# Design of an Intelligent Geographic Information System for Multi-criteria Site Analysis

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***Abstract:*** *Spatial decision-making problems, such as site selection, require appropriate means for handling multiple socioeconomic factors while considering physical suitability. Traditional decision support techniques lack the ability to simultaneously take into account these factors and conditions. Similarly, geographic information systems, while recognized as useful decision support technologies, do not provide the means to handle multiple decision factors. With these issues in mind, this study was developed to provide a framework for integrating the strengths of geographic information systems, expert systems, and the analytic hierarchy process to incorporate the decision maker's preferences on a range of factors used in finding optimally suitable sites. This study illustrates how the integrated system may be applied to industrial site selection.*

## Introduction

Site selection requires consideration of a comprehensive set of factors and balancing of multiple objectives in determining the suitability of a particular area for a defined land use. The selection of an industrial site involves a complex array of critical factors drawing from economic, social, technical, and environmental disciplines. Respect for legislation and public awareness of environmental issues make the selection of suitable locations for facilities increasingly complicated, particularly when the facilities may have an adverse impact on neighbors or the environment. For developers searching for a site and for the city or county that wants to attract industry, the key is the ability to incorporate appropriate information and use it effectively, considering its complexity and diverse nature. The motivation for this study is recognition that current spatial decision making could benefit from more systematic methods for handling multi-criteria problems while considering the physical suitability conditions. Traditional decision support techniques lack the ability to simultaneously take into account these aspects.

With the recent technological development of computer hardware and software, geographic information systems (GIS) have emerged as useful computer-based tools for spatial description and manipulation. Although often described as a decision support system, there have been some disputes regarding whether the GIS decision support capabilities are sufficient (Djokic 1991, Zhang 1991, Jankowski 1995). Since current GIS do not provide decision-making modules that reason a decision and are primarily based on manual techniques and human judgments for problem solving, the individual should have the decision rules in place before GIS can be utilized. Other limitations in current GIS approaches include a failure to provide methods to consider individual preferences and to evaluate trade-offs among the decision criteria essential to multi-criteria problems such as site selection.

Thus, two perspectives on developing better decision capabilities of GIS can be identified: one by including a 'decision' module and the other by including a 'prioritization' capability. This study demonstrates how decision processes can be included into GIS by coupling them with the expert system's programming capabilities based upon experts' decision logic. Just as an expert possessing knowledge and experience in a specialized domain uses reasoning rules and expertise to solve a problem, an expert system can embody the logic of such expertise. Logical decision steps can be programmed into the computer to solve problems or provide information in a specialist's domain.

In addition to an expert system, this study employed a method for assigning priorities to conflicting decision criteria called the analytic hierarchy process (AHP) developed by Thomas Saaty. The AHP is a multi-criteria decision method that uses hierarchical structures to represent a problem and then develops priorities for alternatives based on the judgment of the user (Saaty 1987a). Saaty has shown that weighing activities in multi-criteria decision making can be effectively dealt with via hierarchical structuring and pairwise comparisons. Pairwise comparisons are based on forming judgments between two particular elements rather than attempting to prioritize an entire list of elements (Saaty 1980). Adding the prioritization module for setting priorities enhances existing GIS analyses and visualization capabilities. This study illustrates a method for constructing an integrated system of these three decision support tools (the GIS, the expert systems, and the AHP module), and applies it to an industrial site selection problem that searches for sites for manufacturing facilities in a regional scale.

## Remarks on GIS-integration Issues

Although the capabilities of GIS have proved their usability in a multitude of applications, there has also been increasing interest in coupling GIS with other decision support systems. However,

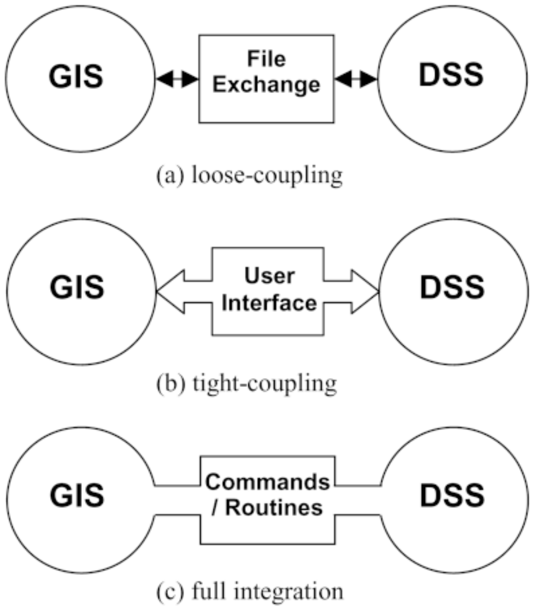



**Figure 1.** Classification of GIS-integration methods in terms of the extent of integration.

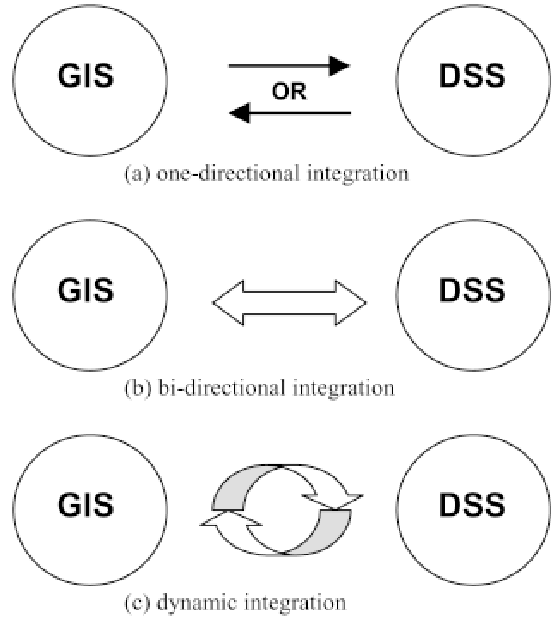



**Figure 2.** Classification of GIS-integration methods in terms of the direction of interaction.

due to the relatively limited experience and insufficient understanding of the needs and technical capabilities, the proper integrated use of GIS with other decision tools has been limited. In addition, these systems generally originate from or are used in different backgrounds, or user communities have sometimes discouraged researchers and practitioners from obtaining their integrative potential. In this section, previous approaches are examined for the purpose of clarifying the relevance of this study to them. First, different viewpoints in classifying the integration approaches are described. Alternative methodologies found in the literature are then categorized and compared, particularly centered around expert systems and mathematical models as the counterpart modules of the GIS.

