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Land-Use Suitability Analysis in the United States: Historical Development and Promising Technological Achievements

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ABSTRACT / Various methods of spatial analysis are commonly used in land-use plans and site selection studies. A historical overview and discussion of contemporary developments of land-use suitability analysis are presented. The paper begins with an exploration into the early 20th century with the infancy of documented applications of the technique. The article then travels through the 20th century, documenting significant milestones. Concluding with present explorations of advanced technologies such as neural computing and evolutionary programming, this work is meant to serve as a foundation for literature review and a premise for the exploration of new advancements as we enter into the 21st century.

Land-use suitability analysis is a tool used to identify the most suitable places for locating future land uses. Suitability techniques enable environmental managers and planners to analyze the interactions among three types of factors: location, development actions, and environmental elements. Analysts then are able to map these interactions in a variety of ways. For example, a map might show (1) which land uses will have the least adverse impact on environmental processes, (2) qualitative predictions of environmental impacts of proposed developments, and (3) the most and least propitious locations for specific development proposals. Public officials and private developers can use these maps to set policies and make decisions regarding the use of land.

Today's environmental managers and planners are becoming increasingly aware of the technological advancements in land-use allocation and suitability modeling. These new methods of spatial analysis are now commonly used in the development of land-use plans, environmental impact reviews, and site selection studies for many different land uses and public and private facilities. But getting caught up in technological advances and failing to recognize the historical underpinnings of the method makes impossible any useful discussion of the merits of the process or future advancement in this field. For those who are interested in these issues beyond dealing with the immediate availability of sophisticated software-assisted land-use modeling techniques, the intent of this discussion is to provide some help in elevating the discourse.

This article presents a historical overview and discussion of methodological and technological developments of land-use suitability analysis in the United States over the past 100 years. It begins with an exploration back into the early 20th century where we witness the infancy of documented applications of the technique for circulation and land-use planning. The paper then travels through the past century, documenting significant technological and methodological milestones in land-use suitability practice. Concluding with our present explorations into the application of advanced technologies, such as neural computing and evolutionary programming, this work is meant to serve as a foundation for literature review on the subject matter and a premise for the exploration of new advancements in the field as we enter into the 21st century. To provide a structure and framework for our discussion, we classify the development of land-use suitability methods and methodological advances into five general stages. These stages are distinguished by changes in representation, technology, and theory and include: Stage 1: early hand-drawn, sieve mapping;

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Stage 2: advancement in the literature; Stage 3: computer-assisted overlay mapping; Stage 4: redefinition of spatial data and multicriteria evaluation; and Stage 5: replicating expert knowledge in the process (current state). These five stages of development overlap, particularly as rapid advances in computer technology have influenced research and practice.

Stage 1: Early Hand-Drawn, Sieve Mapping

The earliest applications of suitability analysis took the form of hand-drawn, sieve mapping overlays. Scant documentation remains about the technique by those pioneering it. This use of hand-drawn overlays by American landscape architects in the late nineteenth and early twentieth century is an early predecessor of modern land-use suitability analysis. Miller (1993) and McHarg (1996) credit Charles Eliot and his associates in the office of Olmsted and Eliot with inaugurating such overlays with the use of sun prints produced on their office windows.

In 1912, Warren Manning, a protegé of Olmsted and Eliot, used soil and vegetation information together with topography, and their combined relationship to land use to prepare four different maps of the town of Billerica, MA. Manning's Billerica plan displayed recommendations and changes in the town's circulation routes and land use (Steinitz and others 1976, Manning 1913). Eliot (1902) left a detailed explanation of the sun-print overlay process, but neither he nor Manning left explicit explanations of their underlying intellectual rationales.

After Eliot's and Manning's work, additional studies used the overlay technique; but again a theoretical explanation about the rationale for using it was missing (see, for example, Abercrombie and Johnson 1922, Regional Planning Staff 1929, Forshaw and Abercrombie 1943). Thomas Adams, who directed the extensive 1929 New York regional planning study, addressed suitability in his 1934 *Design of Residential Areas*, but mostly from an economic perspective rather than an environmental one (see Adams 1934).

