive the coefficients of f which will serve as a spatial generalization of the phenomenon (i.e., variable). Subsequently, the coefficients of f can be used to estimate a Zijk value for any arbitrary point (Xk,Yk). A composite function "g" which is a linear combination of weighted "f" functions is developed to estimate a utility surface measuring suitability for the development of a highway route. A grid is established over the study space, values interpolated from the utility surface, and a minimum path algorithm used to select routes.

The major difficulty with this approach rests with its reliance upon spatial generalization associated with the functional interpretation of the phenomena. Discrete events in effect are averaged. In addition, the use of linear combinations to obtain the utility surface appear to impact on the resolution in the route finding state. The examples Turner provides show a tendency for straight line routes.

Route Finding Methods

In general, mathematical approaches to route selection have been developed using the concept of graph theory.

A graph may be defined as a series of points called vertices (sometimes called points or nodes) which may be connected by an edge (sometimes called an arc or a line). Edges may be assigned an associated value or weight. The weights can represent a cost associated with traversing the edge measured in some arbitrary way.

Dantzig [6] and Dijkstra [9] independently developed general solutions to find the least cost, or "shortest path" between two arbitrary vertices in a graph. Numerous algorithms are available to perform this task. The methods are known to locate accurately minimum cost paths and have been extended by the author and others to find all paths of the same minimum cost or within some arbitrarily defined small cost increment. Recently developed algorithms have improved on the original general solutions, but the best implementations require computer time on the order of \( N^2 \), when \( N \) is the number of vertices in the graph [28]. This, and the requirements to store details of vertex and edge associations, has limited practical application of these exact solutions to graphs with less than 10,000 vertices.

Some Major Considerations

Fisher and Davies [11] observe that "once thresholds are exceeded by cumulative developments, disproportionate cumulative environmental changes are induced and the environment is permanently altered." This requires assessment methods which detect and locate specific threshold conditions. The methods outlined above do not clearly address this problem.

Local environmental discontinuities and indirect and dependent impacts which result from a project must be included in the total assessment. Only input-output analysis appears to have been used this way, but not on a locally precise level. All methods seem to disregard the interactions between immediately adjacent local areas; land unit analysis, cartographic, and information system approaches only assess associations within a region.

Various authors and interest groups [19;26;4] have criticized established assessment methods for their lack of comprehensibility. In particular they object to confusing arrays of technical coefficients, dollar valuation of intangibles, discount calculations and statement of expert opinion. With the requirement for public participation in the planning process [12;13], assessment and route selection methods must make clear the information weights and considerations used in making an assessment. It is desirable that partial and final results be made available in a more easily understood graphic form.

An Application for Information, Transformations and Networks

The need to route utilities through extensive tracts of land
requires environmental impact assessment and route selection oriented toward moderate to large scale projects. The proposed method will reduce a large scale problem to a tractable "solution space". It is not intended to perform precise alignments but rather select a series of narrow "corridors" in which precise alignments can be determined by later field work. A four phase assessment and planning method is proposed as follows:

1. A "tolerance to development" discrete valued impact surface is generated using a small area specific database potential impact over the whole study area. This surface and supporting data and interpretations are mapped.

2. The tolerance to development surface is placed in graph form and its planar dual obtained. The dual graph is contracted by factoring out strong components and forming a contracted digraph. In this form, each vertex represents an area of similar characteristics and the directed edges weighted by distance give the relationships between areas.

3. A modified Dijkstra shortest path algorithm finds all minimum costs paths (possibly within an arbitrary epsilon) on the area of similar characteristics and the directed edges connecting vertices represent the connection relationships between areas.

4. The data for and interpretations of the original tolerance to development surface are interfaced with each possible alternate route to develop tabulations describing the characteristics of each alternate corridor. The corridors are drawn on the tolerance to development map and individual corridor tabulations displayed.

Tolerance to Development Surface

The "tolerance to development" surface is the image of a complex mapping from terrain, land use, economic, and biotic data organized on a grid representation of the study area. The suitability of corridors for eventual location of precise alignments requires that the analysis be sufficiently accurate to detect and process any discontinuities in phenomena which could affect planning at this scale. As shown by Steiner [32], Peuker [27], and Krauskopf and Bunde [17], this necessitates detailed assessment of the study area on an arbitrary grid square basis. Grid cell size will be selected to accommodate the significant data discontinuities and should be related to the level of resolution available in the spatial sources.

A mapping is performed for each individual unit area or grid location, usually assessing an ordinal value (for example, from 1 to 6) indicating tolerant to prohibitive. Each unit area is represented by a data vector (Xa, Xb, Xc, Xi). If G is a mapping on a unit area's variables and N is a mapping on a set of variables belonging to neighbors of the unit area, then the general mapping for a unit area is:

\[ Z = U(Xa, Xb, ..., Xi), G(Xa, ..., Xn), N(Xp, ..., Xl) \]

for \{a, b, ..., z\} some suitable indexing set.

Usually a number of mappings \( U_j \) are defined, each of which addresses a specific area or topic of concern. For example, \( U_1 \) might assess the agricultural section, \( U_2 \) might assess heavy manufacturing, etc. A summary of impact factor

A Graph Representation

A grid organized collection of unit areas is a graph where each unit area is delimited by the edges joining the four vertices which are located at its corners. The planar dual graph to the graph in Figure 1(a) is shown in Figure 1(b) where each unit area is now represented as a vertex and the edges connecting vertices represent the connection relationships between unit areas. When areas of non uniform size are involved, as shown in Figure 1(c), the dual graph (see Figure 1(d)) still maintains the connection relationships. Inter-area distances can be represented in the dual graph by developing a table of "weights" for each edge.