## Classifications of Systems Integration

Some discussion on this topic has presented different viewpoints by which the methods of linkage between GIS and other decision-making tools can be identified. The most frequently cited classification scheme is the architectural basis for integration, where integration is expressed in terms of the closeness or the extent to which two separate systems are interfaced (Goodchild et al. 1992, Nyerges 1992, Fedra 1993). Examples of this include loose coupling, tight coupling, and full integration (Figure 1).

In loose coupling, two systems exchange files such that a system uses data from the other system as the input data. Actually, at this level of integration, the two systems run independently and no system modification or programming takes place except that the data of one system need to be edited as necessary for the proper format to the other system. Due to its simplicity, this technique is found in most approaches that involve integration of systems; however, manipulating the exchange files tends to be cumbersome and error prone. Tight coupling involves writing some form of programs to automate or facilitate the integration process between the components. The two systems share not only the communication files but also common user-interface. This is achieved by using macro languages such as Arc Macro Language (AML) which is provided by the Arc/Info GIS package. Although the AML is not suited to perform complex numerical manipulations, relatively simple forms of calculations can be formulated inside AML codes and it can invoke external programs, which enables the user to interact with both systems through a user-interface without having to quit either system. In full integration, a more complete integration can be achieved by creating user-specified routines through generic programming languages such as FORTRAN or C and adding them into the existing set of commands or routines of the GIS package. This requires such resources as source codes or command libraries and relatively complicated programming, which is not available to most GIS users.

Anselin et al. (1993) classified the integration approaches based on the direction of interaction between the systems into three broad types: one-directional integration, two-directional integration, and dynamic integration (Figure 2).

One-directional integration moves information via a single flow that originates either in the GIS or in the decision support tool of interest. In the movement of information from the GIS to the other decision support module, the data generated in the GIS serve as the input data to the second module. Comparatively, the flow in the opposite direction involves using the data from the decision tool in the GIS for direct visualization or further analyses. Two-directional integration links the systems in a form that simply combines the two aspects of the one-directional integration. Most approaches that employ this method start from the GIS module generating the appropriate data for the counterpart decision support module. This performs the required operations in the second module, and ultimately uses resultant data to add to the existing attribute data set in GIS and creates maps based on this newly created information. While two-directional integration involves one-time flow of information, dynamic integration enables the data flow between the decision tool and the GIS to move back and forth flexibly based on the user's needs. Such dynamic iteration can be performed by developing the user-interface that allows the user to interact with either system through graphical menu-based tools. This type of integration may be especially useful in cases where revision of data or the decision scenarios is desired after examining the results obtained from an intermediate iteration.

## Integration with Expert Systems

Expert systems (often called knowledge-based systems) comprise a software technology that can replicate certain aspects of expertise and can manipulate both qualitative and quantitative knowledge. This technology offers planners new ways of organizing, formalizing, and manipulating context-specific knowledge and problems (Masri and Moore 1993). Such systems are viewed as a means of overcoming the limitations found in current deterministic model-based approaches to problem solving (Han and Kim 1989).

Numerous expert systems have already been developed for spatial problems promising the possibilities of incorporating spatial information into expert reasoning processes. One popular area in applying the expert systems technique was assisting local planners in municipal regulations (Davis and Grant 1987, Shaw et al. 1993). Although it was demonstrated that an expert system can adequately embody planning regulations, it could not represent the relationship between spatial location and nonspatial regulation, which is crucial especially when decision rules depend on a geographic location. Similar limitations in utilizing stand-alone expert systems for solving spatial problems include concern with applications in site selection and suitability analysis (e.g., Suh et al. 1988, Han and Kim 1990, Han et al. 1991, Amha et al. 1994).

The expert systems in spatial problem solving became more sophisticated as GIS data began to be associated into the system processes. Efforts to fix the deficiencies of GIS utilizing expert system techniques have increased since the mid 1980's (e.g., Peuquet 1984, Coulson et al. 1987, Robinson et al. 1987, Fisher 1989, Wright 1990, Lu and Xiang 1992, Lam and Swayne 1993, Maidment and Evans 1993, Navinchandra 1993, Cowen and Ehler 1994). An integrated expert system and GIS have been referred to as an expert GIS or a knowledge-based GIS, when focusing on the stored facts or rules. An expert GIS have shown such benefits as enabling a novice GIS user to carry out a range of operations similar to an experienced user by making user interaction with GIS easier.

One category of expert GIS contains those applications that mainly address GIS for spatial feature extraction or classification. An early example of such applications was a study by Peuquet (1984) that used stored logical rules as a self-checking mechanism to detect and correct data errors. A similar study was done by Leung and Leung (1993a, b). In this, the expert system was used for spatial data classification with remotely sensed data and regular GIS data layers. A notable aspect was that they employed fuzzy logic to correct the unrealistic regional classification by which the borders of a region are sharply defined based on Boolean logic.

Another broad category includes applications that incorporate GIS data and operating capabilities into an expert system to form a geographic decision support system for resource management, territorial planning, or land suitability analysis. Djokic (1991) linked the Arc/Info GIS with an expert system to create a drainage network assessment system that checks for completeness and connectivity of network elements of GIS data. Evans et al. (1993) stated in their study that the improved version of SITE CODE (Shaw et al. 1993) can provide regulatory information to the user by linking regulatory facts stored in a database to sites located in a GIS through an expert system query interface. A study by Miller (1994) illustrated an increased utility of integrated decision tools by showing how the GIS can be coupled not only to the knowledge base but also to the environmental model to address vegetation change problems.

## Integration with Mathematical Models

Although a model can be viewed, inclusively, as an attempt to generalize or simplify the relationships observed in nature, this examination concerns the scope of mathematical models as external decision support tools from the viewpoint of the GIS. Rather than examining types of models exhaustively, efforts were made to elicit how the GIS were used for representative types of mathematical models among those found in GIS-related literature.

The most frequently observed research topic involves the use of GIS as the data provider for establishing some sort of constants of a model (e.g., Fisher 1991, Campbell et al. 1992, Chuvieco 1993, Haddock and Jankowski 1993, Xiang 1993, Brown et al. 1994, Cromley 1994; Warwick and Haness 1994). Campbell et al. (1992) and Chuvieco (1993) presented the application of linear programming (LP) in combination with GIS in planning land use strategies. The LP model is a mathematical model that maximizes or minimizes some objective function subject to a set of constraints. Chuvieco (1993) designed a test application of the LP-GIS to maximize the most labor-intensive organization of land use. The objective was constrained by limited resources and the GIS were used for demarcating resource availability by means of overlay map analysis.