Stage 2: Advancement in the Literature

The second stage in the evolution of land-use suitability analysis began with the surfacing of the first academic discussion of the overlay technique in 1950 with the publication of the *Town and Country Planning Textbook*, which included an article by Jacqueline Tyrwhitt that dealt explicitly with the overlay technique (Steinitz and others 1976). Tyrwhitt gave an example of four maps (relief, hydrology, rock types, and soil drainage) drawn on transparent papers to the same scale and referenced to common control features. These data maps were then combined into one land characteristics map, which provided a synthesis, interpretation, and a judicious blending of the first four maps (Tyrwhitt 1950; Steinitz and others 1976). This overlay method was widely accepted and incorporated into the large-scale planning of the British new towns and other development projects in Great Britain as well as North America after World War II (Lyle and Stutz 1983).

The planning literature from this period begins to include documentation and professional discussion of land-use suitability techniques and planners' and designers' widespread use of transparent overlays. This discussion continued throughout the 1960s with many more references to the overlay technique (Hills 1961, Alexander and Manheim 1962, Lewis 1964, 1969, Belknap and Furtado 1967). Philip Lewis (1963) produced recreation plans for Illinois and Wisconsin as the composite of various environmental factors. The appearance of this literature and the use of the overlay technique in specific projects and studies in the late 1960s and early 1970s marked the formal acceptance of the overlay technique (see, for example, McHarg 1968, 1996, 1997, Wallace and others 1969, 1972, 1976, Juneja 1974, Brandes 1973, Hopkins 1977). The availability of stable photographic material in the 1950s also contributed directly to the advancement of the overlay mapping process based on photographic exposure using multiple negatives (Chrisman 1997).

The most significant methodological advance during the 1960s was the development of the ecological inventory process. McHarg, the originator of this process, mapped information on the human-made as well as the natural attributes of a study area; he then presented this information on individual, transparent maps using light and dark values (Belknap and Furtado 1967, 1968, McHarg 1969, Gordon 1985). Then, McHarg superimposed the individual transparent prints of light and dark values over each other to construct the necessary suitability maps for each land use. These x-ray-like composite maps illustrated intrinsic suitabilities for broad land-use classifications, such as conservation, urbanization, and recreation for the specific planning area. Finally, he combined these composite maps as overlays to produce an overall composite suitability map (McHarg 1969). Such maps indicated the best, or most suitable, location for various land uses, that is, where uses could occur most economically with the least negative environmental consequences.

During the 1970s, many graduate students were attracted to the University of Pennsylvania because of the widespread influence of McHarg's *Design with Nature.*

These students became engaged in applied research projects, such as the plan for Medford Township, New Jersey. Some also worked at the firm Wallace, McHarg, Roberts and Todd (WMRT), which was active in numerous planning efforts, such as the ecological plan for the Woodlands in Texas. These academic and professional projects provided case study material for student research related to suitability analysis. For example, Charles E. Brandes's 1973 thesis on methods of synthesis for ecological planning (see Brandes 1973). This thesis provided a useful explanation of the various methods McHarg and his Penn and WMRT colleagues had applied through their numerous projects. A contemporary of Brandes at Penn, Lewis Hopkins (1977, 1980), pursued an academic career and published several of the important scholarly papers on the topic. Based in part on Stevens's (1946) early work dealing with measurement frameworks associated with the arithmetic of spatial attributes, Hopkins presented a rather complete consideration of the possibilities for map combination (Chrisman 1997). The work of Brandes and Hopkins helped distinguish the variety of approaches and theories being employed in suitability analysis up to that time.

Stage 3: Computer-Assisted Overlay Mapping

Many practical difficulties in land-use suitability arose as the number of maps that needed to be manually superimposed increased significantly during the late 1960s and early 1970s. This increase occurred because, as the popularity of suitability analysis spread and more diverse disciplines became involved, the range of map information advocated for consideration grew. At the same time, the amount of mapped data increased with the advance of computing technologies. A practical limitation on the number of maps, and thus the amount of information, that could be used manually, led those involved in suitability analysis to look to computers. This relatively new technology offered many advantages for mapping and combining large amounts of data. The advent and use of the computer in land-use suitability analysis marks the third stage of its evolutionary development. Although McHarg and his colleagues at the University of Pennsylvania were deeply involved in this work (see McHarg 1996 and Hopkins 1977), groups at Harvard University and the University of Massachusetts became better known for applying computer technology to land-use suitability analysis. Bruce MacDougall (1975) provided an important bridge between the Penn and Massachusetts approaches because he was a member of both faculties. MacDougall criticized the accuracy of hand-drawn map overlays and made constructive suggestions about how they could be made more accurate, in part through the application of computer technology.