Graph reduction techniques are applicable to directed graphs where strong components are located and replaced by a single vertex. Strong components are "factored out" of the original dual graph.

The resulting reduction in number of vertices and edges required to represent the area relationships reduces computer memory demands and makes possible large scale studies. In addition, the reduction in number of vertices and edges can greatly reduce the computer time required to perform routing analysis. The reduction preserves value discontinuities over space as originally recorded in the unit area graph. Efficiency has been gained by recording with detail (i.e., a number of vertices and edges) areas of maximum discontinuity, while using minimal information (i.e., only a few vertices and edges) to record areas of similarity.

Corridor Route Selection

An arbitrary mapping \( \delta \) can be defined to map the "cost" of impact per unit distance from the impact rank of a unit area. Such a mapping can be described in tabular form as shown in Table 1.

<table>
<thead>
<tr>
<th>RANK</th>
<th>IMPACT</th>
<th>COST x ( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
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</tr>
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<td>5</td>
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<td>16</td>
</tr>
<tr>
<td>6</td>
<td>32</td>
<td>32</td>
</tr>
</tbody>
</table>
Three sample mappings are shown. The mapping shown in column (a) equates cost with impact rank as a power of two. This shows, for example, impact rank five as twice as costly as rank four. The mapping shown in column (b) is the same as (a) except "cost" for the prohibitive or "no-go" rank 6 is declared to be infinite. The mapping shown in column (c) shows a very heavy cost being associated with high ranking impacts.

The "cost" for a connection between area i and area j denoted as Cij can be expressed as a function of the mapping s on the impact ranking for area i denoted R_i and the impact ranking for area j denoted R_j. Let b denote the point of intersection of the common boundary between areas i and j and the line i,j. Then Dib represents the distance from the centre of area i to the intersection point. Thus the function:

\[ C_{ij} = s(R_i) \times Dib + s(R_j) \times Djb. \]

can be used to calculate the inter-area distances.

It is equivalent in path development to consider an absence of connection between areas i and j as a connection between i and j with cost of infinity. This feature can be used when costing prohibitive impact areas. Setting the cost map to infinity as shown in columns (b) and (c) of Table 1 would have the effect of completely removing the connections between any area coded 6 and any other area.

Route development proceeds, using the cost function Cij to establish edge weights in the contracted dual graph. The Dijkstra [9] algorithm can be easily extended to identify alternate minimum cost routes. These are displayed overlayed on the supporting maps.

Alternate Corridor Comparison

Routing algorithms specify a series of points in space which, if connected, provide minimum cost routes from an arbitrary source to an arbitrary destination. While each such route may have an aggregate impact cost which is equal to all other routes, it is possible that routes may be quite dissimilar one from another with regard to the kinds of impact each possesses. The components of the tolerance to development surface for the area covered by the various alternate corridors can be summarized in tabular form. This is achieved by establishing route polygons and intersecting them with the values of the U_j mapping, the composite mapping, and raw data variables. For each alternate route a tabulation similar to the following can be developed.
Table 2

<table>
<thead>
<tr>
<th>Classification</th>
<th>Per-cent Classification</th>
<th>Area (Acres)</th>
<th>Valuation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - no impact</td>
<td>5</td>
<td>15</td>
<td>500</td>
<td>7,500</td>
</tr>
<tr>
<td>1 - negligible impact</td>
<td>25</td>
<td>75</td>
<td>700</td>
<td>52,500</td>
</tr>
<tr>
<td>2 - light impact</td>
<td>55</td>
<td>165</td>
<td>1,200</td>
<td>198,000</td>
</tr>
<tr>
<td>3 - moderate impact</td>
<td>10</td>
<td>30</td>
<td>2,000</td>
<td>60,000</td>
</tr>
<tr>
<td>4 - heavy impact</td>
<td>3</td>
<td>9</td>
<td>8,000</td>
<td>72,000</td>
</tr>
<tr>
<td>5 - severe impact</td>
<td>2</td>
<td>6</td>
<td>10,000</td>
<td>60,000</td>
</tr>
<tr>
<td>6 - prohibitive impact</td>
<td>0</td>
<td>0</td>
<td>450,000</td>
<td>0</td>
</tr>
</tbody>
</table>

Agricultural -
- class 1 area 5 15
- class 2 area 20 60
- class 3 area 40 120

WOODLOTS 14 42

WILDLIFE STAGING
- NESTING AREAS 6 18

CLASSIFIED BIOLOGICAL
- VALUE AREAS 3 9

RESIDENTIAL 0 0

COMMERCIAL 7 21

INDUSTRIAL 5 15

This provides a good basis from which policy planners and public officials may select the most acceptable alternatives.

References


5. Coleman, D. J., An Ecological Input to Regional Planning. Waterloo: School of Urban and Regional Planning, Faculty of Environmental Studies, University of Waterloo, 1975.


32. Steiner, D. "Data Needs and Data Specification", in R. F. Tomlinson (ed.), Geographic Data Handling, 2 volumes; Ottawa: International Geographical Union Commission on Geographic Data Sensing and Process-