A similar study by Xiang (1993) employed a multi-objective LP technique. In many practical situations, it would be desirable to achieve a solution that is "best" with respect to multiple criteria rather than one criterion as in Chuvieco (1993) (i.e., maximizing labor productivity). In multi-objective LP, all objectives are assigned target levels for achievement and a relative priority on achieving these levels. It then attempts to find an optimal solution that is "as close as possible" to the targets in the order of specified priorities. However, the major drawback of multi-objective LP is that it requires the user to formulate the model by specifying constraints and variables and to quantify the priorities in advance, which is difficult in reality.

By contrast, preference-oriented methods generally interact with the user for preference setting during the analysis. The multiple criteria decision making (MCDM) techniques have proved useful in situations that require the selection of the best alternative from the number of feasible choices in the presence of multiple decision criteria and diverse criterion priorities. Some applications coupled with the GIS are found in recent research approaches (e.g., Carver 1991, Eastman et al. 1993, Jankowski and Richard 1994, Jankowski 1995, Hickey and Jankowski 1997). Jankowski and Richard (1994) illustrated how a land suitability problem can be solved using the MCDM-GIS by enabling the procedure to select a site and set priorities in a systematic manner, taking into account spatial and nonspatial information. A study by Hickey and Jankowski (1997) was notable in terms of the level of coupling. In this, the contribution of the GIS was considered not only as a method for data gathering but also as the tool for mapping the result. A composite overlay map was visualized in the GIS that reflects the weights for criteria obtained from the MCDM module.

Other MCDM techniques include a method called the analytic hierarchy process (AHP), which has recently gained attention in GIS applications due to its ability for dealing with the multiple factors required in most GIS site suitability analyses. The primary popularity of this method can be found in the fact that users with a non-mathematical background are provided with steps to handle complex criteria through forming a hierarchical structure and performing pairwise comparisons. Banai (1993) used this technique in combination with GIS. Banai (1993) had the search for landfill area guided by the relative weights of the suitability factors obtained in the AHP. Notably, the fuzzy set theory by Zadeh (1990) was also employed in assigning shadings with the union of various polygon buffers generated by GIS overlay operations. Although the approach by Zadeh (1990) is viewed to be notable for addressing the trade-off problem among conflicting criteria, it leaves some room for improvement as a land evaluation technique as follows. First, decision-making processes such as site suitability analysis not only require numerical weighting of criteria as in Zaheh's approach but also involve steps using judgment. Such qualitative processes can be effectively manipulated using the expert systems as described in the previous section. Second, as Zadeh (1990) included in the final remark for future improvements, instead of performing the AHP operations outside the GIS environment, the applications can be linked 'tightly' by developing user-interface, which has been dealt with in this study.

Some key points found during the brief examination on the GIS-integration agenda may be summarized as follows: (i) more researchers are becoming interested in developing a closely integrated GIS decision module utilizing macro languages such as AML to be able to perform both modules in a flexible and user-friendly environment; (ii) the benefits of using expert GIS become obvious, especially when the type of problem requires analysis of factors that depend on information of geographic location or when complicated GIS data processing steps controlled by experts' decision rules need to be simplified or automated; (iii) the research trend of GIS-mathematical modeling integration indicates that multi-criteria MCDM techniques are preferred over deterministic optimization models especially in areas that require consideration of MCDM trade-offs and of the user's intervention for priority setting.

# The Framework of the System

## Two-phase Process

The search process for potential industrial sites involves multiple steps that can be divided into two general phases—a physically suitable area search and a community search. The physically suitable search phase, or Phase 1, refers to finding areas that meet ideal physical, environmental, or geographical conditions such as soils, vegetation, slope, hydrology, and transportation. The community search phase, or Phase 2, identifies a set of preferred communities and their surrounding areas among the alternative communities. This represents the process for industrial site selection seeking to narrow the search scope from larger and more inclusive regional potential areas to specific communities (Moriarty 1980).

The proposed system was designed to make it possible to identify feasible sites that satisfy a set of criteria included in the decision process. The system then continues its operation to permit a comparison of the communities based on their attributes. The final result will be identifying suitable sites as potential industrial areas within the vicinity of a chosen community.

## Identification of Decision Criteria for Each Phase

The two phases utilize different decision criteria: one extracts the spatially feasible areas by means of land suitability analysis based on the physical or geographical conditions for the given task. The other searches for or places in order preferred communities according to their social, economic, or environmental characteristics, including labor climate, economic costs, and living conditions. Tables 1 and 2 illustrate a framework of how the criteria for each phase can be organized. The criteria in Table 1 represent physical or engineering suitability criteria that can be delineated on maps. Depending on the intended purpose of a task, measurements may be chosen for expressing the land suitability using nominal, ordinal, and ratio scales. These measurements are also categorized into judgmental or objective scales: judgmental scales rely on expert judgment to provide the scores while objective labels employ scientific measurement methods to represent the appropriate values.

Table 2 shows an example of community criteria and values used for comparing the communities. As in Phase 1, the criteria are determined using objective data or are assessed judgmentally and can be categorized using nominal, ordinal, and ratio scales. For example, the number of public schools in a city measured using the ratio scale and given as objective statistics can be evaluated judgmentally to represent the education climate by means of ordinal scales such as good, fair, and poor. The primary difference between the two phases is that Phase 1 criteria such as soils, slope, or vegetation can be constituted as a thematic map for the suitability analysis. The decision criteria in Phase 2, the community search phase, typically do not involve mappable attributes. Because one city is considered as one point in intercity comparisons at a regional scale, the characteristics for a city function as point attributes rather than as physical regional attributes that can be depicted in two-dimensional polygons or regions.