Arguably, the most important computer-related advances occurred at Harvard. In 1963, Howard Fisher elaborated on Edgar M. Horwood's idea of using the computer to make simple grid maps by printing statistical values on a grid of plain paper (Sheehan 1979; Burrough 1990). Fisher's program called SYMAP (synagraphic mapping system) included a set of modules that manipulated data to create choropleth or isoline interpretations that allowed the results to be overprinted creating suitable gray scales. The first application of SYMAP to a large geographic region occurred at the Laboratory for Computer Graphics at the Harvard University Graduate School of Design. In 1966 Carl Steinitz, at that time an associate professor at Harvard, created DELMARVA, a landscape planning study of the Delaware, Maryland, and Virginia Peninsula. Steinitz used SYMAP to analyze the effect of one map factor upon another and to incorporate weighted indexes such as the capability of an area to support grain agriculture (Steinitz 1993).

Another of the more widely documented predecessors of modern computer-based land-use suitability was the Honey Hill study (Murray and others 1971), named after the study location in New Hampshire. In this instance, Steinitz and colleagues used SYMAP to evaluate a proposed flood-control reservoir and parkway for their suitability for recreation and other land uses. The Honey Hill study offered important insights into the power of computers to combine different land-use modeling techniques to create a composite, fiscally optimal plan (Steinitz 1993). Other mapping programs of this stage included the well-known grid-cell (raster) mapping programs GRID and IMGRID (Steinitz 1993). These overlay programs adapted principles of overlay analysis in a quicker and more reproducible environment than ever before.

Working with Steinitz and J.K. Berry of Yale, Dana Tomlin (1983) proposed a method for defining what he called "map algebra" and wrote an experimental program to implement his ideas. The program was called the Map Analysis Package (MAP). By October 1982, the MAP had been acquired by 71 university departments, 38 public agencies and government research institutes, and 35 private organizations around the world (Berry 1983). A similarly important contribution came from the Metropolitan Landscape Planning Model (METLAND) developed by researchers at the University of Massachusetts in the early 1970s (Fabos and others 1978). Led by Julius Fabos, the Massachusetts team included several key researchers recruited

Table 1. Comparison of Boolean and fuzzy logic (adopted from Banai 1993)

Boolean logic	Fuzzy logic
1. Clean definition of boundaries to include or exclude an element in a set.	1. Allows flexibility in defining variable boundary thresholds to be set.
2. An element is either included or excluded in a set.	2. The inclusion of an element in a fuzzy set is a matter of degree.
3. Does not permit partial membership of an element in a set.	3. Permits partial membership of an element in a fuzzy set.
4. Membership functional values are restricted to two points (0, if element is not in set, 1 if element is in the set).	4. Membership functional values take the range of values between and including 0 and 1.

from Penn including, initially, MacDougall, Mier Gross and, subsequently, Jack Ahern.

Further advances in the field of computer mapping technology resulted in the formal development of geographic information systems (GIS). These technologies store, analyze, and display spatial and nonspatial data and are capable of creating new data through automated overlays and spatial searches (Goodchild and others 1993, Antenucci and others 1991, Niemann 1989). Examples of the application of GIS suggest a wide acceptance of computer-based techniques for a very wide range of planning applications since the 1980s (Lyle and Stutz 1983, Sperry and Smail 1985, Buckley and Hendrix 1986, Burrough and others 1988, Moreno and Seigel 1988, Davis and Goetz 1990, Harris 1992, Batty and Xie 1994, Landis 1994, Burley and Brown 1995, Xiang 1996, Klosterman 1997, Landis and Zhang 1998, Hopkins 1999).

