

A SPATIAL DECISION SUPPORT SYSTEM  
FOR AGRICULTURAL LAND CONSOLIDATION

by

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## **Abstract**

Agricultural land consolidation is the process of equitably reallocating agricultural landholdings into fewer, more regularly shaped parcels. Despite its social significance and intrinsically spatial problem solving characteristics, the process of consolidation has received scant attention from geographers. Instead, researchers have concentrated on determining the costs and benefits of existing consolidation methods. This thesis uses this extensive background information to reformulate consolidation into a formal problem, develops a model of an improved solution procedure, and implements the model into a spatial decision support system. This system is able to assist planners in creating improved consolidation plans.

Several countries of the world, particularly in Europe, enforce consolidation on farmers to reduce the problems associated with the present spatial configuration of landholdings. Consolidation seeks to increase agricultural efficiency by redrawing cadastral boundaries and assigning ownership to farmers based on the location and value of their present holdings, other assignments, and the location of the parcel. However, past consolidation initiatives have resulted in more efficient configurations at the expense of ecological diversity, equity, habitat, aesthetics, and employment. Redistributing land by hand to overcome these shortcomings is a formidable task. Existing manual methods

are unable to deal with the complexity inherent in the problem. Without more advanced tools planners are forced to oversimplify the problem into a small set of objectives and constraints.

The model presented in this thesis uses more sophisticated methods to enable planners to manage the problem in its more realistic and complex form. The problem is changed from an existing continuous space approach, to a spatial assignment problem where small, discrete units of land are amalgamated to form fields.

Approached in this way a solution can be created as follows. Parcels of land are assigned to farmers based on a series of objectives and constraints. The model adds two constraints to the traditional problem. Firstly, communal equity is managed through tolerances set on the several non-commensurate attributes of parcel worth. This ensures that a more accurate reflection of equity is maintained unless planners take explicit steps to overrule the tolerance.

The second constraint ensures that the personal preferences of farmers are considered. Before consolidation, farmers are asked which parcels they wish to retain and, of the parcels they do not currently own, which they would wish to acquire. Ideally, a parcel should not be taken from, or assigned to a farmer without it being his or her stated preference.

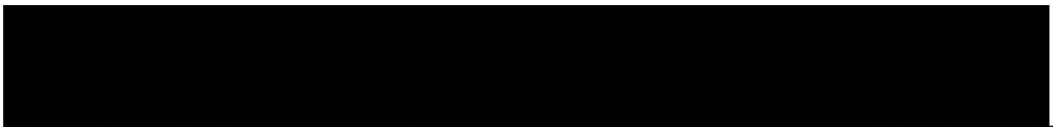
Of those parcels that meet the above constraints, parcels are allocated to farmers using one of five routines. The first three routines assign parcels that are desired by less than two farmers. Users can assign contested parcels using either of two additional routines which seek to maximize contiguity and equity, respectively.

One of the strengths of the routines is their ability to facilitate interaction with the users as the solution emerges. This interaction enables planners to control the solution

process so that other, less mathematically amenable objectives are considered. Promoting such interaction defines spatial decision support systems (SDSS).

These routines and assorted ancillary routines are implemented into a SDSS by appending a module onto an existing geographical information system (GIS). This is accomplished by using a soon to be released application program interface (API). With further development, this powerful method of GIS customization will present a promising tool for SDSS creation.

The SDSS is evaluated for its algorithmic validity, human interaction capabilities, and practicality using data from a recent consolidation program in Spain. While additional research is needed to evaluate the model further, and to improve the system's flexibility, the proposed model presents an important first step in improving land consolidation methods.



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# Chapter One

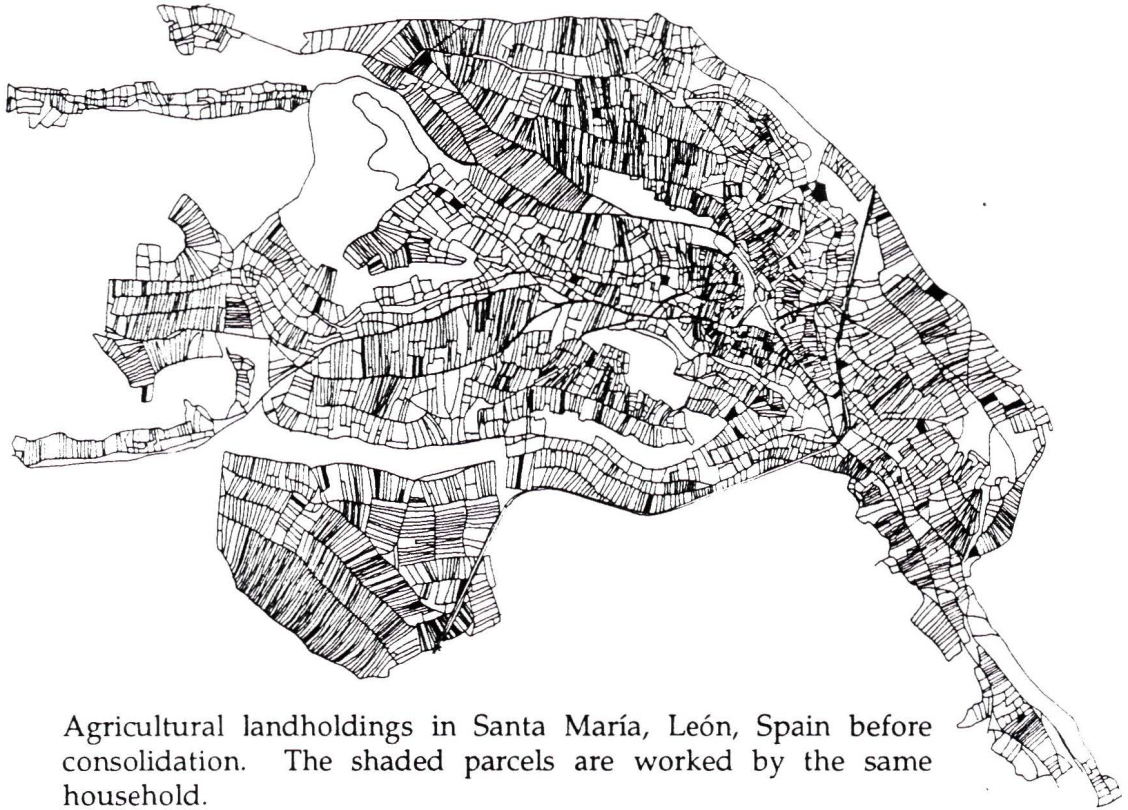
## Introduction

In many cultures of the world, private ownership of land is one of the most fundamental components of an individual's worth. Nowhere is this more evident than in agriculture, where a farmer's livelihood, and possibly survival, depend very directly on his or her landholding. Therefore, it is important that any government policy that affects the ownership of farmland be conducted with a thorough knowledge of its consequences. Every effort should be made to enhance the program's overall benefits while avoiding any detrimental personal effects.

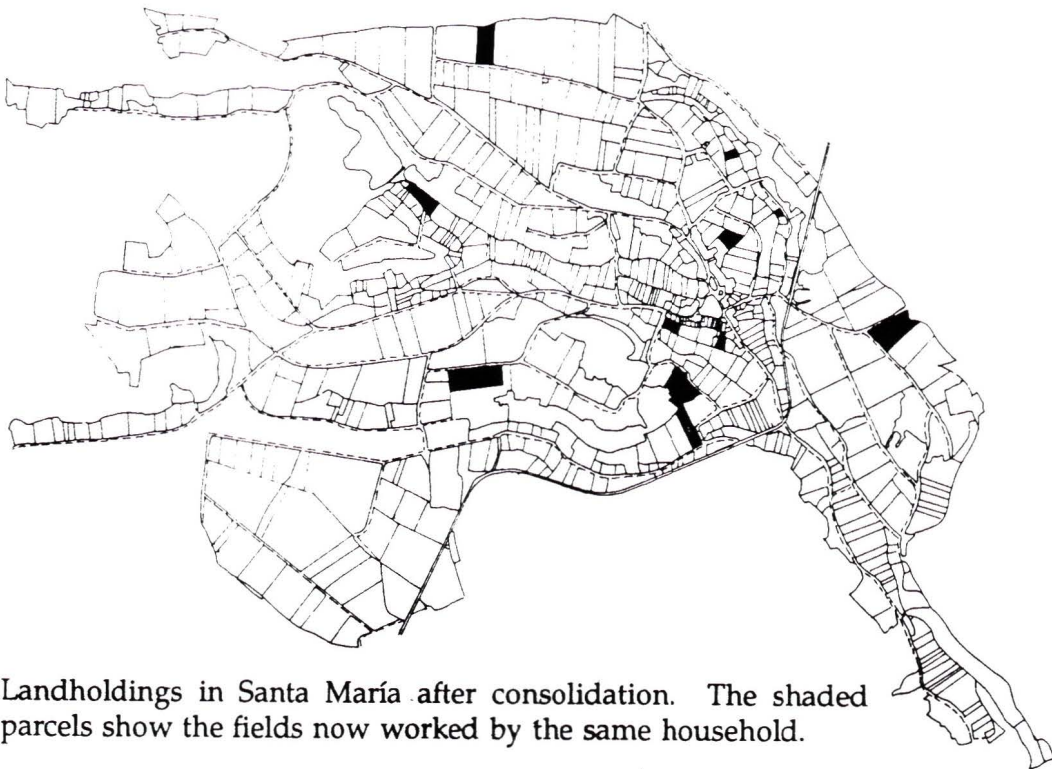
In numerous agricultural areas of the world, landholdings of individual farmers are scattered throughout a large area into many small parcels. This is *land fragmentation*. While benefits may be derived from fragmentation, it can cause farmers to waste considerable time travelling between farms, restrict the use of machinery, and inhibit other development initiatives, such as irrigation and transportation improvements.

Several countries have concluded that the problems of fragmentation merit the risks of dictating changes to the system of land ownership. *Land consolidation* is the process of improving the spatial structure of landholdings by redistributing land whereby farmers receive the same value of land, but in fewer, more compact parcels. The process is best portrayed on a map. Figure 1.1 plots the cadastral boundaries before and after a consolidation program undertaken between 1981 and 1984 in northwest Spain.

Unlike other land reforms, consolidation is not concerned with redistributing wealth, but assumes there are inherent problems in the present spatial system that can be alleviated to the benefit of all. However, individuals participating in consolidation can experience considerable loss. As a result of imposed consolidation individuals have



Agricultural landholdings in Santa María, León, Spain before consolidation. The shaded parcels are worked by the same household.



Landholdings in Santa María after consolidation. The shaded parcels show the fields now worked by the same household.

**Figure 1.1** 'Before and After' maps of consolidation (Behar, 1986, 294-295; no scale provided).

become landless, relinquished good land in return for poor, and lost valuable ecological diversity. The challenge, therefore, is to develop a model of land consolidation that increases the overall benefits without sacrificing the welfare of some participants. The model should quickly create consolidation plans without excluding input from decision makers.

This thesis is a response to that challenge. It seeks to conceptualize, implement and evaluate a spatial decision support system for agricultural land consolidation. Conceptualizing a decision support system for land consolidation entails formalizing the problem into a model consisting of a set of objectives and constraints; separating the problem into a series of sub-problems; and developing solution algorithms for each sub-problem. However, because of the complexity and political nature of consolidation, the entire problem cannot be formalized into concise mathematical statements. Therefore, each solution algorithm follows the principle of interactive decision support; meaning, quantifiable objectives are formalized into a mathematical model, while non-quantifiable objectives are recognized through extensive interaction with the decision maker. This combination of approaches works toward a solution that incorporates the decision maker's qualitative criteria as well as those that can be mathematically defined.

Implementing these solution procedures within an interactive framework necessitates developing a computer system with a cartographic display, database management, and user interface tools. To provide these functions the model is implemented by coding and appending a module onto a commercial geographical information system (GIS). Commercial GIS provide a platform for the maintenance and display of the spatial data; however, to date they have generally not provided the analytical tools necessary for a system of this type. One innovative tool to overcome these limitations is application program interfaces (API). API provide programmers with the tools to incorporate GIS routines within their own application source code. Programmers can use the API functions for spatial and attribute management and the user interface routines, and therefore can concentrate on the analytical component of the system.

The model is evaluated to determine its algorithmic validity, ability to interact with the user and practicality. A sample of data from a recent land consolidation

program in Spain provides an application of realistic size and complexity. While tested on a Spanish example, the system is argued to be applicable to any consolidation plan.

## **CLARIFICATION OF TERMS**

While the uniqueness of fragmentation and consolidation have been recognized and studied for several years, only recently through the work of researchers like King, Burton (Burton, 1988; Burton and King, 1982; King and Burton 1982, 1983) and Bentley (Bentley, 1987, 1990) has a consensus emerged over definitions and terminology.

Land fragmentation can be defined formally as the spatial scattering of the land for a single farm into many non-contiguous parcels. These parcels are often small and awkwardly shaped. Other terms for the same phenomenon are parcellization (Roche, 1963; Sanderatne, 1972), pulverization (Clout, 1972), morcellement (de Vries, 1974) and scattering (Farmer, 1960).

Land fragmentation is distinct from (though often in coexistence with) a similar phenomenon, namely farm fragmentation or subdivision (Farmer, 1960). Farm fragmentation denotes the division of agricultural land to many farmers resulting in several, very small farms (Bentley, 1990). This form of fragmentation has wider implications, related to overpopulation and income distribution, and is alleviated through more conventional land reforms. Throughout this thesis fragmentation will refer to land fragmentation, not farm fragmentation.

Land consolidation, sometimes referred to as land redistribution, is the process of reducing fragmentation by reallocating agricultural land, whereby farmers retain equal amounts or value of land, but in fewer, more compact parcels. Consolidation may be undertaken independently, or in conjunction with other land reform initiatives, such as road improvements, farm enlargement, or resettlement. The Food and Agriculture Organization (FAO) of the United Nations extends the definition of consolidation to include these initiatives. But, as King and Burton (1983) note, while these initiatives are important, this definition digresses from the essence of consolidation as a process of redistribution. While other land reform initiatives are considered, the focus of the thesis will be on the land redistribution aspects of consolidation.

There are other programs similar to, but distinct from agricultural land consolidation. Consolidation in urban areas is termed land readjustment (Doebele, 1982).

Issues and ultimate objectives of readjustment are substantially different from agricultural land consolidation. Another similar agricultural reform, called farm amalgamation, is the merger of holdings into cooperatively owned and operated farms. It has primarily been used to address problems of farm fragmentation (Hirsch and Maunder, 1978).

## ACADEMIC SIGNIFICANCE

Despite its socio-economic significance, and its intrinsically spatial complexity, land consolidation has not received much attention in the geographical literature (King and Burton, 1982). Most of the work completed to date concentrates on the causes, costs and benefits of fragmentation, and advantages and disadvantages of consolidation. Those few researchers who have studied methods of consolidation have concentrated on its legal and administrative aspects (Binns, 1950; Jacoby, 1959; Meliczek, 1973; Moral-Lopez and Jacoby, 1962; von Dietze, 1963).

The paucity of research into the spatial problem solving facets of consolidation can be explained by two factors. Most consolidation programs have been undertaken in non-English speaking countries of Europe, and thus research appears in other languages (for example Van Huylenbroeck, 1989). Also, research into consolidation has primarily been undertaken by anthropologists and economists. They have been concerned with the effects of consolidation, not the process itself (King and Burton, 1983).

Not unexpectedly, the two disciplines have arrived at very different conclusions about consolidation. Anthropologists have documented its negative social effects (Behar, 1985; Bentley, 1990), while economists have noted the productivity gains (Agarwal, 1972; Bonner, 1987; Simons, 1986). Although there is much work still to be done in these areas (King and Burton, 1982), these disparate perspectives provide valuable insight into the important aspects of consolidation and into ways in which the solution process may be improved.

The academic innovation of this thesis is to use the insights of other researchers to develop a multiobjective spatial assignment model for the land consolidation problem. The complexity and uniqueness of consolidation warrants its introduction to the spatial optimization community, and as King and Burton (1983) note, those undertaking consolidation can profit from applying more sophisticated methods to a very important and complex problem.

## PRACTICAL SIGNIFICANCE

Multiobjective programming (MOP) has the potential to improve traditional manual decision making in land consolidation. The size, complexity, and multiobjective nature of the problem forces planners working manually to simplify several key aspects of the problem in order to produce an acceptable solution within a reasonable time frame. MOP enables the rapid derivation of solutions that consider the problem's many objectives in their more realistic and complex form (Cohon, 1978).

However, while many of the objectives of consolidation can be well represented in mathematical formulae, several crucial objectives cannot be modelled with adequate rigidity to be included in an optimization model. Some, such as dynamic shortest path computation, are too complex. Developing a metric to these sub-problems that can be operationalized is doubtful. Others, such as encouraging crop switches, are very political. These objectives may not be in the best interest of individuals, and formal statements of intent from decision makers are unlikely.