**Phase 1: Site Suitability Analysis.** The steps involved are shown in Figure 3. These steps represent the flow of tasks and the individual modules of the system where the tasks take place. As described above, the decision criteria and corresponding GIS map layers required for the task are prepared. For community decision criteria, statistics are obtained from various sources. Depending on the types of criteria, especially in the case of qualitative criteria, some values need to be assessed judgmentally on an or-

**Table 1.** Selected physical suitability decision criteria for industrial facility siting.

| Criterion | Measurement |
|---|---|
| **Geology** | |
| ■ distance to faults | Ratio |
| ■ absence of permeable rock | Nominal |
| ■ depth to aquifer | Ratio |
| **Topography** | |
| ■ slope | Ratio |
| ■ protection from flood | Ordinal |
| **Soils** | |
| ■ soil drainage | Ordinal |
| ■ erodibility | Ordinal |
| ■ soil strength | Ratio |
| **Hydrology** | |
| ■ drainage density | Ratio |
| ■ flood frequency | Ratio |
| ■ hydrologic classes | Nominal |
| **Transportation** | |
| ■ Highway accessibility | Ratio |
| ■ Accessibility to truck terminals | Ratio |
| ■ Accessibility to railroads/air/water | Ratio |
| **Hazards / Environmental Sensitivity** | |
| ■ Seismic zone | Nominal |
| ■ Danger of rock disintegration | Nominal |
| ■ History of land slide | Nominal |
| ■ Natural habitat | Nominal |
| ■ Soil fertility | Nominal |

( Adapted from Briassoulis 1995, p. 300-304 )

**Table 2.** Selected community decision criteria for industrial facility siting and an example of comparative analysis.

| Characteristic | City A | City B | City C | Measurement |
|---|---|---|---|---|
| **Labor Climate** | | | | |
| ■ Availability | good | good | fair | Ordinal |
| ■ Population | 231,000 | 379,000 | 296,000 | Ratio |
| ■ Productivity | fair | good | good | Ordinal |
| ■ Unionization | extensive | little | moderate | Ordinal |
| **Transportation** | | | | |
| ■ Access to major highways | good | good | good | Ordinal |
| ■ Number of truck terminals | 8 | 11 | 6 | Ratio |
| ■ Railroads | good | good | fair | Ordinal |
| **Economic Costs** ($ per year) | | | | |
| ■ Labor ($ per hr. ) | 3.45 | 3.46 | 3.50 | Ratio |
| ■ Freight | 1,982,000 | 2,243,000 | 2,019,000 | Ratio |
| ■ Utilities | 650,000 | 677,000 | 516,000 | Ratio |
| ■ Taxes | 376,000 | 212,000 | 276,000 | Ratio |
| **Living Conditions** | | | | |
| ■ Urban population | 51,000 | 60,000 | 38,000 | Ratio |
| ■ Housing | reasonable | very good | very good | Ordinal |
| ■ Public education | fair | 2 | 3 | Ordinal |
| ■ Colleges | 0 | good | good | Ratio |
| ■ Hospitals | good | good | good | Ordinal |
| ■ Recreation | fair | good | good | Ordinal |

( Adapted from Moriarty 1980, p. 136 )

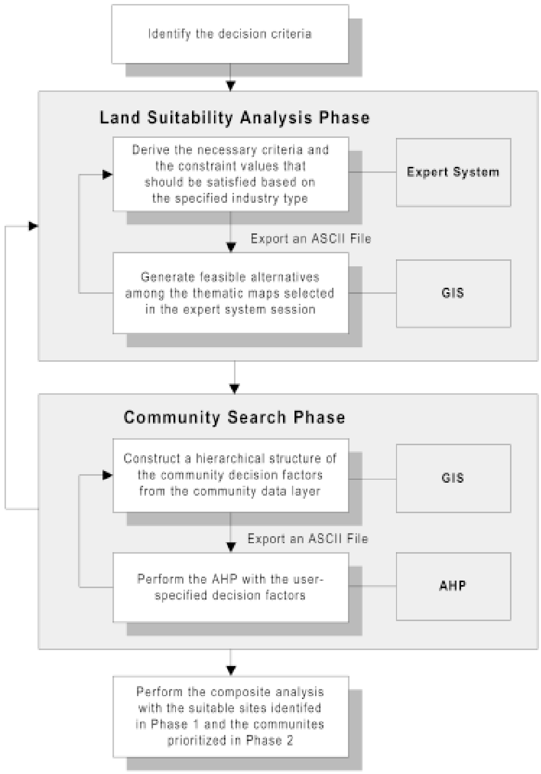



**Figure 3.** The procedure for industrial site selection using the proposed methodology.

dinal scale. These criteria are organized and attached to the community data layer for the community search phase.

Next, the expert system module is used to derive the necessary map layers and the expert-recommended constraints to be processed in the following step choices. The expert system allows the user to specify data layers for analysis and, based on the user-provided industry type, reviews the stored decision rules and makes inferences regarding threshold values that should be satisfied when producing the feasible alternatives. The user is also able to accept, reject, or modify the recommended values as necessary. The end result of this step is the creation of map layers such as soils and slopes and their corresponding constraints. When the user wishes to view the set of extracted criteria and values, they are written to an ASCII file and exported to the GIS.

The role of the GIS is to generate a set of feasible solutions representing the relative land suitability with respect to any given map layers and to display it. The GIS read the communication file exported from the system that contains the expert-recommended or the user-specified map layers and the minimum conditions to be satisfied. The GIS user-interface displays these maps and feasible values, allowing the user to choose any combination for visualization. When a single map is selected, the GIS show the map layer on which the feasible areas satisfying the required condition are depicted. When more than one map layer needs to be displayed, spatial analysis operations are used between the layers to create a composite map layer that satisfies all the minimal threshold values of the chosen maps. Thus, the GIS analyze and show the sites that meet the required suitability conditions of the user-chosen map layers.

In brief, Phase 1 uses the expert system to produce the desirable criteria values for the different environmental criteria and the GIS to determine the alternative sites that best satisfy these values. To facilitate the iterative and complementary nature of these two steps, the GIS and the expert system are integrated with the methodology described in the next section. With the iterative characteristics of the system made possible by the integration and the development of the user-interface, it is possible to make a more informed decision by viewing the alternative outcomes regarding a broad range of criteria.

**Phase 2: Community Search.** After identifying the geographical areas best suited for the given type of industry, selection of the most appropriate community within the predefined region can be made. Comparing alternative communities involves consideration of the multiple criteria that have nonspatial and conflicting characteristics and, hence, a systematic method is required. The AHP was employed to address this multi-criteria problem. When coupled with the GIS, the AHP becomes a module that can be accessed within the GIS without the need to quit the other components of the program.

The community search phase begins by preparing the decision factors and constructing a hierarchical structure that will serve as the input data in the AHP module. The AHP involves prioritizing the decision factors based on the hierarchical framework, descending from a goal of the task, to group criteria, down to subcriteria (and further to their children criteria if they exist), and finally to the alternatives (i.e., communities to be compared). Table 2 shows an example of how the hierarchical structure of decision factors can be established, in which economic costs is one criteria, while wage, utilities, and taxes are subcriteria, and three cities are presented as final alternatives. A user-interface and an effective strategy have been developed to extract the decision criteria and the corresponding attribute values from the community GIS data and to organize them hierarchically as the user-preferred tree structure. The extracted criteria structure and the values are written to an ASCII file as the means to export information required by the AHP module.