Stage 4: Redefinition of Spatial Data and Multicriteria Evaluation

Two new research directions marked the fourth stage: Boolean logic and alternative methods for using preferences. The first was the evaluation of Boolean logic and its capacity to handle indiscriminant spatial boundaries in a GIS-based analysis. Several researchers, including Reza Banai and Michael Goodchild, published investigations in this area (see Banai 1993, Goodchild and others 1993). As evidenced by their work, many problems with traditional Boolean methods of land unit classification were observed. For example, in Boolean classification, a land unit is classified based on a precise definition. Homogenous land units with values that fall outside of the given definition are not included in the class. On the contrary, fuzzy set theory suggests that the inclusion of a land unit within a class is a matter of determination to the degree of belonging, not a strict classification based on a precise definition (Table 1) (Banai 1993). Considered as an extension of Boolean set theory, Zadeh's fuzzy set theory (Zadeh 1965, 1990) became a prominent topic of discussion and research during the 1980s for use within GIS and land-use suitability analysis (see for example Banai 1993, Burrough and others 1992, Goodchild and others 1993).

The second research direction marking the fourth stage of development in land-use suitability analysis centered on finding alternative methods to incorporate decision-makers' preferences within land-use allocation and suitability analysis. One such alternative was the use of multiple criteria decision making (MCDM) or multicriteria evaluation (MCE) methods for analyzing multiobjective decisions using mathematical programming (optimization) methods. Dyer and others (1992) provide an excellent review of literature on MCDM and MCE and present future research directions. Yoon and Hwang (1995) present a variety of different MCDM and MCE methods and examples of application. There are several examples of the application of these multicriteria methods within land-use allocation models (Moreno and Seigel 1988, Carver 1991, McCartney and Thrall 1991).

Moreno and Seigel (1988) provide a comprehensive discussion on the application of MCE for an impact analysis for siting of a highway corridor in Colorado. A modified Delphi approach was used to identify land-use allocation criteria and suitability weights. Composite factor maps were created, and a weighted overlay was used to combine the factor maps into a composite map for each criterion. These composite maps were then combined to find suitable corridors with minimal environmental impact (Moreno and Seigel 1988). Following Moreno and Seigel, many planners and researchers experimented with the use of MCE for suitability analysis and contributed to the literature of the subject (see, for example, Jankowski 1995, Jankowski and Richard 1994, Janssen and Rietveld 1990, Janssen and van Herwijnen 1991, Carver 1991, Eastman and others 1993, Pereira and Duckstein 1993, Malczewski 1996, among others).

Pereira and Duckstein (1993) developed a programming approach that evaluated alternatives on the basis of their closeness (distance) to the ideal point that serves as a frame of reference. This method was also used by Carver (1991) for an analysis of site selection for the disposal of radioactive waste. Carver (1991) integrated two MCE techniques: hierarchical optimization and concordance/discordance analysis within his proposed method (Malczewski 1996).

Banai (1993) offered the integration of a now popular multiobjective decision making method, the Analytic Hierarchy Process (AHP) within a GIS environment as a mathematical method for estimating a value function based on various pairwise comparisons, and this value function was then used to rank the alternatives. The AHP was developed by Saaty in the 1970s (Saaty 1980; see Saaty 1994 and 1995 for recent presentations of this approach) as a scenario approach to multiobjective decision making where the relative values of possible decisions or outcomes were given a function value based on a mathematical representation of pairwise comparisons. Applications of the AHP to landscape planning and assessment (for example, McDonald and Brown 1984, Nieman and Meshako 1983), site-suitability analysis (for example, Banai 1993, Banai-Kashani 1989, Miller and others 1998, Malczewski 1996), and land conversion simulation (for example, Wu 1998) are well documented. There have also been several discussions in the scholarly literature of the advantages and disadvantages of the AHP relative to other available decision analysis methods. Articles by Dyer (1990a,b), Harker and Vargas (1990), and Saaty (1990) provide an overview of this discussion.

As an extension of AHP, Xiang and Whitley (1994) developed a Priority for Land-use Suitability (PLUS) method to deal with the problems of preference acquisition, synthesis, and inconsistency diagnosis that were not completely solved by the Saaty's AHP method. Collins (1996) and Miller and others (1998) demonstrate the use of the PLUS method for a greenway suitability analysis in central Arizona.