Therefore, for any mathematical model developed for consolidation to be an effective operational tool, it must recognize its limitations. The model should quantify those aspects that are quantifiable, while supporting non-quantifiable objectives through extensive interaction with participants and decision makers. Developing methods to support this interaction where desired is crucial to the model's effectiveness.

Systems that encourage the input of the decision maker to develop more effective solutions to complex problems are called *decision support systems* (DSS). Spatial decision support systems (SDSS) aid decision makers in producing effective solutions to geographical problems. The decision support framework recognizes that the ultimate goal is to reach a 'good' solution to a problem, not necessarily the 'optimal' solution as defined by a mathematical model.

In order to create a system that can produce a practical solution to this complex problem, the decision support framework is followed. Therefore, algorithms developed for the consolidation problem in this research are designed for practical feasibility as well as algorithmic efficiency. To test the practicality of the model a complete core of a SDSS is built. This includes not only the solution algorithms, but also routines to display and query the map. Development of such a comprehensive system is accomplished through the use of software development tools. Application program interfaces (API) enable a

programmer to create a program that accesses the data and routines of the commercial system directly. The GIS industry is just starting to provide these tools for development of custom software for spatial data. It represents a major change in direction for the industry and one that should be encouraged. The system created as part of the research presented here would not have been practical without these tools.

## **SUMMARY OF CHAPTERS**

There are eight chapters to the thesis including this introduction. Each subsequent chapter highlights a different stage in the evolution of the spatial decision support system. Chapter Two discusses SDSS in more detail. It explores the relationships of SDSS with geographical information systems and generic decision support systems, and argues for more interactive algorithms.

The debate over consolidation is reviewed in Chapter Three. Policy makers have long argued the many benefits of land consolidation; however, other researchers have documented extensive social, environmental and economic damages. A review of the two positions yields a fuller understanding of the complexity of the problem, and identifies areas where consolidation practices can be improved.

The first step in developing a model that fulfils this goal is to define precisely the problem's objectives and constraints. Only then can a solution algorithm be proposed or evaluated. The opening section of Chapter Four identifies and classifies the many objectives of consolidation. Once objectives are defined, similarities of land consolidation to other multiobjective spatial assignment problems become evident. Researchers in geography, regional science and operations research have had some success in solving these problems with mathematical algorithms. They have examined, formalized and developed solution procedures to problems such as school assignment, political districting, land use zoning, and land acquisition. Their approaches to these four problems are explored in the second half of Chapter Four to determine potential solution approaches to consolidation.

From the foundation established in Chapter Four the process of agricultural consolidation is formalized into a model. This model is described in detail in Chapter Five. Following an overview of the model, the adaptations to existing procedures

necessary to operationalize the problem into a mathematical model are outlined. More detailed discussions of the model and the solution algorithms are then provided.

Chapter Six describes the implementation of the model into a complete core of a SDSS. This entails not only coding the solution algorithms, but conceptualizing a database model, and providing a powerful, interactive user interface. Therefore, included in this chapter is a discussion of the use of APIs in creating the system.

Once the SDSS is completed, the interaction capabilities and algorithmic design can be tested. Evaluation of a SDSS is complicated by the nature of the problems it solves. Comprehensive evaluation of a SDSS for consolidation would require extensive analysis over several years. Therefore, Chapter Seven describes how the algorithmic validity and interactive capabilities of the system were evaluated using the sample data.

The final chapter summarizes the thesis, and outlines its research contributions.

## Chapter Two

# Spatial Decision Support Systems

This chapter is concerned with spatial decision support systems (SDSS). The relationships of SDSS to decision support systems and geographical information systems are explained. It is then argued that the SDSS framework presents an opportunity for a new algorithmic approach to spatial problems. These algorithms more fully utilize existing computer technology by reaching solutions interactively with the decision maker.

### THE NEED FOR DECISION SUPPORT

SDSS are growing more popular because of their practical success in solving real-world spatial problems (Densham, 1991). Traditional methods of spatial problem solving have not been successful in practice for two primary reasons.

Firstly, spatial problems have a social significance that traditional optimization methods have all but ignored. Because of their spatially extensive nature, solutions to spatial problems affect many diverse groups. Determining corridors for new highways, school assignments, or warehouse locations, for example, have a very significant personal impact on all those living in the area, as well as the direct users of the facilities. Because of the many people involved, and the personal nature of the effects, determining and defining all of the objectives of a spatial problem may be impossible. However, simply ignoring some crucial, usually non-quantifiable objectives will result in unacceptable solutions that are also ignored.

Secondly, many spatial problems have important characteristics which cannot easily be modelled mathematically. Complex spatial relationships are difficult to relate in the terse calculus needed for formal models without gross oversimplification of the problem.

Spatial decision support systems (SDSS) are explicitly designed to assist people in developing more effective solutions to important spatial problems where all objectives cannot be mathematically modelled. They are applicable whenever there are several non-commensurate objectives. However, unlike multiobjective programming methods (see Cohon, 1978 for more detail), SDSS do not require all pertinent objectives to be formally defined. Therefore, SDSS are valuable when a decision maker is unable or unwilling to articulate all objectives. Objectives of this form are termed unstructured or ill-structured (Hopkins, 1984; Keen and Scott Morton, 1978). SDSS offer the decision maker tools to make informed decisions to degrade the solution from strictly optimal in mathematical terms to one that is more effective in real-world terms.

Unfortunately, to date, most SDSS have restricted the decision maker's interaction with the system to specifying inputs and editing final outputs. Few systems have enabled decision makers to become an integral part of the solution making process. It is argued later in this chapter that interactive solution procedures offer many advantages over existing SDSS approaches. To provide the background for that argument, the evolution of decision support systems and their relationship to spatial problems and other systems must first be explored.

## **DECISION SUPPORT SYSTEMS**

The principles of SDSS are derived from decision support systems (DSS) developed in the business data-processing community. While SDSS is a new research area, DSS has a relatively long history (over fifteen years) and a rich literature (including several books and a regular journal).

DSS were developed in the 1970s in response to dissatisfaction with management information systems (MIS) and management science / operations research techniques. MIS do not provide management with the decision making tools needed to make decisions, beyond standard, inflexible reports. They only operate on tasks "where standard operating procedures, and information flows can be reliably predefined" (Keen

and Scott Morton, 1978: 1). Management science techniques can provide solutions to well structured problems, but often require oversimplification of the problem into highly defined objectives and constraints. These techniques make little allowance for the crucial, but more unstructured aspects of decision making (Rushton, 1992). DSS seek to assist decision makers to make better decisions using a combination of the modelling techniques of management science, the computer technology of MIS, and the insights of decision science and human - computer interaction.

However, despite agreement on the need for more decision support, extensive research and many commercial applications, no comprehensive definition of DSS has been established. Many definitions of DSS such as:

the application of available and suitable computer-based technology to help improve the effectiveness of managerial decision making in semi-structured tasks (Keen and Scott Morton, 1978, quoted in Er, 1988: 356),

and

a coherent system of computer-based technology used by managers as an aid to effective decision making (Bennett, 1983: 1),

are so vague that almost any interactive computer software for managers can be called a DSS if desired. To more precisely describe DSS, Keen (1987) and Er (1988) choose to concentrate on its elements: *decision*, *support* and *system*.

The word *decision* implies problem solving. Problems are worthy of a DSS when the impacts of the decision to be made are of sufficient importance to justify the investment. This suggests that organizational and public policy decisions are more likely to warrant a DSS than individual decisions. In order to provide competent tools for solving an important problem, an individual DSS must concentrate on a very specific problem domain. Finally, because the systems are decision based, they are oriented toward those who make the decisions, most likely managers or senior policy people.

The *support* aspect of DSS indicates that DSS are to assist existing decision makers. This support orientation differentiates DSS from expert systems, where the goal is to replicate and ultimately replace experts (Connell and Powell, 1990; Ford, 1985; Harmon and King, 1985). DSS recognize that a computerized system can never incorporate expert knowledge without loss of important information and complexity. Any knowledge that is incorporated into a DSS is placed in a knowledge-base and is directly available to the

user. A DSS builder expects the user to have the same knowledge as the knowledge-base and be capable of improving the information when necessary (Davis and Grant, 1987; Smith and Yiang, 1991).

The term *system* denotes the integration of diverse technology and theory. DSS consist of four components:

- database management software (DBMS);
- analytical modelling;
- reports and displays; and,
- a user interface.

Each of these components is changing rapidly with advancements in technology. While these modules are important in designing a DSS, the user should see an integrated system.

The database management component of a DSS contains information about the specific implementation. This information can be accessed directly by the user. However, more frequent access is probably required by the analytical and display components. Data must be stored in a way to facilitate quick retrieval of the information needed by the user and other system components and in a suitable format.

Analytical modules offer routines to answer complex questions and assist in the understanding of relationships. Virtually all management science techniques have found their way into a DSS. Most of these techniques are applicable to only a very specific problem domain.

More emphasis is placed on the user interface of a DSS than on many other computer systems. The user must interact with the system extensively. Because many users are experts in the problem application, and not computers, the system must present a 'user-friendly' interface that belies the underlying sophistication.

Displaying and reporting of results of analytic modules must be flexible and provided in a format that is quickly understood by the user and public. Graphical display of data provides an excellent method of presenting information in an easily understandable form (de Sanctis, 1984).

## **SPATIAL ISSUES IN DECISION SUPPORT SYSTEMS**

Spatial decision support systems are sufficiently different from DSS to warrant a different designation. SDSS are explicitly designed to support decisions of a highly spatial nature. These are problems where the solutions are a set of locations, routes or areas and, as such, are best portrayed on a map.

SDSS are significantly different in all four components of DSS. First, SDSS have unique database management concerns. Spatial data have inherent aspects that do not lend themselves to storage and manipulation in existing relational database models (Armstrong and Densham, 1990). Because important decisions depend on the database, representing data accuracy and integrity are important aspects of SDSS.

Analysis of spatial distributions and relationships is a field of study entirely different from management science. The complexity of spatial data has driven the development of a host of unique spatially-oriented statistics and models.

SDSS have the additional considerations and potential in the cartographical display of the problem information and solutions. Portrayal of information via a map is one of the oldest and most effective ways of communication. It has its own set of grammar and syntax for effective communication. Manipulation of these rules can produce very different messages from the same information (Monmonier, 1991).

Builders of a user interface for a SDSS have the opportunity of using an on-screen map as an effective tool for user input. Selection of a point on a map by pointing at it with a mouse is much more intuitive than using the keyboard to type a coordinate pair or an identifier. Users are also able to quickly relate intricate shapes and areas by simply drawing on the map (Buttenfield and Wackaness, 1991).

Creating a non-spatial DSS requires proficiency in each of its four components. Not only must developers have knowledge of standard software development procedures to create a database management system, user interface and reporting mechanism, they must also be able to implement the necessary analytical routines specific to the problem. When building a DSS to solve a spatial problem, additional knowledge of the many complexities inherent in displaying, managing and analyzing spatial data is required. Many of the issues related to incorporating spatial data into computer systems have already been addressed in the development of geographical information systems. The relationship between these systems and SDSS are addressed in the next section.

## **GIS AND DECISION SUPPORT**

*Geographical information systems* (GIS) can be defined as computer systems that manage the input, storage, manipulation, modification, analysis, display, and output of spatial data and associated attributes (Berry, 1986; Burrough, 1986). Researchers applying GIS are using the terms *decision support* with increasing frequency. However, it is apparent that many researchers are unable to differentiate a SDSS from a GIS (Fotheringham, 1990). GIS appear to offer many of the characteristics needed for a SDSS. In fact, some have defined a GIS as a SDSS (Cowen, 1988). However, as several authors have noted (Beaumont, 1991; Densham, 1991; Densham and Goodchild, 1989; Openshaw, 1991), GIS lack the analytical functions needed to provide effective decision support. They note that the majority of the research and development of GIS has gone into data collection and inventory, not spatial analysis.

Furthermore, even with the addition of spatial analysis functions to GIS, a SDSS will not be created. GIS do not offer the interaction needed for decision making. Most processes conducted with GIS operate in a set sequence of small batch processes. This is to allow the GIS to remain flexible to several different applications. A SDSS is directed toward and optimized for one specific application.

However, despite their limitations, GIS do offer an excellent platform from which to create SDSS. GIS have well established mechanisms for the entry of spatial data through digitizing, scanning or remote sensing. Once the data is entered, GIS have spatial and attribute databases, cartographic displays and a consistent (if often limited) user interface. As a result of these functions, GIS serve well as a platform for SDSS development. The challenge is to customize them into a system that provides effective decision support.

## **REACTIVE, PROACTIVE AND INTERACTIVE SDSS**

Other taxonomies of DSS have been presented by different authors (for example, Alter, 1980; Keen, 1987). A simpler classification of SDSS is presented here to make a point about research needs. SDSS can be arranged into three categories: *reactive*, *proactive* and *interactive*. Each of these types has different ambitions and requires a different level of interaction from the user.

A *reactive* SDSS simply provides information about an action initiated by the user. Most commonly, this is conceptually a link between a spreadsheet and a map. Changes in the map are reflected by different values in the spreadsheet. Linkages may also be in the opposite direction, i.e. changes in the values in the spreadsheet produce changes to the map. Cooke (1991) describes such a system for devising sales territories. Cartographic changes in the sales districts are reflected in updates of area and population in the spreadsheet. Other examples of a reactive system include IBM's early work on the Geodata Analysis and Display System (described in Keen and Scott Morton, 1978) and the commercial system, Facet<sup>1</sup>.

Reactive systems do not offer any suggestions about the best actions to take. Solutions are only determined through repeated trial and error. In order to assume a more active role in the decision making environment, many SDSS incorporate more advanced analytical models. Simulation and optimization models have proven especially applicable for spatial problems.

*Proactive* systems use these analytical modelling techniques to produce draft solutions. Solutions are then edited using a reactive system to account for unstructured objectives. The majority of SDSS presented in the literature to date follow the proactive form. This includes work by Densham (1990) in settlement reorganization, Witiuk's (1990) work in census area delineation (described in Tallon, 1990), districting programs reported by Honey *et al.* (1991), and extensive research in locational modelling (Armstrong *et al.*, 1990; Densham and Rushton, 1987; Massam and Malczewski, 1990).

Unfortunately, in proactive systems such as these, the user has little interaction with the solution algorithm beyond specifying inputs and weights. The analytical module is essentially treated as a 'black box'; producing results without clear indications of how the solution was obtained. As a black box, proactive SDSS have little to differentiate themselves from *post hoc* editing of traditional optimization methods (for example Robertson, 1982), except now the technology is available to conduct more extensive and informed editing interactively.

In this form, SDSS is little more than a new term for an old concept. Routines for the user, database and analytical modules are present, but must be accessed individually.

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<sup>1</sup> Facet Decision Systems, Inc., Vancouver, B.C.

Little attempt is made to present an integrated solution environment (Dyer and Mulvey, 1983). This is unfortunate, because only with integration of the SDSS modules can users exert control over the entire solution process. With successful integration, an *interactive* SDSS is created. Interactive SDSS allow the user to communicate with the system as the solution is determined. This enables the decision maker to incorporate additional objectives directly into the solution procedure, resulting in fewer draft solutions needing to be evaluated.

Many optimization models used in spatial modelling rely on heuristic techniques where early, often arbitrary, steps can have a significant impact on the final solution. Empowering the user to affect these steps can eliminate unwanted solution paths sooner. Also, involving the user encourages understanding of the process. While many spatial algorithms may be complex in their implementation, most are conceptually simple.

Many existing algorithms for spatial problems are spatial in their nature and therefore amenable to interactive approaches. Others, such as the Teitz and Bart (1968) heuristic for location-allocation, are non-spatial. Interactive portrayal of the evolving solution on a map is less appropriate for non-spatial algorithms. Despite possibly slower performance, more spatial algorithms should be encouraged to promote interaction. As computer technology diminishes the importance of algorithmic efficiency, spatial algorithms will prove to be more valuable in producing acceptable solutions.

Unfortunately, while considerable advances have been made in the database, display and user interface modules of SDSS, and the display and cartographic research needs of interactive SDSS have been identified (Densham and Goodchild, 1989), there has been little recognition of the need to adapt and recreate analytical modules to allow more user interaction throughout the process. Few improvements have been made in the analytical models to take advantage of powerful new technology now available. The impressive processing power of today's computer hardware results in much faster completion of complex algorithms, compared to the time when most algorithms were developed. Graphical displays now have sufficient power and speed to display rapidly changing spatial information without lengthy screen refreshes. Finally, graphical user interfaces enable the user to quickly convey considerable amounts of information to the computer. As a result of these advancements, the technological impediments to interactive decision making are being overcome.