Once the necessary information is prepared using the GIS, the AHP can begin. In the AHP, it is possible to attach a relative preference measure to each criterion selected in the previous step. The hierarchy of the decision criteria that has been established facilitates this process by permitting the focus to be on comparing a small number of criteria at a time. Setting priorities is aided by the pairwise comparison aspect of the AHP, which allows a comparison of only two criteria at once, eliminating the potential confusion of having to estimate multiple criteria simultaneously. The acquired relative weights of the criteria in different stages of comparisons are synthesized, yielding the composite priorities of all criteria and eventually the relative weights of the alternatives (i.e., the communities).

As depicted by the feedback loops in Figure 3, the community search phase with the AHP and the GIS is iterative along with the site suitability analysis phase, allowing the user to toggle between modules. To reestablish the hierarchical structure and decision factors, it is possible to return to the GIS to interact with the user-interface and to extract the desired values and structure from the community data layer.

When the community prioritization phase is finished, a composite analysis can be processed permitting an evaluation of the communities that have been ranked according to their priorities with relation to the physically suitable sites obtained in Phase 1. If the maximum distance to locate the facility from a given city is specified, the GIS generate a composite overlay map that narrows the scope of suitable areas to the prescribed circumference around the alternative communities. Finally, the end evaluation is performed on the screened sites within or around the communities with the necessary information (e.g., the total area of the sites is displayed as an optional choice). Having evaluated these results as intermediate decision products, either the suitability map generation or the community prioritization can be reprocessed as necessary.

## System Development

### Building an Expert System

Jackson (1990) defines an expert system as "a computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice." An expert system can simulate the reasoning process of a human expert in a specific problem domain. The primary utility of an expert system is that it can generate with speed and reliability a solution to a complex subject matter that normally requires a considerable amount of human input. As described in the previous section, the role in this system is to store the expertise of the site suitability analysis and to derive the suitability conditions based on a specific industry type. As a siting expert would do, the expert system checks the rules or principles to locate ones that meet the siting criteria associated with the input industry type and to generate the expert-recommended siting conditions.

This study uses the C Language Integrated Production System (CLIPS) for the development of the expert system module in the integrated system. CLIPS is a development and implementation tool for expert systems that was developed by NASA at the Artificial Intelligence Section of the Johnson Space Center (Software Technology Branch 1993). CLIPS provides a forward-chaining rule-based feature. The justification for using forward chaining (see Prerau 1990) instead of backward chaining is that the type of problem in this research is to reason from facts (which match conditions) forward to conclusions and not to posit definite goals first. Other reasons for using CLIPS are its ease in integrating with external systems and its availability for using procedural support, which are essential in writing a file exchange module and the control of user-interface.

The system was designed to determine the suitability conditions for a given industry type (e.g., chemical industry). It has rules regarding several disciplines (e.g., topography, environmental protection, and transportation). These disciplines act as classes and the subcriteria for each are regarded as objects (e.g., soils, slope, streams protection, land use, and access to highway) with their attributes (e.g., soil-drainage heavy industry, slope warehouse industry, and stream-buffer heavy industry). Table 3 shows an example of how the acquired decision criteria are organized.

**Table 3.** A selected list of knowledge representation.

| | |
|---|---|
| **Class** ➔ | TOPOGRAPHY |
| **Object** ➔ | **SOILS** |
| **Attribute** ➔ | ■ Soil drainage condition for warehouse industry |
| | ■ Soil drainage condition for heavy industry |
| | **SLOPES** |
| | ■ Appropriate slope range for warehouse industry |
| | ■ Appropriate slope range for heavy industry |
| | ENVIRONMENTAL PROTECTION |
| | **STREAMS** |
| | ■ Stream buffer distance for warehouse industry |
| | ■ Stream buffer distance for heavy industry |
| | **LAND USES** |
| | ■ Appropriate land uses for warehouse industry |
| | ■ Appropriate land uses for heavy industry |
| | TRANSPORTATION |
| | **HIGHWAY ACCESS** |
| | ■ Highway access for warehouse industry |
| | ■ Highway access for heavy industry |
| | **RAILROAD ACCESS** |
| | ■ Railroad access for warehouse industry |
| | ■ Railroad access for heavy industry |

The organized decision criteria are converted to the knowledge base of the expert system in the form of "if-then" rules such as "If <conditions> are true, then <consequences> are true," or "If <conditions> are true, then do <actions>." Many "action-oriented" rules are included whose consequent parts either asks for input from the user or sends the result to the GIS for visualization. When a "visualization rule" is triggered, the suitability conditions inferred from the industry type are written to a text file to be transferred to the GIS for map operation and visualization. Figure 4 shows examples of rules in the system.

The decision rules organized using "if-then" statements are translated into the operational CLIPS programs. The rules are classified into two parts. The first set of rules is for controlling the procedural methods, which includes gathering information from the user, assigning values to variables, and writing the necessary information to an ASCII file. The second set of rules is for

**Rule Name : pollutant bearing_industry**
IF the industry type is chemical
OR the industry type is petroleum
OR the industry type is concrete product manufacturing
THEN the industry type is pollutant bearing

**Rule Name : chemical airport access**
IF the industry type is chemical
AND user needs airport access
THEN the recommended airport access is 20 mile

**Rule Name : chemical airport & interstate access**
IF the industry type is chemical
AND user needs airport access
AND user needs interstate access
AND user needs transportation zone analysis
THEN the recommended airport access is 20 miles and
interstate intersection access is 10 miles
( Display the zone in GIS : Write to an ASCII file )

**Rule Name : pollutive industry & hydrology**
IF the industry type is pollutant bearing
AND user needs hydrology analysis
THEN the recommended area is 2 mile off the streams and avoid flood plain
( Display the zone in GIS : Write to an ASCII file )

**Figure 4.** Examples of rules in the system.

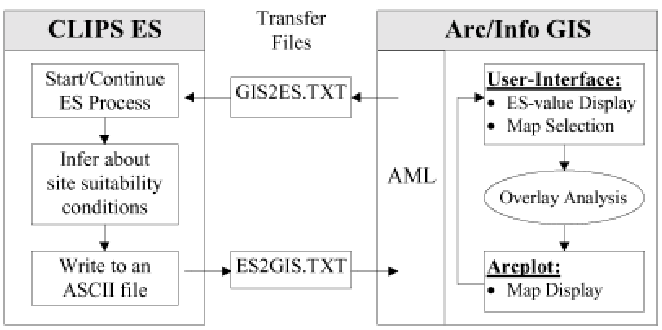



**Figure 5.** GIS-expert system integration.

heuristic reasoning to find a conclusion or solution. Based on the forward chaining method, the system takes all the facts (initialized by the user input (i.e., an industry type) and distinguishes what can be determined from them. The rule is "proved" and the conclusion is added to the existing set of known facts.