Wu (1998) used MCE and AHP methods to recover preference weighting in land-use allocation modeling. This model, based on cellular automata (CA), attempted to mimic how land development potential is evaluated via the tradeoff of multiple development factors. The approach differs from other similar models by linking the parameter of potentiality calculation with the characteristic of land development in different regimes (Wu 1998). Malczewski (1996) demonstrated the implementation of the AHP method for criterion weighting with the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) for the siting of a noxious facility. The method defined a set of procedures to rank alternatives according to the preferences of a number of individuals that evaluate the alternatives on the basis of multiple, conflicting, and noncommensurate criteria (Malczewski 1996).

Other researchers during this stage also continued to experiment with new ways of land-use allocation modeling. For example linear programming (LP) was used by Chuvieco (1993) to deal with the optimization (i.e., minimization or maximization) of a linear suitability function. Chuvieco (1993) experimented with LP to optimize spatial distributions and guide the integration of variables in a land-use modeling scenario. Other interesting applications of LP to land-use allocation and suitability studies were in the optimization of transport planning (Horton and Wittick 1969), the location of central facilities (Revelle and Swain 1970), and land-use planning (Charnes and others 1975, Heroux and Wallace 1975, Killen 1983, Dykstra 1983). Arthur and Nalle (1997) present an extended discussion on the use of LP and GIS for land-use modeling.

Stage 5: Replicating Expert Knowledge in the Process (current state)

Stage 5 marks the integration of artificial intelligence (AI) in land-use suitability analysis and is the current stage of research in the field. The last 10 years have seen the development of AI methods and tools that are capable of being applied to many practical geographical problems. This development has been characterized by surges of enthusiasm with each AI innovation followed by waves of recrimination as these developments seem to fall short of general expectations (Openshaw and Openshaw 1997). Table 2 provides a general overview of the development of AI tools over the past 50 years.

The use of AI in the fields of planning and geography is only in its infancy, and thus few examples of its application to land-use suitability are present. The technology at this point is much too experimental, high-tech, and expensive to be considered for main-line planning. There is a growing movement, however, toward the identification of AI tools for various GIS-based land-use allocation and modeling applications. This direction of research is establishing a foundation for the extension of AI technology into solving land-use planning and suitability problems. The following section provides a more in-depth discussion of these new technologies and the potential applications and adapt-

Table 2. Development and contributions of AI technologies in geography

Decade	Major focus/development	Primary contribution to geographical application
1950s	Primitive neural networks	Engenders considerable enthusiasm in the promise of AI technologies.
1960s	Heuristic search	Permits complete enumeration of all solutions considered relevant.
1970s	Expert systems	Provides the preservation of critical expertise as a future resource beyond the life span of any human expert(s).
1980s	Neurocomputing, genetic algorithms, and artificial life	Ability to learn by example, to generalize from the specific to the abstract and to handle noisy data and chaotic and nonlinear modeling tasks.
1990s	Genetic programming and hybrid intelligent systems	Provides robust and reliable technology for solving nonlinear optimization problems.

ability of the methods within the land-use suitability process.

Artificial Intelligence and the New Horizon of Land-Use Suitability Technologies

Early examples of the application of AI technology to geography and land-use planning include the use of heuristic search processes, expert systems, neurocomputing, and genetic programming. These new technologies are being presented as potential development platforms for the process and provide a new potential for rediscovery and growth in the methodological processes by which we conduct the analysis.

There is considerable literature documenting the use of what we consider heuristic search methods for spatial pattern identification and combinatorial optimization (for example, see Gould 1966, Scott 1971, Massam 1980). An early example of blind or brute-force heuristic search methods used for the analysis of large spatial data sets for localized patterns can be found in the Space Time Attribute Machine (STAM) of Openshaw (1991). This automated heuristic search process sought patterns in data sets with measurements taken from three different spaces (geographical, temporal, attribute). One application of the STAM was the evaluation of rare diseases and the identification of at-risk populations in the United Kingdom. Other examples of heuristic search methods for spatial analysis include the identification of nuclear power station locations (Openshaw 1986); optimization analysis for nuclear bombing strategies (Openshaw and Steadman 1982); the optimization of automobile showroom locations (Barkin and others 1995); and optimal zone design (Openshaw and Rao 1995, Openshaw and Alvanides 1996).