## CONCLUSIONS

While a growing amount of research in spatial problem solving has been oriented towards spatial decision support systems, much of the research initiatives in SDSS have concentrated on developing more appropriate database models and improving user interfaces. Algorithmic development has been limited to incorporating traditional optimization and simulation methods into a SDSS shell. Further conceptual research is required to produce solution algorithms that better reflect real world situations by involving decision makers directly.

Subsequent chapters of this thesis will develop interactive algorithms for the land consolidation problem. These algorithms will recognize and respond to the need for input from decision makers as consolidation plans are derived.

## **Chapter Three**

### **Issues in Land Fragmentation and Consolidation**

Consensus in opinion and policy is unlikely to exist in a topic as complex and important as the reorganization of land rights. Over the past four decades a prolonged debate has continued among researchers and policy makers over the costs and benefits of agricultural land fragmentation and whether such a far-reaching program as consolidation is warranted.

This chapter reviews this debate. Following an introduction to consolidation, the costs of fragmentation are addressed. The opposing viewpoint focuses on the benefits of fragmentation and the problems of consolidation. The result of the review ought to be a better understanding of the effects of spatial structure on agriculture and the limitations of current consolidation methods.

#### **BACKGROUND**

##### **Extent**

Fragmented agriculture has been reported in several countries around the world. In his recent literature review of fragmentation, Bentley (1987) listed English language, academic reports of fragmentation in countries on every continent, including North America and Australia. From reviewing the literature, it becomes evident that fragmentation is most acute in Western and Southern Europe (Chisholm, 1979). Most non-European countries (with exceptions including India; Blaikie, 1971; and Japan; Hyodo, 1963) average under three parcels per farm — for example Taiwan (Vander Meer, 1975), the Philippines (Wong, 1987a), Malaysia (Wong and Tan, 1980) and Canada

(Carlyle, 1983). In comparison, many European countries average between six and twenty parcels per farm (King and Burton, 1982; Mayhew, 1970; Vander Meer, 1975). Some farmers have to contend with 200-400 small scattered parcels (Chisholm, 1979; Naylor, 1959; Vander Meer, 1975).

Not surprisingly, consolidation has therefore been a predominantly European initiative. Programs have been undertaken in virtually every Western European country at one time or another in the past five centuries (King and Burton, 1983). Of those, the most recent English academic reports of consolidation schemes have been from:

- Cypress (Burton, 1988);
- Denmark (Skovgaard, 1952 in King and Burton, 1983; Vanderpol, 1963);
- France (Roche, 1963);
- Germany (Mayhew, 1970);
- Ireland (O'Sullivan, 1970);
- Norway (Lambert, 1963 in King and Burton, 1983);
- Spain (Behar, 1986; O'Flanagan, 1980, 1982; Guedes, 1981; Peters and Guedes, 1984); and,
- Sweden (Ytterborn, 1963).

It is expected that consolidation will become increasingly important as Eastern European countries encourage large numbers of privately owned farms. Unfortunately, comprehensive research into consolidation programs is not being undertaken. For many years the United Nations Food and Agriculture Organization (FAO) was the primary promoter of inquiry into both fragmentation and consolidation (Binns, 1950; Jacoby, 1971; Meliczek, 1973; Moral-Lopez and Jacoby, 1962). However, the FAO has published very little material on either subject over the last two decades (King and Burton, 1982; Bentley, 1987).

### **Preparing for Consolidation**

Although documentation is sparse and details vary between individual countries, most of the data needs of consolidation appear to be common to all programs. Much of the preparation involves enacting legislation to establish administrative bodies and to control expropriation and allocation of land. The legal aspects of consolidation are daunting. Consolidation's operational aspects are of more concern in this thesis.

Despite the relative wealth of administrative infrastructure available in European countries, land consolidation projects usually take several years to complete (King and Burton, 1983; OECD, 1972). A typical project affects a few hundred farmers during a period of three to seven years. Much of this time is spent convincing the farmers to participate, and collecting the large amounts of data required.

Most governments prefer to consolidate on a voluntary basis. However, usually farmers are initially distrustful of consolidation schemes and very few spontaneous consolidation programs have occurred (see Adams, 1981; and Schmook, 1976; cited in Bentley, 1987 for exceptions). This, combined with the fact that a few key non-participants can wreak havoc on a consolidation plan, has resulted in most consolidation schemes being enforced (Bentley, 1987; King and Burton, 1983; Meliczek, 1973). In these cases, initiation of consolidation is usually based on the preference of some majority of the land owners. For instance, in Austria 33 per cent of the farmers owning at least 50 per cent of the land must agree (King and Burton, 1983). In Spain, both proportions are 60 per cent (O'Flanagan, 1980). If the minimum level of support is reached, those opposed to consolidation are legally compelled to participate.

The minimum vote is usually attained, partly because the government undertakes a vigorous publicity campaign preceding any consolidation vote (Figure 3.1 is a poster used in a consolidation campaign in Cyprus). Opposition to consolidation is unlikely to be as organized (Aceves, 1976).

Once consolidation has the approval of the participants, determining ownership and producing a cadastral map agreeable to all land owners and renters is the first major task. In a fragmented system there are many complex boundaries and property rights. In India, for example, there may be a series of intermediaries between the owner and farmer of a parcel, all possessing rights and expecting profits (King and Burton, 1983). Disputes over ownership and boundary location are common. Thus, it can take several months or years before all conflicts are legally settled.

The second task is to determine the value of land that each farmer currently owns. This is usually completed with the assistance of community representatives to better reflect the participant's perceptions of a parcel's value. The results are circulated to farmers, who can appeal their individual assessments.



**Figure 3.1** Poster used by the Land Consolidation Authority of Cyprus to publicize and advocate consolidation. The title reads: "Land consolidation: the fundamental effects for the Cypriot farmer" (King and Burton, 1983: 474).

This information is used to ensure that no farmer 'loses' as a result of consolidation. Losing is defined as a farmer acquiring land of total value below the value of his or her original holdings. However, planners realize that valuation is not exact. Also, it can be impossible to create new parcels totalling precisely the same value as the original. Therefore, planners specify a tolerance, usually a percentage, under which no farmer should fall. For example, if a farmer has \$1000 worth of land before

consolidation, and a five percent tolerance is used, then that farmer should receive at least \$950, but no more than \$1050 worth of land.

In some countries, such as Spain, limited attempts are made to include farmers' preferences into the consolidation plan (Goh, 1991). When all farmers have agreed on land ownership and value, each farmer is allowed to select parcels they wish to retain, in order of preference. This enables farmers to express a desire to keep parcels near their homes, containing buildings, or ones with other, more sentimental appeal.

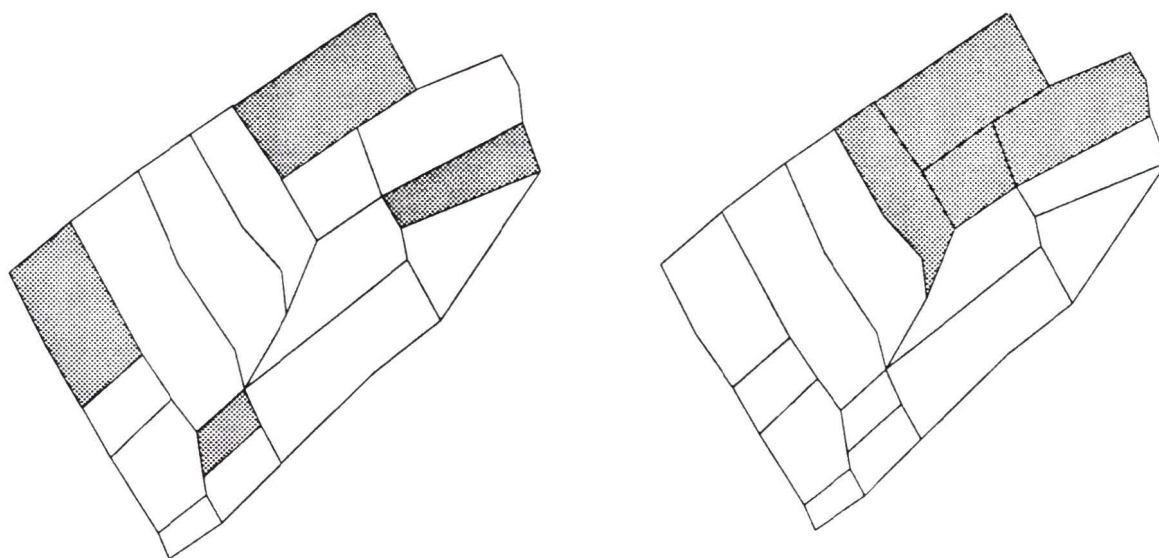
### **Existing Methods of Consolidation**

Once the above information has been acquired and verified, planners are ready to prepare a consolidation plan. In contrast to the rigorous legislation governing land valuation and implementation of consolidation, the process of developing a plan is one of undocumented, subjective strategies learned through trial and error.

Although documents on actual consolidation procedures are sparse, two treatments of space can be identified: discrete and continuous. *Discrete space* consolidation is simply the exchange of ownership between existing parcels. Adjacent parcels owned by the same farmer after consolidation are merged into one. The existing parcels form the building blocks to create new parcels (Figure 3.2). Planners attempt to assign a farmer land adjoining his or her largest parcels until the total value of these parcels approximately equals that which was relinquished (Meliczek, 1973). Several possible assignments may meet that requirement.

Consolidation in this form eases land valuation by limiting the problem to assessing independent parcels. As a result, it is easier to promote community consultation and may better reflect farmers' perceptions of value. Farmers are able to relate to and discuss parcels by name.

Discrete space consolidation is cheap to plan and implement. It reduces disruption to existing facilities. Only fences and hedges separating parcels now owned by the same farmer are removed. However, by using the existing boundaries the shape of the new parcels is restricted by the shape and configuration of existing parcels. Planners are limited in the number of possible different redistributions and may not be able to produce a desired apportionment. Also, given that the existing boundaries are likely not conducive to straight roads and canals, a discrete space approach impedes other development plans, such as improvements to drainage and roads.



### Before Consolidation

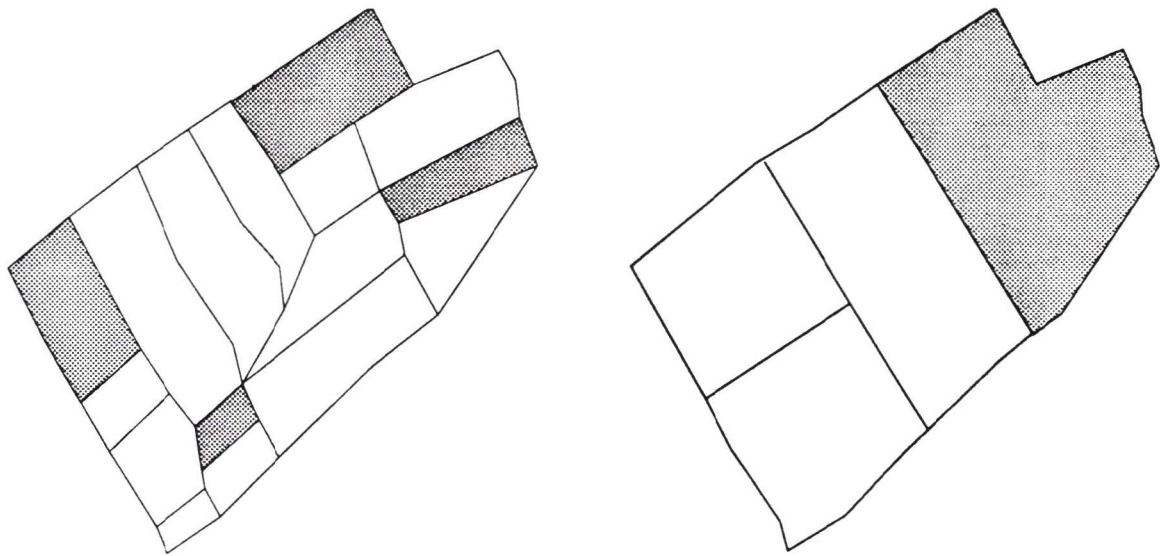
### After Consolidation

**Figure 3.2** In discrete space consolidation the original parcels form the 'building blocks' for new parcels. The shaded parcels are owned by the same household.

As a result of the limitations of discrete space approaches, *continuous space* consolidation has been more common. Continuous space strategies delineate new parcels independently from the existing parcels. New property lines may or may not follow the original boundaries (Figure 3.3). Therefore, there are an infinite number of possible consolidation plans.

In the latter approach, valuing each farmers' holdings is accomplished by categorizing land into several classes and then dividing land into areas of equal class. The areas delineated are independent of the original parcels. Assessors determine a value per square unit of land for each class. The cadastral and agricultural capability maps are overlaid, and the amount of land in each class for each parcel is determined (Figure 3.4). Multiplying the area in each class by the respective per unit value results in the value of the parcel.

This method makes two key assumptions. First, it assumes that land is divisible. For instance, a 100 ha parcel of class I land is assumed to be worth exactly twice as much as a 50 ha parcel also of class I. Second, it assigns cardinal values to originally ordinal land classes. Classes I and VI may be given values of \$250 and \$25 per hectare



### **Before Consolidation**

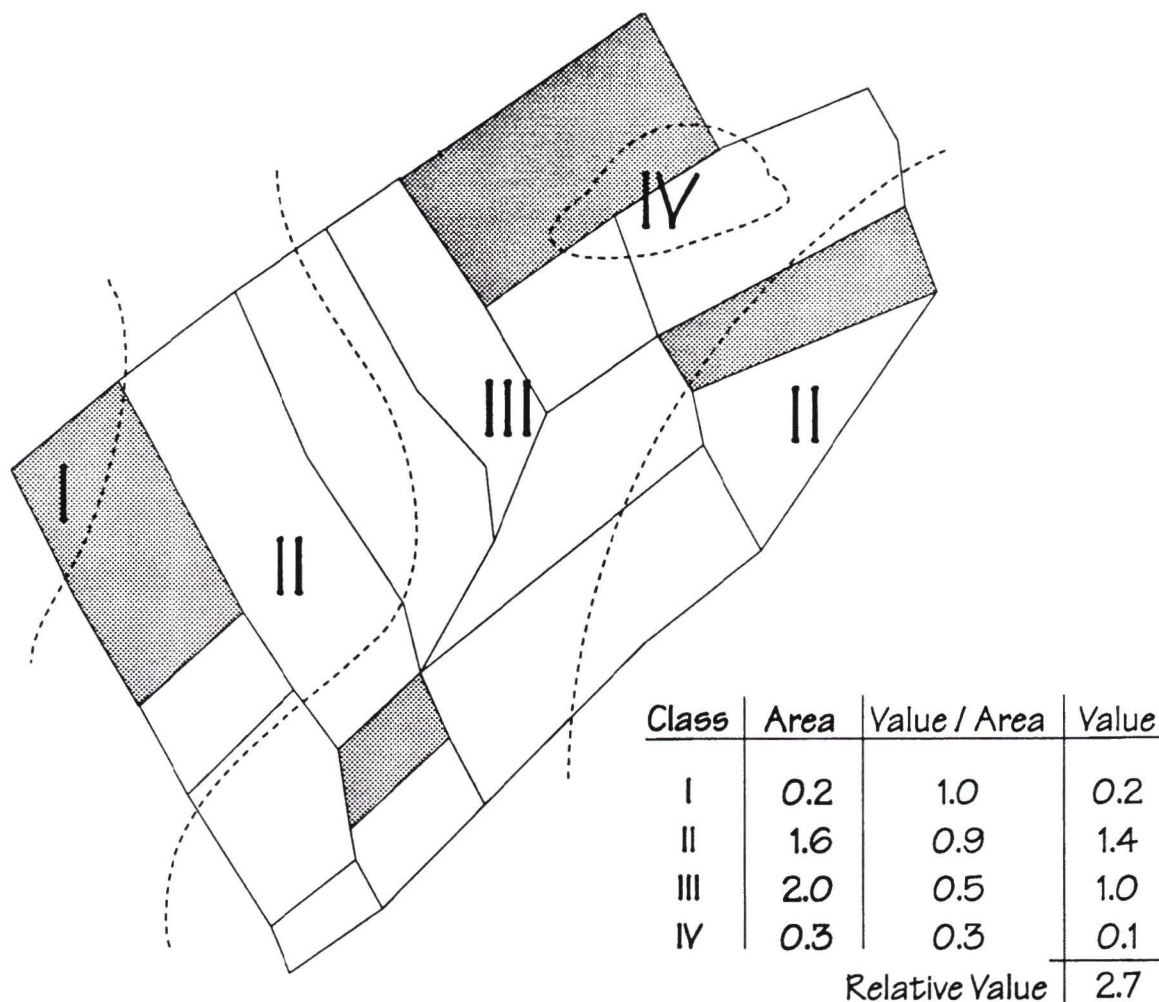
### **After Consolidation**

**Figure 3.3** In continuous space consolidation planners are free to create parcels independently from the original parcel boundaries. Again, the shaded areas are owned by the same household.

respectively. If so, a 50 hectare parcel composed of class I land is equal in value to 500 hectares of class VI.