## Communication between Expert System and GIS

The GIS and the expert system are interfaced at the level of file sharing, or 'loose coupling,' where both programs can send information or input to each other (Figure 5). This is achieved by using ASCII files as the communication means in a format that either the GIS or the expert system can read as input data. The Arc/Info GIS software provides its interpretive control language, AML, that makes it possible to sequence Arc/Info commands, invoke other programs, and accept external inputs. This study used the AML when reading and executing information written in an ASCII text file sent from the expert system and when writing a file for returning to the expert system module.

If the expert system activates rules that require GIS operation and display of a result, it writes in an ASCII file the necessary information, such as the kinds of thematic map layers to be evaluated and the respective suitability conditions. On the GIS side, the AML takes the ASCII file, translates the contained information, and displays it on the user-interface. For example, the text file may contain lines that cause the GIS to perform a map overlay operation to display the good-access areas among the moderate slope areas determined during the expert systems processes. In the GIS suitability analysis phase, it may be desirable to return to the expert system for another set of map layers or a modification of the recommended constraints. The AML writes the returning signal required by the system, which is in a waiting mode, and control is returned to the expert system, which continues its process. The system was designed to work under the UNIX operating system, which supports full multitasking windows enabling the GIS and the expert system to be active simultaneously.

## The Analytic Hierarchy Process

The most frequently raised problem in MCDM is how to establish weights for a set of activities according to importance. Location decisions such as the ranking of alternative communities are representative multi-criteria decisions that require prioritizing multiple criteria. Saaty (1980) has shown that this weighting of activities in MCDM can be dealt with using a theory of measurement in a hierarchical structure (i.e., the AHP ). The AHP is a decision analysis technique used to evaluate complex multi-attributed alternatives with conflicting objectives among multiple players (Weiss 1987). The AHP employs a systematic procedure for representing the elements of a problem hierarchically, enabling the subproblems to be easily comprehended and evaluated. By breaking down a problem into homogeneous clusters and subdividing the clusters into smaller ones, large amounts of information can be integrated into the structure of a problem and a more complete picture of the whole system can be formed (Saaty and Kearns 1985). Simple pairwise comparisons are fundamental in the process and are used for developing priorities in each hierarchy. Theoretical background of the AHP can be found in voluminous literature (e.g., Yager 1979, Saaty 1980,1987a,b, 1990, Saaty and Kearns 1985, Zahedi 1986, Weiss 1987) and is not discussed here.

## Integration of the AHP with the GIS

Once the hierarchy for a problem is established, the same prototypical methodology can be applied level by level, regardless of the complexity of the hierarchy. Basically, the process seeks to assess the weights of the lower hierarchy level with respect to the level of criteria immediately above. Locally obtained weight values are used to generate the composite weights of the next lower hierarchy level and, ultimately, to produce the global weights of the alternatives with respect to the overall objectives of the problem.

The structuring in the first step is crucial in that it prescribes the sequence of the entire process; as a result, the outcome is heavily dependent on this step. Choosing factors that are important to the decision and organizing them into a hierarchy should reflect the problem as thoroughly as possible. At the same time,

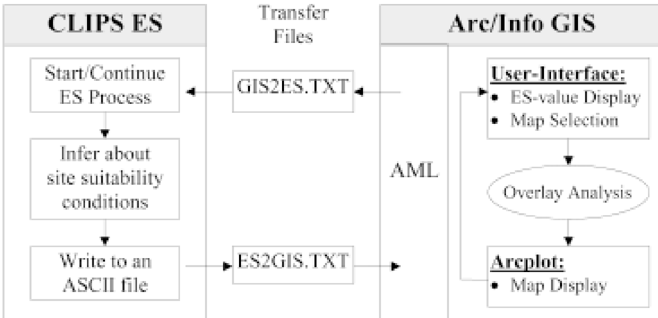



**Figure 6.** Hierarchy for selecting a community.

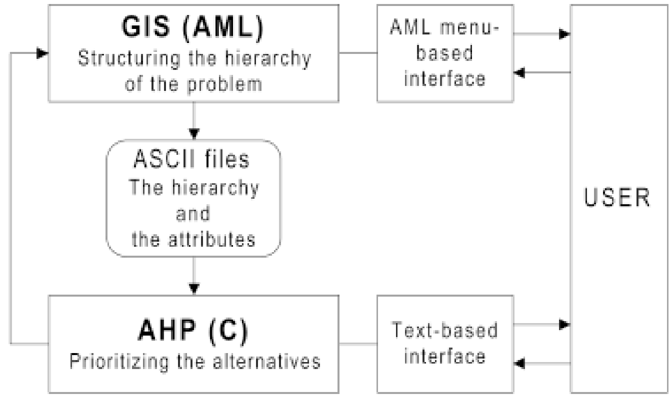



**Figure 7.** The system architecture for the integration of the GIS and the AHP


| # | PAT Items | Labor-Avail | Popul | Acs to Hwy | Rail | Wage ($/hr) | Util | Taxes | ... |
|---|---|---|---|---|---|---|---|---|---|
| 1 | ... | 3 | 231000 | 3 | 3 | 3.45 | 650000 | 376000 | ... |
| 2 | ... | 3 | 379000 | 2 | 3 | 3.46 | 677000 | 212000 | ... |
| 3 | ... | 2 | 296000 | 3 | 2 | 3.50 | 516000 | 276000 | ... |

**Figure 8.** The structure of the community data layer and the INFO file.

this task should allow for the restructuring of the hierarchy when necessary, which is highly possible considering the multiple and diverse elements. To facilitate the structuring task, this study developed an effective program logic and the user-interface to be used in the preliminary step for the AHP. The user-interface allows formulation of the hierarchy while the internal routines access and read the necessary database portion (in Arc/Info, "info") of the GIS data layer (in this study, the community layer) to construct data files that serve as input when required by the steps of the AHP. Such criteria as shown in Table 2 can form a hierarchy as seen in Figure 6. There is no limit to the number of levels in a hierarchy since this method can be applied level by level until the lowest alternative level is evaluated.