Considerable effort has also been devoted to the pursuit of building intelligent computer systems that could replicate the expert knowledge of humans. These expert systems (ES) have been developed to provide much more than just rudimentary puzzle or problem solving capabilities in geography. Herbert and others (1992) and Joao and others (1993) describe a map generalization machine that uses ES to assist the user in interpreting the landscape generalization process. Wadge and others (1993) linked ES to GIS to assist users in landslide hazard assessment in Cyprus. Other examples of ES approaches to spatial analysis that evaluated case-based or memory-based reasoning systems include Stanfill and Waltz (1986), Stanfill and Kahle (1986), and Creecy and others (1992).

Another recent development is the emergence of neurocomputing as a tool to apply computation to problems previously restricted to human intelligence, with the appearance of procedures that enable machines to learn and remember in ways that bear some resemblance to the human mental process (Anderson 1987). Researchers have already found neurocomputing methods or neural networks as having the ability to spontaneously learn a desired function from training examples (see Wasserman 1989, Khanna 1990, Aleksander and Morton 1990, Openshaw and Openshaw 1997).

Neural networks have long been successfully used for remote sensing image classification (Hepner and others 1990, Benediktsson and others 1990, Civco 1993) and GIS spatial analysis and modeling (Sui 1993, 1994, Fischer and Gopal 1994). Sui (1993) successfully integrated a neural network with GIS for development suitability analysis and found that a neural network can make a close approximation of experts' decisions without the explicit expression of experts' knowledge into the classification rules (Zhou and Civco 1996). Other examples of the use of neural networks in geography include Openshaw and Wymer (1991), Fischer and Gopal (1993), and Hewitson and Crane (1994). Fischer and Gopal (1994) used a neural network for interregional telecommunication traffic analysis in Austria and found that it outperformed traditional regression approaches.

Wang (1994) provides a good example of neural networks in land-use suitability assessment for wetland rice, soybean, sugarcane, pasture, and acacia crops in the north coast of west Java, Indonesia. Wang demonstrated that neural networks could assess land suitability from a more complex rating rule and provide more accurate analysis than other traditional methods. The results of the analysis revealed that neural networks were capable of providing both absolute and relative suitability in a complex environment, provided that no ambiguity exists in the rule and that patterns in the problem space are separable by the rule (Wang 1994).

There is also a growing interest in evolutionary programming (EP) as a means of solving complex spatial problems or land-use optimization tasks. The concept is based on Darwin's concept of evolution and the natural process of genetic inheritance that biological systems use in their fight for survival. This new field includes previous research areas such as evolutionary computing, genetic algorithms, evolutionary strategies, and genetic programming (see Fogel and others 1966, Holland 1975, Koza 1992, Openshaw and Openshaw 1997). Significant geographical applications include intelligent exploratory searches of GIS databases (Openshaw 1994), and new spatial interaction models (Turton and others 1997, Diplock and Openshaw 1996). From a planning perspective, EP has the potential to offer a robust and reliable technology for solving nonlinear land-use optimization problems.

The experimentation with AI documents the most recent effort to implement advanced technologies and computational methods within the land-use suitability analysis field. This technology appears promising for the automated integration of multidimensional data in a fuzzy environment for large and complicated land-use allocation models. It also appears to provide sophisticated spatial analysis tools to aid in the development of complex multicriteria land-use suitability and optimization analyses. Applying this new technology to the land-use modeling and suitability process has not been simple. The costs involved with the development and implementation of these technologies within main-line planning is quite restricting. The sheer magnitude of the AI technologies can be imposing to the most ardent and technologically sophisticated researcher in the planning field.

Whether technology has improved the efficacy or validity of land suitability analysis beyond Eliot's sunprint overlay process or McHarg's ecological inventory process is the subject of another debate. For sure however, new technologies offer tremendous opportunity to explore new land suitability frameworks that benefit from advanced data development, manipulation, and visualization systems. It is hoped that this reflection on historical developments and promising technologies in the field will provide a foundation on which further development of land suitability analysis can take place. Such models have the opportunity to enhance the suitability function in empirical and interpretive dimensions.

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