Once land value maps are created, planners are ready to delineate new parcel boundaries. A common method is to divide the study area into smaller, more manageable regions, usually bounded by roads and other permanent boundaries. The total land value for this region is then determined. The planner must decide which proportions of this small region are to be assigned to which farmers. This is determined in part by the current ownership within the region, and by assignments completed elsewhere in the study area.

Because the region is not homogeneous in land class, actually drawing boundaries to accomplish a desired distribution is a difficult task. The analyst repeatedly draws a parcel boundary and then calculates the land value within the created parcel until the desired apportionment is reached. Some firms, for example Digital Resource Systems of Nanaimo, B.C., use a GIS to determine the location of this line automatically. An iterative routine automatically determines the location of such a boundary given a desired total land value and a perpendicular line on which to move the parcel boundary

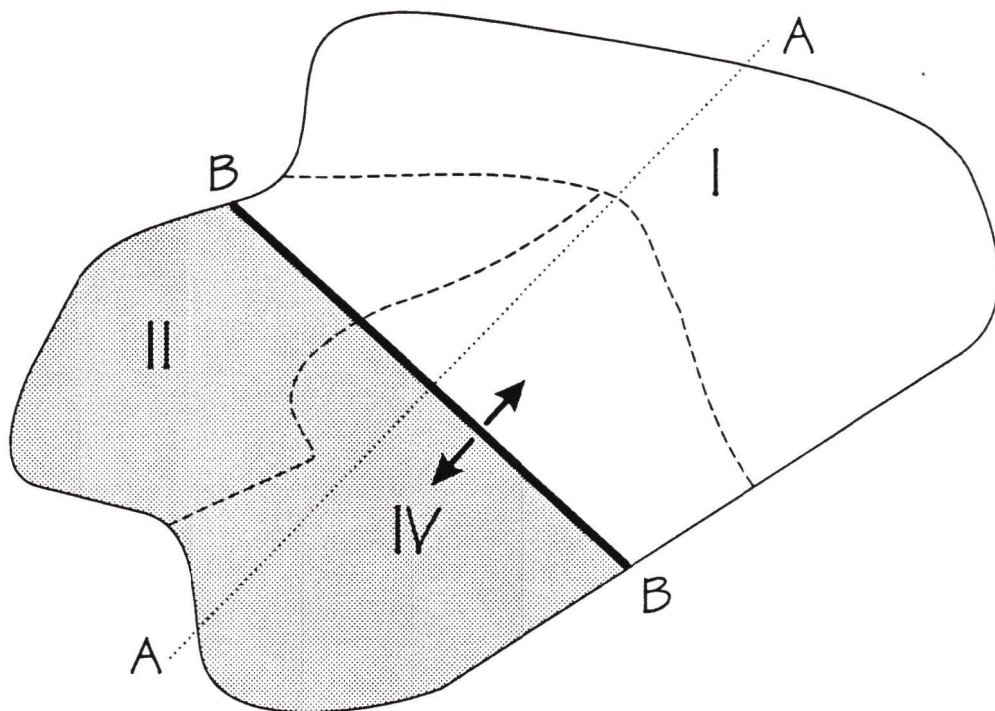


**Figure 3.4** Continuous space valuation entails the overlay of the cadastral and land classification maps. In this example the shaded parcels contain land in four classes and are worth a relative value of 2.7 units.

(Figure 3.5). Even with a custom routine like this, producing an acceptable consolidation plan is a tedious and complex process. The consolidation problem is composed of conflicts and contradictions. This is evident in the divergent opinions of its merits.

### THE CASE FOR CONSOLIDATION

Fragmentation has long been viewed as a net cost to a farmer and a community and worthy of enforcement of involuntary consolidation. Agricultural policy makers have been particularly adamant in their fight against fragmentation. They call fragmentation a "disease" (Naylon, 1959: 361) and "the blackest of evils" (Farmer, 1960: 225). European policy makers regard fragmentation as the greatest single deterrent to agricultural



**Figure 3.5** Continuous space allocation. Given a monetary value per hectare for each land class (eg. II), a bounding polygon, and a line input by the operator (A-A), a routine written by Digital Resource Systems finds the location of new boundary (B-B) perpendicular to A-A, so that the value of the land in the created parcel (shaded) is equal to a specified amount.

development in Europe (Binns, 1950; Dovring, 1965; Jacoby, 1971; OECD, 1969; von Dietze, 1963). Many geographers and economists have also concentrated on its costs (Grigg, 1983; Karouzis, 1971; Naylon, 1961; O'Flanagan, 1980; Smith, 1978; Thompson, 1963). They have identified three major costs of fragmentation.

In a fragmented agrarian system farmers may spend considerable time moving workers, equipment and materials between distant fields (Karouzis, 1971; Thompson, 1963). Yields from parcels far removed from the farmstead may result in significantly lower return than nearby parcels (Chisholm, 1979: 24). This cost is particularly burdensome in Western Europe where farm labour is scarce and workers are paid high wages while travelling between scattered work sites (Jackson, 1970; Meliczek, 1973).

Second, the small and irregularly shaped fields of a fragmented landscape create a serious impediment to the modernization and mechanization of agricultural production (Binns, 1950). It is difficult to manoeuvre tractors around small fields with sharp wedge-shaped corners of fragmented fields (King, 1977, Naylor, 1959; O'Flanagan, 1980). Policy makers assume mechanization provides the means to increase farm productivity substantially, and thus be a net benefit to farmers. Therefore, they argue for fields that are more amenable to mechanization.

The third argument against fragmentation is the administrative and social difficulties, and the conflicts it creates. Farmers can become less committed to parcels as they acquire more over a large area (Bunch *et al.*, 1979, cited in King and Burton, 1982). Fragmentation increases the number of farmers involved in an area and, as a result, may make reaching decisions about that area more difficult. Cadastral authorities have difficulty delineating property lines and establishing land rights in such a complex system. Social tensions can arise over disputes of ownership and access as many parcels are not accessible from public rights-of-way and require trespass on others' land (Herzfeld, 1980; Papageorgiou, 1963; Thompson, 1963).

As well as reducing the above costs, consolidation provides a window for other agricultural reforms such as farm enlargement, implementation of irrigation, and new roads. Development of irrigation systems in fragmented fields is complicated by the lack of suitably straight channel routes and the many outlets required to serve each small field. In documenting the long term benefits of consolidation in two Indian villages, Bonner notes the percent of cultivated land under irrigation increased from 40 to almost 100 as a result of consolidation (Bonner, 1987: 113). Consolidation not only straightens these potential conduits, it creates the administrative structure and community involvement needed to initiate these actions. These are perhaps the greatest benefits of consolidation in developing countries (Bonner, 1987; Meliczek, 1973).

## **THE CASE AGAINST CONSOLIDATION**

This section is divided into two parts. The first part reviews the arguments in support of fragmentation. The second half describes the costs and problems associated with consolidation.

### **The Benefits of Fragmentation**

Some researchers, particularly anthropologists and some geographers have found merit in presently fragmented systems. They contend fragmentation is an adaptation to the local agrarian environment. Most of the benefits of fragmentation arise from exploiting the ecological diversity across an area. This flexibility is particularly evident in alpine areas where climatic changes can be quite dramatic over a very short distance (Netting, 1972; Rhoades and Thompson, 1975).

By planting crops in several different ecological zones, farmers are able to reduce risks of a meagre harvest. This is particularly important in subsistence agriculture. Johnson (1970) showed theoretically that as subsistence becomes more prevalent, fragmentation increases. Others have documented cases of farmers working fragmented farms as a defense against precipitation variability (Blaikie, 1971; Forbes, 1976; Galt, 1979), disease, pests (McCloskey, 1976; Nietschmann, 1973), frost, typhoons, hail and floods (Carlyle, 1983; Hyodo, 1963; Ilbery, 1984).

Crops in different micro-climates ripen at different times. A farmer can use this to his or her advantage. By lengthening the harvesting period, a farmer has more constant labour needs (Forbes, 1976; Friedl, 1974; Galt, 1979; Netting, 1972) and may realize price advantages at the market (Simons, 1986).

Writers defending fragmentation have also disputed its real costs by describing possible adaptations. They argue that the extensive costs resulting from fragmentation are assumed without empirical analysis (Bentley, 1987; King and Burton, 1982; Simons, 1986; Wong, 1987b). When farm production is analyzed first hand the detriments of fragmentation are not always evident. For example, Bentley (1990) found no correlation between milk production and indices of fragmentation for farms in northwest Portugal.

Farmers are able to reduce costs of fragmentation through several innovative methods. By growing labour intensive crops near the homestead and less intensive crops at a distance, a farmer does not have to visit distant parcels as often (DeLisle, 1982; Nietschmann, 1973). Also, visits to several distant parcels can be combined into fewer trips (researchers have tended simply to total distance from each field directly to the homestead; Igbozurike, 1970). Farmers may rent distant parcels to another farmer (Vander Meer, 1975), form cooperatives with neighbouring farmers (Hirsch and Maunder,

1978), or use a temporary second dwelling for particularly remote parcels (Brown *et al.*, 1990; King and Burton, 1982).

### **Problems of Consolidation**

Many of the negative effects of consolidation are inevitable in imposing such a profound change as consolidation. However, several problems resulting from consolidation programs are particularly acute.

Often, the land values used by the consolidation planners do not reflect those of the participants. Farmers believe

that the three, four, or five fields the engineers gave them don't add up to the forty, fifty, and sixty plots that they had accumulated through inheritance, destiny, and their own hard work (Behar, 1986: 293).

This is largely because those valuing land take too narrow a focus. In one of the few first-hand accounts of a land consolidation scheme, Behar (1986) describes the inequities in the consolidation of farmland surrounding the village Santa María del Monte, Spain. Just after consolidation, a woman sold a parcel located near the village for 500,000 *pesetas*. Another woman, attempting to sell a similar parcel some distance from the village, was only able to get 50,000 *pesetas*. The difference was the plot near the village has access to water and sewage, and will one day be the site of a summer house. When rating each parcel, with the help of a few villagers, the consolidation planners only considered agricultural productivity, not real estate value. Consequently, those who receive property near the village, whatever its agricultural value, become 'winners' in what Behar describes as the 'lottery' of consolidation (Behar, 1986: 299).

As described above, one of the rationales for fragmentation is the diversity of land types available to each farmer. Farmers have land of every type — a meadow, a garden, and fields for grains. Unfortunately, many consolidation planners have been unable to understand or appreciate the importance of this diversity (Bentley, 1987). In the Santa María consolidation many people lost their small, nearby garden plots, only to receive expanses of sandy land only good for grains. In response, farmers planted small, irrigated gardens in the middle of the large new fields (Behar, 1986: 296).

Boundaries between existing parcels are not created randomly. Fence lines often follow natural divisions in the landscape. Over time, linear features that restrict passage,

such as creeks and banks, are incorporated into the cadastre. Parcels are moulded to the land's contours to ease farming. However, in drawing the new parcels on a flat desk, planners have produced fields that are very difficult to work. Many require extensive landscaping to create ploughable land and some are perpendicular to steep slopes.

Contrary to contentions that consolidation reduces the land wasted by fencing between many fragmented parcels (King and Burton, 1982), consolidation can also result in waste and inefficiencies. In Santa María, 37 of 459 ha of farmland was lost to new roads, so that every parcel has access to a road (Behar, 1986). The crops encouraged by consolidation require a more extensive approach to agriculture, instead of the less wasteful, intensive approach used before. Consequently, soil erosion and salinization become more prevalent as farmers move to a more modern, mechanized form of agriculture.

Another impact of consolidation is more visual. Consolidation changes the landscape by straightening and widening paths and roads. The result is the loss of many trees and the creation of hot, shadeless footpaths.

Other costs are socio-economic. The provision of large fields ideal for mechanization does not mean all farmers are now able to mechanize. Lack of capital and small farm sizes mean that if farmers are able to purchase tractors and combines they are forced into substantial debt. Alternatively, they resort to hiring others to work their land and harvest their crops, and, as a result, become dependent on their services.

Mechanization also has the effect of decreasing demand for labour. This can dramatically decrease farm production expenses, but in areas where unemployment is a problem this may be a net social cost. Other employment possibilities may not exist in rural areas, and the resulting rural to urban migration puts a great strain on cities (Meliczek, 1973).

Prior to consolidation, crossing another farmer's land was inevitable. This trespassing resulted in arguments, but also reminded farmers that they could not remain aloof from their neighbours. After consolidation, every farmer can access his or her land without crossing another's. Consequently, farmers are liberated from ties to the community. All farmers are free to increase their feeling of self-importance (Behar, 1986: 300).

## CONCLUSIONS

Fragmented agricultural landscapes in Europe and other more developed areas are a legacy of a past era. These practices were well adapted to economical and technological conditions of a past time, but now retard the modernization of agriculture. Many of the effects of consolidation, such as increased mechanization, rising rural unemployment, and loss of community ties are inevitable as traditional agricultural areas become part of the modern world. Consolidation only accelerates the transition in these areas by acting as a catalyst for economic development.

Unfortunately, much of the consolidation that has taken place to date has not benefitted all participants. Simplification of the procedures to value and redistribute land has resulted in inequities. The value of a piece of land can never be fully represented in a single monetary figure. Not only are there countless attributes to every parcel, each individual has a different perspective on those attributes.

However, even if planners recognize and accept the complexity of land value, they are unable to deal with the profusion of information it requires. Quantitative data on a parcel's size, shape, soil type, topography, access, location and qualitative information portraying the perspective of the participants are reduced to a single monetary value so that planners only have to meet one equity constraint in the complex task of redrawing the cadastre. Much of the information needed to avoid many of the problems of consolidation is lost through this simplification. Existing *ad hoc* methods, based on hand-drawn plans are simply unable to treat consolidation with the complexity it deserves.

The challenge is to create a system to reallocate land so that farmers realize the benefits of larger, more regularly shaped fields, while ensuring that all farmers feel they have benefitted from the process. This requires a much fuller definition of land value and a resulting increase in the complexity of the task. A clearer indication of the effects of a consolidation plan, and tools to manage its complexity, must be provided. The next chapter is the first step in the pursuit of this goal. It formalizes the consolidation problem and examines alternative strategies in creating a model of consolidation that can address these issues.

## Chapter Four

### Formalizing Consolidation

The purpose of this chapter is to develop the foundation of a model for agricultural land consolidation. To accomplish this, the consolidation problem must first be specified as formally as possible by enumerating and classifying its many objectives. Only when these are catalogued can solution approaches be conceptualized. To assist in the conceptualization of solution algorithms, the second section of the chapter identifies spatial assignment problems similar to consolidation. Algorithmic approaches to four of these problems are reviewed to determine their suitability for consolidation.

#### OBJECTIVES AND CONSTRAINTS OF CONSOLIDATION

There are two defining elements of consolidation. Firstly, it is to improve the overall efficiency of agriculture in an area. Efficiency is concerned with eliminating waste. For example, it should result in farmers wasting less time travelling between parcels and manœuvring tractors into tight corners. Consolidation also increases efficiency by introducing other agricultural development initiatives, such as farm enlargement, or irrigation. These initiatives result in greater productivity from the available land.

The second aspect of consolidation is equity. In meeting the above objectives, planners must ensure that the plan is fair. *Every* farmer should benefit from consolidation, and no farmers should gain at the expense of others.

This section describes both of these elements of consolidation in detail. Three different forms of efficiency are identified: parcel efficiency, spatial efficiency, and system

efficiency. Objectives within each are enumerated. Equity considerations are then discussed.

### **Parcel Efficiency**

Parcel efficiency measures relate to an individual parcel's shape, and proximity to relevant common fixed facilities. A parcel's attributes in these objectives can be determined in isolation.

#### *Shape:*

Planners seek to create parcels of a shape conducive to farming. Parcels in fragmented countrysides often have very sharp, acute corners that discourage mechanization. The ideal parcel shape has few corners, and no sharp turns. Circles are exemplary in isolation; however, they leave voids when packed together. If the circles are expanded to hexagons, too many corners are created (King and Burton, 1983).

Square or rectangular parcels are preferred in most consolidation programs. Lee and Sallee (1974) have shown theoretically that a square field is the optimal shape to maximize the time a tractor spends ploughing, and minimize the time it spends travelling to the morning's work. Other advantages of square or rectangular fields are their cadastral simplicity, fencing ease, and their ability to pack well together.