A computer program written in C language to implement the AHP was designed to use the hierarchy of decision elements as step-by-step input data. To structure hierarchy, a separate program was written in AML. These programs can be accessed by the user from the main menu and used separately in the multitasking environment, one in the user-interface of AML and the other in text-based mode in a different window.

The hierarchy-structuring module functions as the preparation for the input data required by the AHP mode. The data are integrated at the file communication level where the earlier module writes information regarding the user-specified hierarchy and decision factors to ASCII files (Figure 7). When the AHP is launched by the user, the program takes the ASCII files as arguments and continues the process while interpreting the information in the files. The feedback loop between the modules (depicted in Figure 7) represents the case in which the decision criteria or the hierarchical structure are modified. The hierarchy and the criteria contained are not fixed and are subject to change as necessary. Portions can be altered to accommodate additional criteria for more precise evaluation of the problem or to remove criteria that are no longer pertinent. This iterative feature enables the user, who in many cases does not have a clear understanding of the problem, to shape ideas and to refine the problem by examining the consequences of the judgment choices and appropriately altering them.

In constructing the hierarchy, the AML accesses the INFO part of the community data layer to acquire the attribute data stored in the form of quantitative values. Figure 8 shows how the decision criteria and their values, such as those presented in Table 2, are stored in the INFO table. The shape of the hierarchy, including the number of levels and the number of tree branches, can vary according to the evaluation method. When the items in the INFO table are selected as subcriteria to be placed in the hierarchy, the corresponding values are extracted and written to an ASCII file.

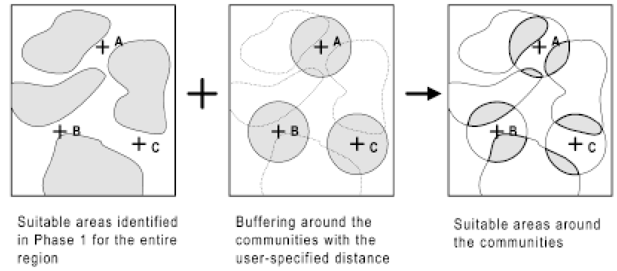
As the structuring progresses, the AML writes to an ASCII file the step-by-step information representing the current status of the element in the hierarchy and the attribute values acquired from the INFO table. Supposing the hierarchy is designed as in Figure 6, the complete ASCII files containing data such as the current level, the accumulated tree information, the order of the parent tree, the order of the current element in the level, the name of the factor, the number of the descendant elements, and the value of the items will be read in the AHP program and interpreted as shown in Figure 9.

## The Composite Analysis

The composite, or final, analysis identifies and evaluates the candidate areas by taking into account the results from the suitability analysis phase and the community prioritization phase. After identifying the suitable sites for a given industry and evaluating the characteristics of the communities, it might be desirable to check the site suitability around these communities. These areas can be displayed on the screen by defining the circle radius (i.e., the buffer zone) to be drawn around each community and performing a map overlay of this layer on the layer of the suitable sites for the entire region. Since the community prioritization

```
*********************< THE CONTENTS OF INPUT INFO >**********************

       CURRENT ACCUMUL.ASCEND. FACTOR  FACTOR       CLASS  ITEM  NUMBER
  No.   LEVEL   TREE    TREE    ORDER  NAME        (F/I/V) ORDER NEXTFAC
-------------------------------------------------------------------------
   1 :    1        0       0      1    GROUP          F      0      3
   2 :    3       11       1      1    LABAVAIL       I      1      3
   3 :    3       11       1      2    POPUL          I      2      3
   4 :    3       11       1      3    PRODUCTIV      I      3      3
   5 :    2        1       1      1    LABORCLIMT     F      0      3
   6 :    3       12       2      1    ACS2HWY        I      5      3
   7 :    3       12       2      2    TRUCKTERM      I      6      3
   8 :    3       12       2      3    RAILROAD       I      7      3
   9 :    2        1       1      2    TRANSPORT      F      0      3
  10 :    3       13       3      1    WAGE           I      8      3
  11 :    3       13       3      2    UTILITIES      I     10      3
  12 :    3       13       3      3    TAXES          I     11      3
  13 :    2        1       1      3    ECONOMIC       F      0      3
-------------------------------------------------------------------------

Press a key....

************< THE CONTENTS OF INPUT ITEM-FILE >************

   ITEM-NAME              ALT.- 1      ALT.- 2      ALT.- 3
 1 LABAVAIL      :          3.00         3.00         2.00
 2 POPUL         :     231000.00    379000.00    296000.00
 3 PRODUCTIV     :          2.00         3.00         3.00
 4 ACS2HWY       :          3.00         3.00         3.00
 5 TRUCKTERM     :          8.00        11.00         6.00
 6 RAILROAD      :          3.00         3.00         2.00
 7 WAGE          :          3.45         3.46         3.50
 8 UTILITIES     :     650000.00    677000.00    516000.00
 9 TAXES         :     376000.00    212000.00    276000.00
```

**Figure 9.** Example of the information contained in the ASCII files.




```
****< FINAL COMPOSITE PRIORITIES FOR THE ALTERNATIVES & THE DECISION CRITERIA>****

               ALTERNATIVE - 1     ALTERNATIVE - 2     ALTERNATIVE - 3   | ITEM
   ITEMS       PRIORITY( VALUE )   PRIORITY( VALUE )   PRIORITY( VALUE ) | PRIORITY
-----------------------------------------------------------------------------------
 1 LABAVA :   0.1136(      3.00)  0.1136(      3.00)  0.0778(      2.00) |  0.3050
 2 POPUL  :   0.0408( 231000.00)  0.0650( 379000.00)  0.0514( 296000.00) |  0.1572
 3 PRODUC :   0.0159(      2.00)  0.0232(      3.00)  0.0232(      3.00) |  0.0624
 4 UNION  :   0.0139(      5.00)  0.0641(      1.00)  0.0223(      3.00) |  0.1003
 5 ACS2HW :   0.0497(      3.00)  0.0497(      3.00)  0.0497(      3.00) |  0.1491
 6 TRUCKT :   0.0182(      8.00)  0.0247(     11.00)  0.0140(      6.00) |  0.0569
 7 RAILRO :   0.0121(      3.00)  0.0121(      3.00)  0.0083(      2.00) |  0.0326
 8 WAGE   :   0.0247(      3.45)  0.0246(      3.46)  0.0243(      3.50) |  0.0736
 9 FREIGH :   0.0102(1982000.00)  0.0091(2243000.00)  0.0101(2019000.00) |  0.0294
10 UTILIT :   0.0030( 650000.00)  0.0028( 677000.00)  0.0037( 516000.00) |  0.0095
11 TAXES  :   0.0059( 376000.00)  0.0101( 212000.00)  0.0079( 276000.00) |  0.0240
-----------------------------------------------------------------------------------
    SUM   :   0.3082              0.3991              0.2927                 1.0000
```

**Figure 10.** Composite analysis.

was done in a different window under the multitasking environment, the final result and the intermediate steps produced in the program running session can be viewed. Figure 10 shows the final result of the AHP program as displayed on the screen and a conceptual diagram of the overlay analysis.

Although this is the ultimate solution search step throughout the process, the decision scenarios can be modified since the modules for the phases do not proceed based on a one-directional task flow but can be invoked from the main menu separately by returning to Phase 1 or 2. For example, Community B, which has been evaluated as the front runner using the AHP, may not be attractive after the suitable areas have been identified and displayed. This may occur if all the candidate areas in Community B are too small or too far from the center of the community compared to other communities or other positive features are highlighted that Community B does not have. These factors were not counted during the process due to oversight or ignorance of the expected small impact, and may be significant enough to change the course of the analysis and to incorporate those factors for a better decision.

The presented system has usefulness because it is not realistic to expect frequent changes in a project once considerable time and effort have been expended. The system enables a more desired decision to be made by examining the consequences of a series of judgments regarding the selection of objectives, decision criteria, and the attribute values, and easily generating a new set of feasible solutions based on changes in judgment.

## Conclusions

The primary objective of the study was to facilitate the site selection processes in the presence of multiple and diverse decision criteria using expert GIS equipped with multi-criteria decision support capability to incorporate the preferences of the person making the decision. To achieve this, effort focused mainly on the following sub-objectives: (i) to integrate the expert system and the GIS to facilitate the site suitability analysis by means of judgment rules of the expert system in determining various physical suitability constraints for generating and displaying composite suitability maps in the GIS; (ii) to employ a multi-criteria decision tool (in this study, the AHP) to accommodate trade-offs among the multiple and conflicting decision criteria in determining a preferred community; (iii) to design flexible feedback loops throughout the decision-making process to allow the user to revise the intermediate decisions by examining the consequences and to gradually narrow the solution space to reach a desired solution; and (iv) to develop an efficient graphic user-interface by which the modules in the system are seamlessly linked.

The primary significance of this study may be in the effectiveness of the decision-making. The critical aspects of a decision support system are as follows: (i) the system should offer guidance in examining the solution alternatives before arriving at a decision; (ii) the system should help define the problem and consider possible factors; and (iii) the decision steps should be discernible and not cognitively demanding to the user. These characteristics are incorporated in the system presented here and described in detail as follows.

To permit an examination of the consequences of decisions, the system focused on iterative features. With flexible feedback loops connecting steps throughout the system, an evaluation of the results of potential scenarios and a more informed decision can be made. In determining site suitability, overlay maps can be visualized that vary according to the inclusion of experts' recommended values or of user-specified constraints. The site conditions may be gradually formulated to fit to the problem while evaluating diverse feasible alternatives using the combinations of potential threshold values. Also, the AHP methodology has the theoretical basis to allow ideas to be shaped regarding initially uncertain priorities for a list of criteria by permitting a check of the weights or consistencies that change based on the user's input at each step of pairwise comparisons. These characteristics contribute to generating judgments that are more likely to be correct and ultimately reaching a decision by reducing the feasible alternatives. Similarly, the structured framework of the system enables a more thorough decision to be made by reviewing the problem and the situations surrounding it more fully.

Problems regarding site selection or location analysis generally result in a number of alternatives and involve a large and diverse set of decision factors. This may result in confusion regarding the selection of the criteria, how the criteria should be weighted, or, sometimes, how to define the problem at the onset of the problem solving. The way to shape unstructured reality is through understanding the problem, eliciting relevant information, revising the possible consequences of the judgments, and compromising these consequences. The automated suitability analysis module provides an incremental or flexible evaluation scheme applied to relevant map layers, which helps define the desired suitability conditions by examining each composite map. In addition, the hierarchical framework of the AHP and the user-interface designed to interact with the GIS data allow only the tractable size of the entire decision elements to be handled and synthesized. This approach aids in promoting clear thinking and understanding regarding a problem and can reduce the chance of issues being overlooked. The features in the system enhance the ability to tackle complex and unstructured problems while helping to conceptualize the problem and ensuring that the often-crucial elements in the art of decision making are not neglected.

Another utility provided by the system is that the decision steps are explicitly given to the user during the system operations and are cognitively less demanding. In generating solutions, the user can interact with the responses of the system through the user-friendly interface, reinforcing the validity of judgment choices. Also, the flow of the system processes and the hierarchical structuring in the AHP reflect our natural tendency to advance the overall features described above (i.e., features involving iterative, hierarchical, and interactive capabilities of the system all contributing in a systematic and comprehensive manner to an appropriate decision with respect to quality, time, and convenience).

Finally, suggestions for improvement and issues for future research are discussed as follows: (i) as in this research, most applications using the AHP method are based on using crisp numbers such as 1 to 9 in the pairwise judgments. However, to accommodate potential uncertainty associated with one's perception (or judgment) regarding the relative importance of the elements, the use of fuzzy logic is suggested. In this case, the priority among the alternatives may be derived via the use of membership functions to estimate the different degrees involving the evaluation (e.g., of the degree of satisfaction with the judgment); and (ii) the AHP can be used in a multiple user group setting. Although this research assumes a single user in determining the priorities of decision criteria and alternatives, industrial development processes generally involve a range of stakeholders such as informed citizens, industry representatives, elected officials, and professional municipal staff. Very often, individuals differ in the importance of a particular factor in the decision or even the factors that are relevant. Improvements can be suggested using the prototype in such a way that group sessions are imbedded into the integrated system to find a consensus between the participants in a more general and flexible framework. The process will then be focused on determining a compromise to a multi-criteria problem that best coincides with the preference structures of the users. Utilization of AHP and the GIS allows all participants to visualize preferences and consequences during negotiation sessions. The uniform framework and information base represented by this prototype system could play a significant role in developing community consensus regarding proposed industrial development.

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