There are several measures of shape in the geographical literature (Austin, 1984; MacEachren, 1985; Selkirk, 1982); however, all measure compactness by comparing the shape to a circle. Compactness is not a true measure of the desirability of a field's shape. Although a rough circle is more compact than a long thin rectangle, the square corners and straight edges of a rectangular field are more desirable than the many odd corners and curved edges of a nearly circular field. However, no measure exists to compare a shape to a square or rectangle (Bentley, 1987). Compactness measures will have to suffice for approximating the ideal field shape.

#### *Accessibility to Common Facilities:*

Farmers need to be able to access nearby facilities, towns and cities from each parcel for several reasons, including attaining supplies and labour, selling their harvest, and accessing off-farm employment. In the simple case this is one local town (Chisholm, 1979). Quantifying the objective in this form entails measuring distance from parcel to town. Although time consuming, measuring the shortest path from one point to the other along a road network would seem a realistic and practical approach.

However, accessibility to common facilities is more complex than one static distance. Farmers may need to travel to several towns and cities at different times of the year, depending on the crop, method of farming, and personal preferences. Incorporating these more realistic and complex aspects of accessibility is problematic. Accessibility of a parcel can no longer be determined in ignorance of temporal and farming considerations.

***Parcel Access:***

To reduce conflicts over access and ease movement of machinery, parcels should be adjacent to public roads. To improve productivity, where applicable, consolidation should also increase the number of parcels abutting irrigation canals. The marginal gains from creating a common border between a parcel and these features longer than the width of a tractor or drainage ditch are modest. Also, roads and canals can constitute a waste of agricultural land. Consequently, an efficient allocation should minimize the length of road and canals, and each parcel should be adjacent to one road and canal for only a short distance.

**Spatial Efficiency**

Spatial efficiency is concerned with the locational organization of parcels. Many agricultural practices are dependent on the spatial relationships between a parcel and farming facilities, residences and other parcels.

***Contiguity Between Parcels:***

One of the fundamental aspects of consolidation is increasing contiguity. When two parcels are controlled by the same farmer and share a long common border, it is advantageous to combine them into one parcel. Consolidation seeks to increase the instances of contiguous parcels being owned by the same farmer.

The reduction in the number of discrete parcels resulting from consolidation can simply be measured by the change in the average number of parcels per farm or average field size (Binns, 1950; OECD, 1969; Thompson, 1963; Naylor, 1959; Hill, 1984). A similar measure is the percentage of farms comprising more than a fixed number of parcels (OECD, 1969).

Concomitant with the joining of contiguous parcels is an increase in the average area of parcels. Two ratios have been proposed to measure the number and area (*a*) of parcels in unison. Simmons (1964) developed a fragmentation index (*FI*) independent

of overall farm size. The *FI* index is given by the sum of square parcel sizes divided by the square of the total area of all parcels in the farm:

$$FI = \frac{\sum a^2}{(\sum a)^2} \quad (4.1)$$

A value of one signifies a farm consisting of one parcel. Increasing fragmentation is indicated as the index approaches zero.

Januszewski (1968) proposed a similar index:

$$K = \frac{\sqrt{\sum a}}{\sum \sqrt{a}} \quad (4.2)$$

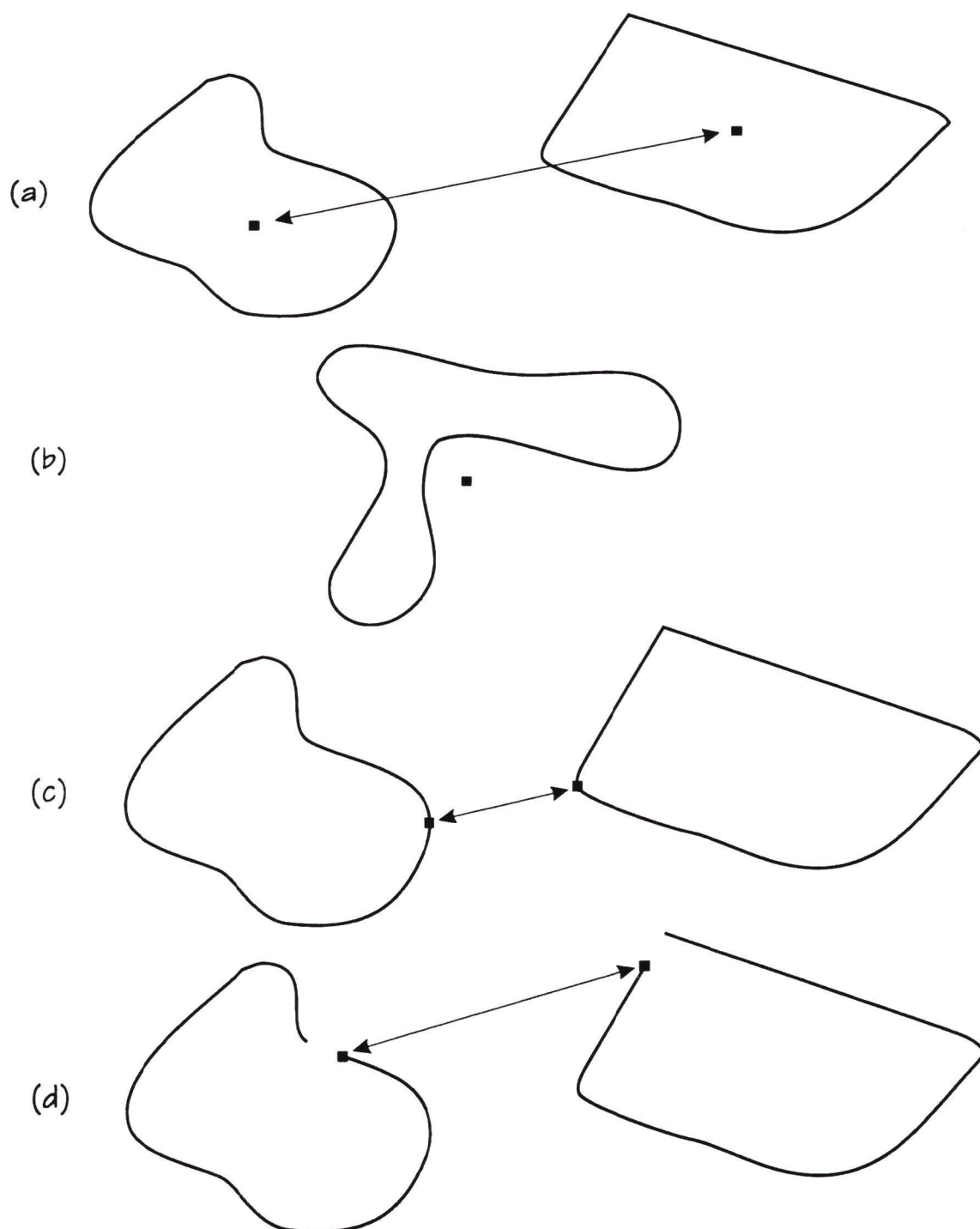
As with Simmon's ratio, a *K* value of one indicates no fragmentation. *K* approaches zero as the number of parcels in a farm increases. Unlike Simmon's ratio, Januszewski's index equates increases in the variability of parcel size with increased fragmentation.

Unfortunately, both of the ratios measure fragmentation for only one farm at a time. To measure fragmentation for a number of farms in an area, simple measures of central tendency and dispersion of the number of parcels and parcel size are likely more discernable than either of the measures formulated by Simmons or Januszewski in isolation.

*Proximity to Other Parcels:*

While greater benefits can arise from combining adjacent parcels into one, there are also advantages to simply having parcels near each other. Proximal parcels decrease travel distance of a tour, ease supervision, and reduce take down and setup time for machinery. In most implementations, the proximity between polygons is approximated by the distance between polygon centroids (Figure 4.1a). However, the odd-shaped polygons of fragmented farm parcels create problems for this approach, as centroids may be near or outside polygon boundaries (Figure 4.1b). A better representation of a farmer's movement between parcels may be obtained by measuring the shortest distance between the two polygons (Figure 4.1c). Neither of the above measures account for entrances and exits from parcels. In other words, the location of gates is not considered (Figure 4.1d).

Other facets of parcel proximity concern the trip between parcels. Certain spatial arrangements may create more desirable movements between parcels for a farmer. When travelling from one field to another, a farmer may stop to visit a relative or friend, a



**Figure 4.1** Proximity between polygons is often measured by the distance between the two centroids (a). However, polygon centroids may be outside of the edges of a polygon (b). More appropriate measures for odd-shaped polygons are the distance between the two nearest points on the polygons (c), or the distance between field gates (d).

store, or the local tavern. The development of a generic measure for this type of objective is unlikely.

***Proximity to Farmer-Specific Facilities:***

Farmers benefit from having parcels close to their facilities. The most obvious facility is the farmer's residence, but the farmer's barn, stable or second home are also personal facilities (Chisholm, 1979). In areas of severe fragmentation, distance cannot adequately be measured using straight-line distance. Roads are rarely straight, and bridges can be sparse. In these instances, distance along a road and path network offers a better representation of reality.

The complexity of measuring distance is increased when actual travel tendencies are included (Igbozurike, 1974). Not all fields must be visited directly from the homestead. Trips to fields can be combined into a tour. Igbozurike attempted to account for tours in his index on fragmentation. His index,  $P$ , is as follows:

$$P = \frac{D_t}{100\bar{s}} \quad (4.3)$$

where:

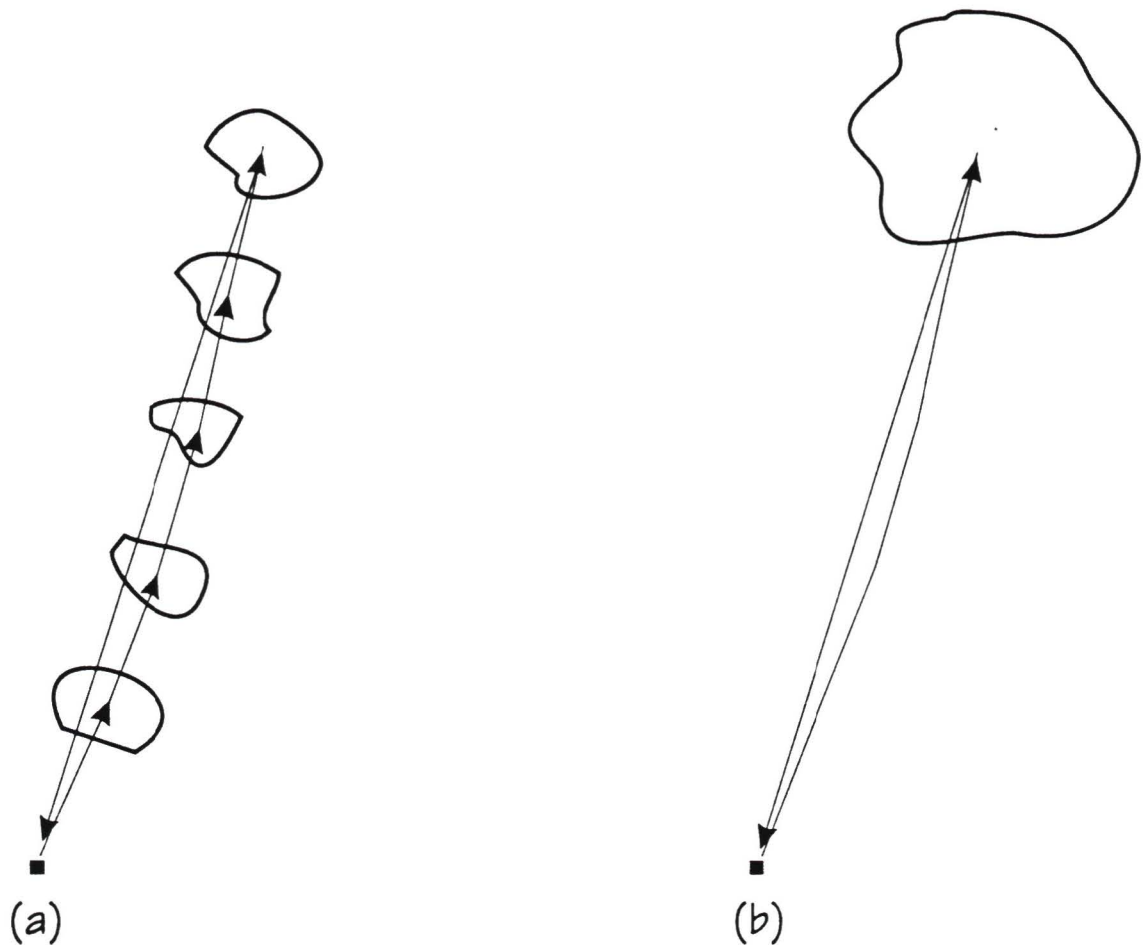
$D_t$  is the length of the round trip to visit all parcels;

$\bar{s}$  is the average area of parcels.

Unfortunately, Igbozurike's index is marred by mistakes in explanation (he confuses the sum of individual distances to fields with a tour), and by methodological issues. The index completely ignores the number of parcels (King and Burton, 1982). Consequently, a tour of several parcels gives the same ratio as a trip of the same total distance to only one large parcel (Figure 4.2). Implementation of the index is hampered by the complexity of determining a tour through a set of parcels. If simply the shortest tour of all parcels is assumed, the problem is NP-hard (Garey, 1979). The complexity increases substantially if the inappropriate assumption that all fields have to be visited with equal frequency is removed (Bodin *et al.*, 1983; Keller, 1985; Lawler *et al.*, 1985). Distant fields may be worked less intensively, and therefore not require as many trips.

***Diversity of Land Types:***

Proximity to facilities is a spatial relationship between the parcels and point locations. Spatial relationships also exist between the locations of parcels and the environmental landscape. More labour-efficient practices may result from crop specialization. On the



**Figure 4.2** Problem of Igbozurike's index. Both field configurations (a) and (b) will produce the same value in Igbozurike's (1974) index, despite the difference in the number of fields.

other hand, it may be desirable to reduce farmers' risk by providing each farmer with a diversity of land types. Either way, knowledge of the different land types available to each farmer is valuable in assessing a consolidation plan. This information is readily measured for individuals by calculating the area or percentage of each land type owned by a farmer.

### **System Efficiency**

The final form of efficiency — system efficiency — concerns the entire area affected by consolidation. This includes land outside of the area actually being consolidated. Improved system efficiency benefits society as a whole. Consequently, these programs may not be beneficial to individual farmers or communities.

***System Development:***

Among the many possible system objectives of consolidation are those that aim at improving the overall economic development of an area. Improvements to the road and irrigation network are facilitated by the straighter edges, and the opportunity provided by consolidation to implement additional changes. In areas of under-utilized cultivatable area, consolidation is often combined with farm enlargement (Bonner, 1987).

Other system objectives strive to create a more efficient agricultural sector for the country. Consolidation has been used as a catalyst for a region to join country-wide crop changes (Alexandratos, 1990; Behar, 1986; Clout, 1984).

***Preservation of Existing Boundaries:***

A second form of system efficiency is more concerned with implementation costs. The demolition of existing fencing, walls and hedges separating fragmented fields is an economic and environmental cost. Hedgerows provide much needed habitat for small animals, wind breaks to slow wind erosion, and they add variety to the visual landscape. Removing existing boundaries and creating ploughable land underneath is especially costly when modern construction equipment is not widely available.

Assuming that all parcel boundaries are of equal importance, the retention of existing boundaries can be measured by using a ratio. There are three factors affecting the measurement of preservation of existing boundaries: the length of parcel boundaries before consolidation ( $e_0$ ); the length after consolidation ( $e_1$ ); and the length of original boundary retained after consolidation ( $e_2 = e_0 \cap e_1$ ). A measure of the proportion of existing boundaries lost to inefficient consolidation (in terms of this measure) can be attained by taking the ratio of the length of boundary retained to the total length of boundary after consolidation:

$$B = \frac{e_2}{e_1} \quad (4.4)$$

A value of  $B$  equal to one indicates that no new boundaries were added. Any length that appears in the boundaries after consolidation that was not present originally would reduce the ratio below one. If none of the original boundaries were maintained  $B$  equals zero.

### **Equity Objectives**

The second defining aspect of consolidation is equity. Consolidation is concerned with the redistribution of land, not the redistribution of wealth. Therefore, it should result in a net benefit for every participating farmer. However, defining the costs and benefits experienced by farmers as a result of consolidation is problematic. To draw plans that result in individual farmers feeling they have benefitted, farmers' perceptions of value must be understood by planners. In addition, farmers must feel that other farmers did not lose or benefit unfairly from consolidation. In other words, there are two perceptions on equity: *individual* and *communal*. Both are important to consider if a consolidation plan is going to be perceived as beneficial to all.

Several characteristics of a parcel of land decide its value from the community's perspective. A parcel's area, soil, slope, topography, sun exposure, and precipitation are all natural endowments well known by the area farmers. Value is improved with fencing, farm buildings, orchards, vineyards, and access to roads and irrigation. Also, there are non-agricultural values. Parcels may be valuable in the real estate market for housing, or other non-farm use. Each of these must be considered in producing equitable redistributions. Finally, communal equity considerations concern parcel efficiency. Consolidation is oriented towards improving the overall shape and accessibility of parcels. However, this should not greatly impair the efficiency of any one farmer.

Individual assessments of parcel worth are much more difficult to define. Not only does worth depend on the characteristics of the parcel described above, but on specific characteristics of a farmer, such as location relative to the farmstead and other parcels, method of farming, and more sentimental appeals that cannot be quantified. These are equally important to consider if individual farmers are going to feel they benefitted from consolidation.

### **The Multiobjective Nature of Consolidation**

A summary of the objectives of land consolidation is provided in Table 4.1. The defining objectives of consolidation, contiguity, parcel access and distance are all well represented by mathematical metrics. Properly portraying farmers' travels by the shortest distance through a network of roads and paths is complicated, but, a reasonable approximation can be determined.

Objective	Quantifiable?	Metric
<i>Parcel Efficiency</i>		
Shape	••	Compactness measures
Access to common facilities	•••	Network shortest path
Parcel access	•••	Adjacency to linear features
<i>Spatial Efficiency</i>		
Contiguity	•••	Binary contiguity
Proximity	••	Shortest distance between polygons
Diversity	••	Overlay of maps of cadastre and land types
<i>System Efficiency</i>		
Development	••	Length of road and canals
Retain existing boundaries	••	Length of boundary maintained
<i>Equity</i>		
Communal	••	Change in value of landholdings
Personal	•	—

**Table 4.1** Objectives and Metrics of Land Consolidation. In the 'Quantifiable' column: ••• indicates that the objective can be well represented in a mathematical metric; •• indicates that a surrogate measure is needed; and • indicates non-quantifiable objectives.

However, it is clear that many of the other objectives of consolidation cannot be accurately modelled in mathematical formulae. Most objectives require a surrogate measure to be represented at all. Shape for example, can only be measured as compactness, not as a true comparison to a rectangle.

Many other objectives present the same complexity. Both categories of system efficiency can only be partially represented in a metric. The value of a boundary for habitat or the expense of removing it is not considered in the ratio presented above. Also, economic and social development initiatives are far more complex than simply measuring the length of roads and canals introduced. Other, more political objectives are not represented in these values.

Finally, assessing land relies on the grouping of parcels into categories. A loss of information about the property is unavoidable in this process. Consequently, all of the measures based on this information, such as diversity of land types and equity measures, cannot be completely modelled.

It is apparent that much of the information planners are provided with is subject to uncertainty and bias. However, each objective remains important in consolidation schemes to varying degrees. Despite their inherent ambiguity, consolidation planners need to recognize that several objectives exist, and be prepared to determine the relative importance of each. Planners must make these decisions because many of the above objectives are in conflict with one another. For instance, it is impossible to create regular, rectangular parcels and maintain the existing, erratic parcel boundaries. It is also impossible to amalgamate every farmer's holdings into one parcel while maintaining ecological diversity and meeting strict equity requirements.

Several other spatial problems must contend with many of the same complications because they also contain many complex and non-commensurate objectives. Some of these problems are directly comparable to land consolidation. The next section examines these problems for similarities and potential solution techniques.

## **SIMILAR PROBLEMS**

Many of the objectives of consolidation, such as shape, contiguity, and equity constraints are common to other spatial assignment problems. Political districting, land use zoning, site selection and school assignment all entail the assignment of land to different uses or locations. This section examines these problems to determine the applicability of their solution algorithms to consolidation. The objectives of each problem are explained and compared to consolidation. Then, various solution procedures are described.

### **Political Districting**

Political districting is the creation of areas to be used as the units for a plurality election. In order to preserve the concept of one person - one vote, each district should contain the same population (Gudgin and Taylor, 1979).

Districts should be contiguous and compact in shape to reduce — or at least appear to reduce — gerrymandering. District boundaries also should follow natural

physical and social boundaries (Morrill, 1981). This allows planners to give a district a name that immediately indicates its location and extent.

One final practical aspect is that most political districting implementations are in fact redistricting. Districts with incumbents already exist. To be acceptable to the political establishment, changes to the existing districts must be minimal.

To address the above objectives, several algorithms have been presented. While some researchers have used location-allocation techniques (Morrill, 1976; Robertson, 1982) or argued that regionalization procedures are more appropriate (Morrill, 1991; Plane, 1982), most districting algorithms are region building heuristics (Bourjolly *et al.*, 1981; Craig, 1977; Hess *et al.*, 1965; Johnston and Rossiter, 1983; Kaiser, 1967; Sammons, 1978). All treat the problem as one of combining smaller electoral polls (or other similar spatial unit) into larger districts.

One of the first approaches to the problem was an implicit enumeration algorithm (Garfinkel and Nemhauser, 1970; Shephard and Jenkins, 1970). First, several individual districts are created that meet compactness, contiguity and size constraints. Next, these districts are combined so that every poll is in one and only one district. While this approach can create desirable districts for a very small problem, the problem soon becomes intractable as the problem increases to a practical size (Gudgin and Taylor, 1979; Nygreen, 1988).

Because of the size and mathematical complexity of the problem, heuristics are popular. The exchange heuristic implicitly recognizes the importance of the existing districts (Cope, 1971; Taylor, 1973). It starts with the existing districts as an initial solution and iteratively improves the configuration through a series of trades. A polling area is traded from one district to another in exchange for another poll. Exchanges are evaluated on their incremental improvement to district shape and population distribution. The procedure is relatively simple for one-to-one exchanges. However, local optima are often encountered without more extensive transactions involving several polls and more than two districts. The complexity of these types of trades limits these algorithms to small problems or limited improvements.

Johnston and Rossiter (1983) adapted Openshaw's (1977) region building algorithm to political districting. The algorithm seeks to combine polls into contiguous districts so that the average variance from equal districts is minimized. Starting polls are

determined randomly. The algorithm then builds districts by randomly adding adjacent polls to the starting poll until the district has reached a maximum population. The program proceeds to the next district once the district is completed. Compactness, if considered at all, must be measured after creation of districts has concluded (Johnston and Rossiter, 1983). Maintaining ties to existing districts is not an objective in this approach.

If approached as a region building problem, political districting has potential for land consolidation. Both are concerned with amalgamating smaller spatial units into larger districts. Size, contiguity, and shape of the districts created are important in each problem. However, in political districting, contiguity is treated as an absolute constraint. A district cannot be composed of two discrete areas. However, only in rare cases does consolidation result in one contiguous farm for all farmers. The creation of non-contiguous districts adds considerable complexity to the problem. Therefore, while the region building approach may form a basis for a consolidation algorithm, substantial changes and additions are necessary.

### **Land Use Zoning**

Land use zoning entails the assignment of permitted land uses and regulations to discrete parcels of land. Enumerating and quantifying the generic objectives for the very domain specific and subjective task of developing a land use zoning scheme is not probable.

In response to the lack of structure to the problem, Davis and Grant (1987) present a knowledge-based assignment approach, where municipal planners enter formal rules they feel should be followed in zoning. For example,

Assign pig keeping to 'as of right' category if current zoning is rural.

Exclude pig keeping from the 'as of right' category if distance to town is less than 5 km and effluent disposal capability is low. (Davis and Grant, 1987: 60).

Once the knowledge-base is completed, the algorithm successively assigns zoning to each parcel until all parcels are designated. The order of assignment is not important because no zone assignment is based on an assignment elsewhere. For instance, a specific rule cannot be entered to exclude pig keeping from being conducted next to a

currently vacant area zoned for residential use. Proximity, adjacency and other spatial relationships between zones are not included in the algorithm for two reasons. Firstly, formalizing spatial relationships such as this can be difficult. Secondly, if completed, the order of assignment becomes very important. Is the pig farming or the residential use assigned first? One will preclude the other.

Davis and Grant's rule-based assignment has potential for land consolidation. However, in consolidation spatial relationships are of the utmost importance, and these are difficult to formalize into generic rules. No simple rule is available to control the order of assignments, which would then be so influential in the procedure.

### **Polygonal Site Selection**

The polygonal site selection problem is the determination of the polygonal areas to form the site for a development initiative. It contains all of the objectives of point specific site selection plus the added concerns of specifying the size and shape of the site. All research to date approaches the problem as one of specifying which smaller spatial units should be aggregated to form the desired site (Diamond and Wright, 1988; Gilbert *et al.*, 1985; Wright *et al.*, 1983).

Gilbert *et al.* (1985) consider the objectives of cost, proximity to positive and negative land features, and the shape of the parcel. The model is based on a regular square grid. Associated with each grid cell is a cost of purchase and development, and a distance to specific existing amenities and detractors (for instance, in locating a residential community, lakes and industrial parks are amenities and detractors, respectively). Shape is measured as a ratio of the parcel's diameter and perimeter<sup>2</sup>. This implies that a compact shape is the best shape to acquire.

Solutions are determined by dividing the problem into four sub-problems; one for each objective. The model determines an initial non-inferior solution. At that point the user decides which objectives he or she would like to improve, and which objective must yield. The two remaining objectives are prevented from deteriorating. The user evaluates the new solution and re-specifies preferences. This continues interactively until the user is satisfied with the solution. Unfortunately, solution times of each iteration are

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<sup>2</sup>See MacEachren (1985) for a discussion of the problems associated with this type of shape measure.

too long to make this approach applicable to a realistic problem (although as digital processing becomes more powerful, future systems may make this approach practical).

A model developed by Wright *et al.* (1983) considers the site's shape, area, and economic costs and attributes. A regular square lattice is also used in their approach. The area of the parcel is assumed to be fixed beforehand as a set number of cells. Therefore, the problem is reduced to two objectives: shape and net costs, and can be formulated as:

$$\min Z = (Z_1, Z_2) \quad (4.5)$$

where:

$$Z_1 = \sum_{i=1}^n C_i x_i \quad (4.6)$$

$$Z_2 = \sum_{i=1}^n \sum_{j \in T_i} S_{ij} (p_{ij} + n_{ij}) \quad (4.7)$$

subject to:

$$\sum_{i=1}^n x_i = M \quad (4.8)$$

$$x_i - x_j - p_{ij} + n_{ij} = 0 \quad \forall i, j \in T_i \quad (4.9)$$

$$x_i, p_{ij}, n_{ij} \in \{0, 1\} \quad (4.10)$$

where:

$i$  is an index to land cells;

$x_i = 1$ , if cell  $i$  is acquired, 0 otherwise;

$S_{ij}$  is the length of border between cells  $i$  and  $j$ ;

$C_i$  is the cost of acquiring cell  $i$ ;

$n$  is the number of cells in the feasible area;

$T_i$  is the set of cells adjacent to cell  $i$ ;

$p_{ij} = 1$ , if  $x_i = 1$  and  $x_j = 0$ , 0 otherwise;

$n_{ij} = 1$ , if  $x_i = 0$  and  $x_j = 1$ , 0 otherwise; and,

$M$  is the number of cells to be acquired.

The ideal shape for the site again is assumed to be the most compact. A surrogate objective for compactness is to minimize the length of the external border of the parcel.

Wright *et al.* present a specialized integer programming algorithm that relies on the characteristics of the regular grid. The algorithm proved able to determine the non-inferior solution set for problems composed of thirty cells.

While multiobjective polygonal site selection has a basic similarity to land consolidation — specifying sites of proper shape and location — it is unlikely that any proposed solution algorithms are applicable. Land consolidation is much more complicated. In consolidation planners must solve the site selection problem for every farmer, and must create sites that coexist so that parcels do not overlap. Holdings do not have to be composed of one contiguous parcel, and thus, proximity is complicated.

The solution approach of Wright *et al.* is not adaptable. They, along with Davis and Grant, assume parcels are amalgamated from a regular square lattice. Wright *et al.* were able to solve problems consisting of thirty cells. Researchers argue that any configuration of land can be represented by such a lattice if the cells are made small enough. While this is true, the number of cells needed to represent a complex fragmented landscape accurately would be unmanageable (Burrough, 1986). For data storage reasons alone, raster data structures have been rejected by those currently using GIS for consolidation (Goh, 1991). Manipulating a raster data set of such a size in an integer programming model would thus be infeasible.

### **School Assignment**

School districting is the process of assigning students to attend existing schools. The basis of the problem is to minimize the distance students travel to school while respecting the capacities of the schools. The problem is usually complex because the locations and capacities of the schools do not enable all students to attend their nearest school. Thus, districts may be composed of non-contiguous, satellite areas, some of which are distant from the school and served by buses. To reduce bussing costs, administrators seek to maximize contiguity and compactness of the satellite districts.

For computational simplicity and practical implementation, students are usually aggregated to a neighbourhood, street block, or lower order school. If the aggregated units are assumed to be indivisible, the problem becomes integer. If neighbourhoods are envisioned as fields, and schools as the farmers' homes, the similarity to land consolidation is evident.

Through the work of many researchers (Bovet, 1982; Bruno and Andersen, 1982; Greenleaf and Harrison, 1987; Henig and Gerchak, 1986; Molinero, 1988; Sutcliffe and Board, 1986; Sutcliffe *et al.*, 1984), dozens of other objectives of school districting have been identified. Goal programming techniques have often been used to develop solutions optimizing some or all of these objectives. Sutcliffe and Board (1986) present the most comprehensive goal programming model. Their model is able to generate a non-inferior solution for several of the above objectives. However, as mentioned, like land consolidation, school assignments must be integer solutions. Sutcliffe and Board's solution has split assignments, meaning students from the same neighbourhood would have to go to different schools. No procedure is in place to make allocation decisions within neighbourhoods. To create discrete solutions, integer programming techniques have been used. Unfortunately, integer programming problems quickly become intractable as the problem increases in size.

The size of most real world problems, and the lack of a suitable solution procedure for integer programming, necessitates a heuristic solution procedure. Ferland and Guenette (1990) present a heuristically-based SDSS for school assignment. The system is broken into three components. Each component assigns street blocks (neighbourhoods) to schools based on different criteria. The assignment is reflected on a map as it occurs. The user may start and stop any procedure at any time.

The first procedure assigns neighbourhoods that are within walking distance of only one school to that school. The second routine assigns neighbourhoods that are within walking distance of more than one school. The neighbourhood is assigned to its closest school with enough capacity. If no school within walking distance can sustain the neighbourhood's students, capacity constraints are ignored and the neighbourhood is assigned to its closest school.

The final routine assigns students who do not live within walking distance of any school. It assigns neighbourhoods to schools based on adjacency to existing assignments. Capacities are maintained as much as possible. Routines are provided to change each assignment interactively. Tabular information on the results of the change are displayed on a second monitor.

This approach offers many advantages for land consolidation. It presents the interactive algorithmic strategy needed to incorporate the decision maker's preferences

directly. Many of the spatial efficiency objectives of consolidation can be incorporated into the algorithm. If consolidation can be broken down into a set of procedures — as Ferland and Geunette separated the school assignment problem — then one should be able to unite them into a system very similar to that of Ferland and Guenette's.

## CONCLUSIONS

Each of the above problems has similarities to consolidation, and offers potential solution strategies.

Existing attempts to automate land use zoning present little immediate benefits. The lack of spatial relationships in the solution procedure reduces its relevance to consolidation. However, if spatial relationships can be encoded, the knowledge-base approach does offer long-term promise, as it contains the flexibility needed for unstructured problems such as these.

Polygonal site selection also offers little immediate benefit. The reliance of researchers on a regular square lattice to represent the area restricts the problem to theory, despite the algorithmic efficiency. Accurately representing reality in this manner would require an intractably small cell size.

In comparison, region building techniques used in political districting offer more potential for consolidation. This algorithm lends itself to an interactive framework, as the procedure continues cumulatively from initial assignments. However, in the consolidation problem, assignments are not likely to be completely contiguous. Other objectives impede the solution from complete contiguity. Therefore, adjustments to the approach are needed if it is to be applied to consolidation.

The multifarious and unstructured nature of consolidation suggests that an interactive model which incorporates the views of the participants as well as the decision makers is crucial. Planners must be provided with a system that enables them to ensure that the solution is acceptable to both the community and individual farmers. With an adaptation of region-building as the core, the decision support approach to school districting of Ferland and Guenette appears to have potential as an overall framework to provide this interaction.

The next chapter uses these conclusions to develop a model for land consolidation. The model borrows from the above approaches where applicable, but due

to the uniqueness of the problem, is forced to create original approaches for much of the model.

## **Chapter Five**

### **Modelling Consolidation**

This chapter describes the SDSS developed for land consolidation in detail. It justifies the approaches taken to several key steps in the formulation of the model. The first section develops a new conceptual approach to the consolidation problem. The needs of a model of consolidation and the complexity of the problem are described. From this discussion it is apparent that a discrete space approach is necessary if the system is to be operational. An appropriate tessellation strategy is provided. In the third section of the chapter a brief overview of the solution strategy is presented. It describes partitioning the problem into objectives and constraints. Approaches to both of these components are introduced. Section four presents the model in more detail. Communal and personal constraints are formulated to ensure equitable programs. Then, each of the routines used for parcel assignment is described in detail. The chapter concludes by revisiting the objectives outlined in the previous chapter to determine the success of the model in meeting the many objectives of consolidation.

#### **MODEL NEEDS**

To provide an appropriate and comprehensive decision support system for land consolidation the underlying model should:

- be sufficiently automated to produce several alternative solutions in reasonable time;
- be able to consider as many of the structured objectives set out in Chapter Four as possible;

- account for unstructured objectives by enabling the decision maker to interact with the solution process as it is derived;
- provide sufficient flexibility so that it can be used in different consolidation programs with highly variable amounts and types of information and objectives;
- be able to produce more equitable solutions by better representing land value through the retention of the innate attributes of a parcel; and,
- provide a mechanism for the direct input of participants' preferences, without resulting in an unmanageable hindrance to planners.

Accomplishing the above goals is a challenge. First, many of the structured objectives enumerated in Chapter Four are highly complex by themselves. They require mathematical solutions to problems that have eluded researchers for many years. For example, the time and demand variable travelling salesmen problem that farmers solve every time they visit their fields is extremely difficult to formalize into a generic solution algorithm (Keller, 1985).

In addition, automatic solution approaches are unlikely to be responsive to interactive procedures or realistic problem complexity. Combinatorial algorithms are most effective when applied to problems with a few, very well defined objectives (Scott, 1971). Not only does the consolidation problem require many objectives, but several of them are highly unstructured. To be considered, these objectives must be incorporated into the solution through external input. Therefore, in addition to solving for several complex structured objectives, algorithms for consolidation have the added burden of user interaction.

Finally, providing a comprehensive generic solution algorithm for a problem as significant and diverse as land consolidation is problematic. While the underlying definition of consolidation is constant, the implementation of programs varies substantially. Different applications have different data availability and system objectives that can substantially change the best solution approach.

Nevertheless, several important improvements to existing consolidation programs can be accomplished by modelling consolidation. The complexity of consolidation is only slightly greater than school assignment. Ferland and Guenette's (1990) decision support approach to school assignment described in Chapter Four was demonstrated to be a

practical success. A similar approach to land consolidation that automates the solution in a way that facilitates user interaction should also be practically beneficial.

To automate the solution procedure in this way the problem must be converted to one that is more computationally amenable. This entails converting consolidation from the traditional continuous space approach to a discrete space problem. Only then can the strength of combinatorial solution approaches be applied. The next section justifies this key change in the approach to consolidation and describes how it can be operationalized.

### **AUTOMATING THE PROCESS THROUGH DISCRETE SPACE**

As explained in Chapter Three, continuous space consolidation has been more prevalent in previous consolidation programs. Its flexibility enables planners to draw better shaped and more aligned parcels, and to incorporate system efficiency objectives more effectively. However, as with other spatial problems, such as location-allocation (Ghosh and Rushton, 1987), corridor selection, and all those described in Chapter Four, continuous space is difficult to operationalize in a formal solution procedure. Accurate storage of continuous space information in a binary format is complicated, if not impossible. Solutions procedures are also complicated by the infinite number of possible solutions. In addition, the problem may be better understood in discrete space. Cadastral information is an inherently disjunctive view of space. Ownership and desire for ownership is conveyed as distinct parcels. A consolidation procedure that operates in the same fashion is therefore better able to communicate with its participants.

The challenge is to develop a tessellation strategy that reduces the consolidation problem to a combinatorial one, but still enables planners to create desirably shaped parcels and meet system objectives. Several possible tessellation strategies exist, beyond using existing parcel boundaries.

Bonner (1987) describes a consolidation scheme in India where a square lattice was overlaid on the landscape (Figure 5.1). Each cell was ascribed a value and then assigned to a prospective farmer. The result is very square parcels. Such an allocation may look good on a map. However, unless the land is very flat and homogeneous, it is unlikely that it reflects true topography. Parcels end up straddling creeks, bluffs, and other boundaries, and roads and canals are forced into impractically straight routes. As

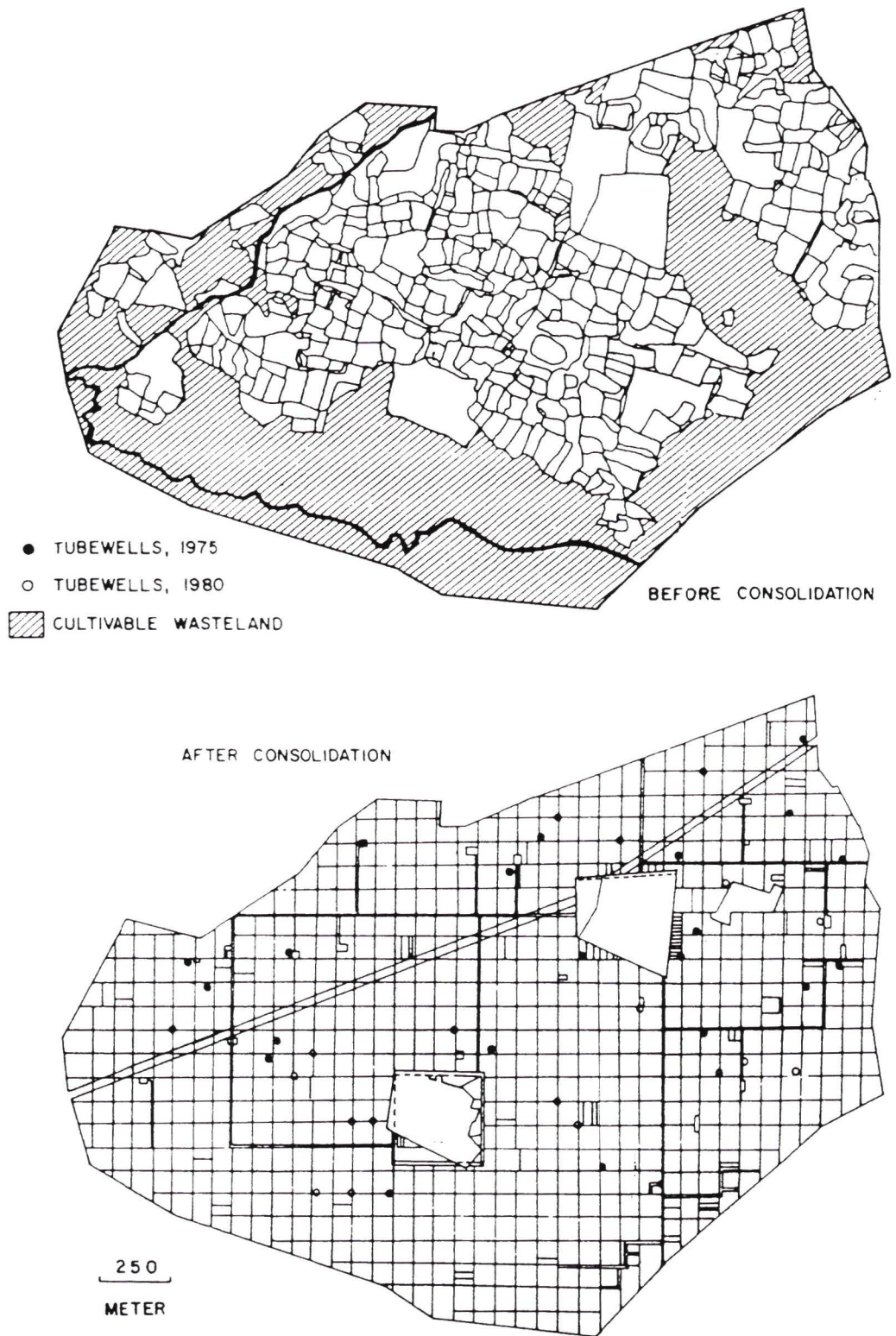


Figure 5.1 A rectangular grid tessellation (Bonner, 1987, 15).

in site selection problems, using a grid fine enough to reflect the landscape accurately results in a dataset of unmanageable size.

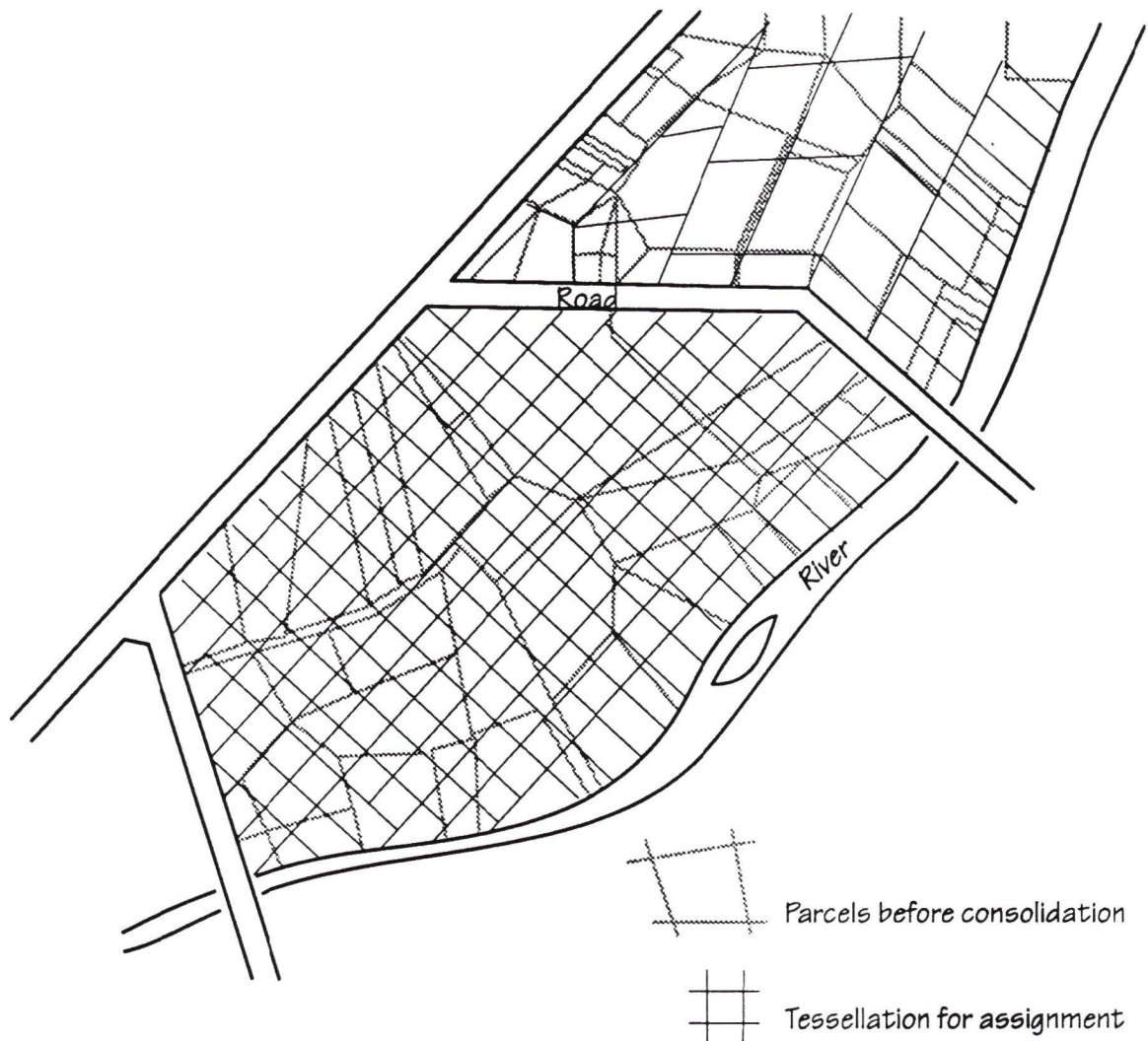
Through the use of GIS, other more sophisticated tessellation strategies are available. Triangulated irregular networks (TIN), for example, divide the landscape into many small triangles. The edges of these triangles more naturally follow physical features than square cell borders. Therefore, while extremely complex, parcels created from a TIN are more likely to match topography (Weibel and Heller, 1991). However, the sharp corners of parcels produced by aggregating TIN facets may be unusable for mechanized farming, and prohibit development of straight roads and canals.

Other generic tessellation strategies, such as a quadtree structure, are also unlikely to meet the needs of consolidation. However, the tessellation does not have to be regular across the study area. An alternative is to use an irregular tessellation specifically designed for land consolidation. Small spatial units that accurately represent the landscape and that will combine into proper fields can be created interactively.

The following interactive procedure is proposed. The first step is to delineate existing parcel dividers, such as rivers, railways, major roads and bluffs. Next, boundaries that will be imposed during consolidation, such as irrigation canals, and new roads are drawn. Within the areas bounded by these features, an irregular lattice is overlaid. This lattice should conform to the terrain, have right angle corners where possible, and be oriented so that when combined, rectangular fields are created. In order to simplify assignments, each cell created should be as homogeneous as possible. See Figure 5.2 for an example.

The actual size of the cells will depend on the size of the fields to be created, the amount of flexibility desired, and the size of largest manageable dataset. Smaller cells will enable fields of more exact specifications to be created. However, storage of the information and creation of parcels becomes more unmanageable as the cell size decreases.

The spatial units created by the tessellation need to be valued for each attribute used in determining farmers' original wealth. In some cases this may require reassessing each parcel individually. However, if land is valued in a continuous space approach (see Chapter Three), valuation of the new parcels can be accomplished through overlays. This approach makes the same assumptions inherent in the original valuation. Planners ought



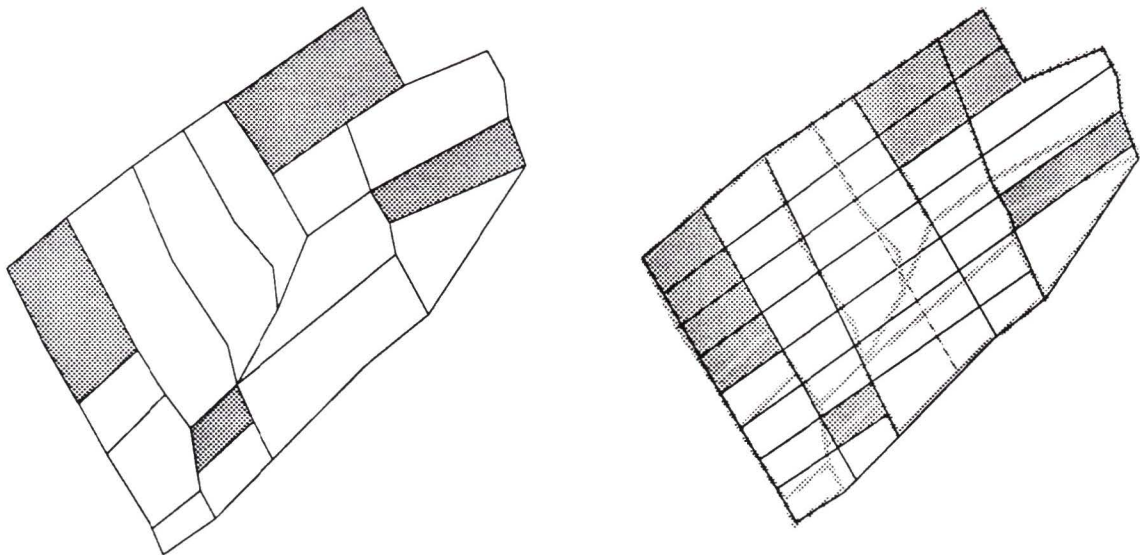
**Figure 5.2** The interactive tessellation strategy requires the user to specify discrete cells to form the basis for assignment. In this example, the pattern in the left portion is simply a grid oriented at right angles to the one road. In comparison, the tessellation on the right side of the road respects the original parcels more, and encourages access to the river; however, more irregularly shaped parcels will be created.

to be aware of the possible errors introduced.

One complication associated with using a tessellation other than the existing parcels is specifying farmers' preferences for retaining parcels. With an interactive tessellation, a farmer's preferred parcel may no longer exist. The land is still there of course, but the boundaries defining the area are different.

Two approaches can be used to retain this preference measure. First, farmers may select parcels they wish to retain from the existing parcel tessellation. Any parcel to be retained must be evident in subsequent tessellations. This approach ensures that preferred parcels are untouched. However, the planners' ability to create well shaped parcels is restricted.

An alternative approach is to reassign original ownership of the new parcels based on ownership before consolidation. Farmers are granted a parcel if they own the largest percentage of it. Figure 5.3 illustrates how this would be calculated. From the set of new parcels reassigned to them, farmers are allowed to select those they wish to retain. Because of the generalization introduced, two restraints should be placed on this reassignment. First, this process may result in farmers acquiring new land. Therefore, the new parcels should only be used for parcel retention, not initial evaluation. Also, to maintain equity, the value of the parcels farmers elect to retain should not be greater than their original holdings.



Ownership with original  
parcel boundaries

Ownership with new tessellation

**Figure 5.3** Ownership of the parcels created by the new tessellation can be determined by allotting a parcel to the farmer that previously owned the largest portion of its area.

Each area slated for consolidation warrants a different tessellation strategy. Although an irregular grid is probably the most applicable, any of the above methods may be appropriate for a given area. Consequently, a solution algorithm ought to be tessellation independent. To reflect this independence, the building blocks of the consolidation, whether existing parcels or a new interactive tessellation, will continue to be termed parcels, as well as cells.

## MODEL OVERVIEW

Once formulated as a discrete space problem, a solution approach becomes much clearer. The problem now can be solved using the solution strategies of the similar spatial assignment problems described in the previous chapter. In solving those problems researchers assigned spatial units to different uses based on different rules. The spatial units remain constant throughout the process. This approach can be adapted to discrete space consolidation. The overall concept starts with farmers not owning any land. Parcels of land are then assigned to individual farmers using one of several routines. Each routine is composed of different objectives and constraints.

In general, constraints of the model ensure that solutions are equitable, from both the perspective of the community and individual farmers. Structured objectives form the basis for decisions made by assignment routines. Unstructured objectives are managed through interaction with the decision maker. Each of these components will be described briefly.

Two forms of equity constraint are present. *Communal equity* is maintained by constraints on each land attribute. Planners specify tolerances for each attribute, so that farmers receive land with a total value near their original holdings in every attribute.

*Personal equity* is also maintained through constraints. Farmers are surveyed before any assignments have taken place to determine which parcels they wish to retain, and, of the parcels they do not own, which they wish to acquire. A constraint is established that, at least initially, no farmer should receive a parcel that he or she did not specify in his or her list of desired parcels.

Once the solution space has been constrained by the above measures, five routines are available to automatically assign parcels to farmers. Each routine acts on a different sub-problem of consolidation:

- *Reassign* re-allocates parcels back to their original owner because he or she wanted to retain it;
- For parcels that no farmer wants to acquire, *Unwanted* reassigns those parcels to their original owner;
- *Uncontested* identifies parcels only wanted by one farmer. That farmer is allotted the parcel;
- *Adjacency* assigns parcels to the farmer owning the contiguous parcel with the longest common boundary; and,
- *Deficit* allocates a parcel to the farmer with the largest deficit in a chosen attribute.

It is expected that the routines would be run in the following order: *Reassign*, *Unwanted*, *Uncontested*, *Adjacency*, and *Deficit*. However, users are able to use routines in any order they choose with two restrictions. The first three routines can only be run once. Once all of the parcels meeting the respective criteria are assigned to a farmer no additional parcels will meet either criteria without a change in the parcels farmers wish to acquire.

The second restriction is that the *Adjacency* procedure must have some assignments already present before it is useful. Only farmers who already have been assigned a parcel will own a contiguous parcel and can therefore acquire another through the *Adjacency* procedure.

To provide more flexibility, the user can interrupt each routine at any time. Unless interrupted, each routine continues until all applicable parcels have been assigned. The independence of the routines enables users to develop their own solution procedures. The interactive process continues until all parcels have been assigned and planners are satisfied with the solution.

A more detailed description of each these components of the model, including the rationale for each objective and constraint used, follows.

## EQUITY CONSTRAINTS IN DETAIL

This section describes the equity constraints of the model in detail. Communal equity issues are considered before personal equity.

### **Communal Equity**

The first step in any consolidation program is to determine the ownership or rights, and the cadaster of each parcel of land. Only when these tasks are completed can planners assess the need for consolidation and determine the relative status of each participant.

In order to receive equal value from consolidation, each parcel must be assessed. Currently, planners determine this value by collecting information on the parcel's soil capability, slope, accessibility, facilities, etc. A value per areal unit is set for each attribute and a parcel assessment calculated.

However, as noted in Chapter Three, assigning a single figure that reflects the many characteristics of a parcel is problematic. By placing a per unit value on several non-commensurate measures, planners are in effect weighting attributes by importance. For example, assume there are two parcels of land. Both are identical (including area), except one is class III land and five kilometres from town, and the other is class II and fifteen kilometres from town. If planners assign both of these parcels the same value, they are equating ten kilometres of distance with the difference between class II and class III land. Much of the trade-off inherent in allocating parcels is internalized in this procedure. Planners are able to justify their plans to farmers by noting that they received land worth the same, in monetary terms, as they relinquished. However, if farmers' views of the trade-offs between attributes do not directly match those of the planners in all measures, farmers are dissatisfied. The true weighting of attributes is highly variable between farmers and parcels. A preferable method is to be able to determine that a farmer received, for example, land of equal real estate value, slightly poorer soil quality, but much closer to home.

Consequently, one of the goals of the SDSS is to retain parcel attributes in their innate format. Values may stay in their native format if each attribute is treated as an equity constraint. Along with more site specific characteristics, proximity to common facilities can also be formulated as one of these parcel attributes.

In current consolidation schemes a tolerance, usually around five percent, is set on land value. As a result of consolidation with a five percent tolerance, no farmer should receive more than 105 percent or less than 95 percent of his or her original land value. In this model tolerances are set on all attributes, not just land value. No farmer should receive land totalling more or less than the tolerance set for any attribute.

The decisions made by the planners and farmers through their representatives are more explicit in this process. Planners cannot avoid important decisions by relying on a monetary value to hide extreme differences between allotments. The results of these comparisons between attributes are partially manifest by the tolerances they specify on each attribute. Stricter tolerances can be set on more important characteristics, more lenient ones on those less important. For instance, planners may set a tolerance that no farmer will receive acreage more or less than, say, five percent of his or her original holdings. If a tolerance larger than five percent is placed on real estate value, planners are declaring one of two things. Either real estate value cannot be measured with the same accuracy as land area and therefore as strict a tolerance cannot be justified, or, it is of greater importance that land area allotments be more equitable than real estate value.

As a result of consolidation few, if any, farmers are going to benefit in all measures. The important point is that clearer information is available on the effect of consolidation for each farmer, and extreme impacts in any one attribute can be identified and avoided. As the solution is developed, planners may elect to widen tolerances in some traits in order to create a feasible solution. A conscious decision about the importance of attributes, with very direct results, is required to adjust these tolerances.

By representing parcels with several attributes, planners perceptions of a parcel's value are more likely to match those of the communities. However, individual perceptions of value are determined by more factors than can be measured for a parcel in isolation. Farmers' individual perceptions of parcel worth ought to be incorporated directly into the model if their perspectives are to be represented.

### **Incorporating the Participants' Preferences**

The above procedure enables community perspectives on land value to be better incorporated into the solution procedure. However, direct elicitation of the individual preferences is of equal importance. No matter how thoroughly the community's perceptions of parcel value are analyzed, the viewpoints of individuals are still not considered. The challenge is to develop a procedure of incorporating participants' preferences that does not require impractical levels of interaction and can be assimilated easily into a solution procedure.

In existing consolidation plans, direct interaction with farmers is limited. Although communication in fragmented areas is hampered by a lack of suitable technology and the large number of participants, a greater impediment is the shortage of an appropriate method of using their preferences once attained. Existing communication with participants appears to be one of three possible forms. First, farmers may be asked individually which parcels they wish to retain before consolidation. This is usually limited to a maximum area or number of parcels. Second, representatives of the farmers as a whole may interact with planners as the draft solution is being drawn. Finally, farmers are asked to express their opinion of the final consolidation plan. Evaluation of final plans are usually conducted through community representatives as well. No method of incorporating farmers' preferences directly into solution procedures exists. It is logistically impossible to survey all farmers as frequently as needed in the development of a plan. Consequently, some individuals will likely be forced to participate in a consolidation plan with which they had little input and do not approve.

Attaining responses of affected farmers for each individual assignment is not practical. However, using surveys taken before consolidation is also problematic. Methods that seek to allot parcels based solely on which farmer wants a parcel most are limited by the inability to value those preferences. The question is, *how much* does a farmer want a particular parcel? Monetary measures based on willingness to pay approaches are unable to represent a farmer's true preferences (see Sagoff, 1988 for more detail on this argument). A procedure based on ranking parcels cannot compare the preferences of two disparate farmers. Should farmer A be assigned a parcel of land just because he or she ranked it higher in order of preference than another farmer? Other objectives of consolidation are likely to conflict with such a practice.

An alternate approach is to treat preferences as constraints. Two types of information are required from farmers. First, of the parcels they currently own, farmers should list those that they do not want to lose to consolidation. Farmers are often reluctant to participate in a consolidation program because they may lose some of their prized parcels. Allowing them to participate while opting out of some of the consolidation enables them to keep parcels that are not obviously advantageous to planners and that may not be granted in consolidation.

The second preference elicitation entails allowing farmers to list the parcels which they currently do not own, but wish to acquire through consolidation. Farmers group these parcels into categories of desirability. Some parcels may be highly desirable (level one), somewhat desirable (level two), and so on. By default, parcels not included are not desired. Level one parcels form a subset of level two parcels for each farmer.

Assignment of parcels is based on other factors. Personal preference acts as a constraint only. Ideally, farmers should not relinquish a parcel they want to keep, or receive a parcel they do not want. As the solution emerges, many of the parcels highly desired by farmers will be assigned. By successively using lower levels of desire, planners can eventually assign all parcels and still incorporate farmers' preferences as much as possible. This gives planners the information they need to delineate plans more to the liking of participants without imposing impractical methods or restricting their ability to meet other objectives.

The approach is limited in that it does not enable participants to express conditional preferences. For example, a farmer cannot say that he or she wants parcel A if and only if he or she also acquires parcel B.

It is possible to not set a limit on the number of parcels a farmer can 'want'. If routines are run in the expected order, parcels that are desired by only one or no farmers will be assigned first. Of the parcels a farmer desires, he or she is likely to acquire parcels that are not wanted by as many others before more desired parcels are assigned. Therefore, farmers who select all or most parcels as 'wants' are likely to fulfil their equity constraints with land that others do not want. Presumably, these are the less desirable parcels. Consequently, there is little advantage for farmers to select parcels they truly do not want.

This assumes that any uncontested parcels are given to farmers early in the assignment and that farmers are aware of how parcels are to be allotted. If communication of the solution method is not possible or desirable, a maximum and minimum number of parcels — based on the number or value of parcels currently owned — that a farmer can 'want' is advisable. In fact, a minimum number is necessary to ensure that planners are given enough flexibility to fulfil other objectives, beyond satisfying individual wishes. A maximum number ensures that some suggestion of

farmers' preferences is retained. It would be interesting to see if, given the choice, farmers select parcels that would actually result in consolidation.

This approach enables those most affected by consolidation to have direct input into the solution procedure. Their perceptions of parcel worth are therefore better represented. As a result, if planners respect their wishes, farmers are more likely to receive land they feel is valuable. This is accomplished without substantially increasing the complexity or manageability of the process.

### ASSIGNMENT PROCEDURES IN DETAIL

Once planners have assessed each parcel in as many attributes as desired, set tolerances for each attribute, elicited farmers' preferences, and established farmers' original wealth, they can begin assigning parcels. This section describes each of the assignment procedures in detail.

Four types of parcels can be identified based on different combinations of 'wants'. These consist of:

- those retained by farmers;

$$W_{i^0j} = 1 \quad (5.1)$$

- those not wanted by any farmer;

$$\sum_{i=1}^m W_{ij} = 0, \quad W_{i^0j} = 0 \quad (5.2)$$

- those wanted by only one farmer; and,

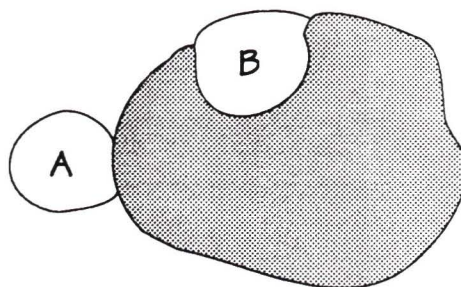
$$\sum_{i=1}^m W_{ij} = 1, \quad W_{i^0j} = 0 \quad (5.3)$$

- those wanted by more than one farmer,

$$\sum_{i=1}^m W_{ij} > 1, \quad W_{i^0j} = 0 \quad (5.4)$$

where  $i^0$  is the farmer owning the parcel before consolidation,  $m$  is the number of participating farmers and  $W_{ij} = 1$  if farmer  $i$  wants parcel  $j$ , 0 otherwise.

Different assignment rules are warranted for each type of parcel. The first three procedures, *Reassign*, *Unwanted*, and *Uncontested*, assign parcels meeting criteria 5.1,



**Figure 5.4** Creating compact shapes using the length of common border. The addition of parcel **B** to the shaded parcel will result in a more compact shape than the addition of **A**. Parcel **B** has a longer common border with the shaded parcel than **A**.

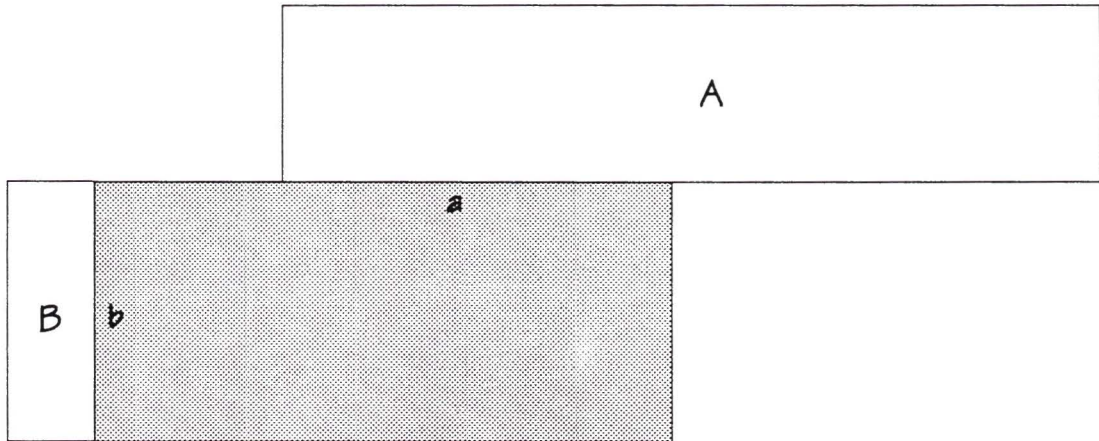
5.2, and 5.3 respectively. The algorithms for these routines are relatively trivial and do not warrant extensive discussion. When more than one farmer wants a particular parcel, assignments are much more complex. Therefore, detailed explanation is focused on the two routines that assign parcels where there is a conflict — *Adjacency* and *Deficit*.

### The Adjacency Procedure

The primary objective of consolidation is to create larger, more compact parcels. To accomplish this objective, parcels must be assigned to encourage equivalent ownership of contiguous parcels. Boundaries between these parcels can then be removed to create one parcel.

The *Adjacency* routine is the manifestation of this rationale. It decides which farmer gets a contested parcel based on contiguous parcels. Disregarding equity constraints for now, of the farmers who want a parcel, the one who owns an adjacent parcel with the longest common boundary acquires it. Taking the parcel with the largest common boundary encourages compact shapes. In Figure 5.4, the combination of the shaded parcel and the parcel with the longest common border (**B**) creates a more compact parcel than the same parcel and parcel **A**.

Common border lengths should be standardized so that large parcels are not unfairly considered first. In Figure 5.5, combining the shaded parcel with **B** results in a more compact parcel than **A** despite the length **a** being longer than **b**. This is because of the larger size of **A**. Therefore, to standardize the common border lengths, each length



**Figure 5.5** Standardized common border lengths. The addition of parcel *B* to the shaded parcel will result in a more compact parcel than *A*, despite *a* being longer than *b*. This relationship can be recognized by noting that ratio of *b* to the perimeter of *B* is greater than *a* to *A*.

is taken as a ratio to the maximum length possible. Now parcel *B* will correctly be preferred to *A*.

The *Adjacency* routine is constrained by the farmers' preferences and equity constraints. An assignment is not considered unless the farmer expressed a desire to acquire the parcel. The addition of the parcel must not place the farmer over his or her tolerance in any attribute. A parcel adjacent to the parcel to be assigned must be owned by the farmer to be considered.

The above conditions can be expressed as follows:

- Let  $L_{jk}$  be the length of the common boundary between parcel  $j$  and  $k$ ;
- A value  $l_{ijk}$  for each farmer  $i$  and each adjacency  $jk$  can be set to 0 if  $X_{ij}$  equals 1 (i.e. the parcel  $j$  is already assigned to farmer  $i$ ), otherwise,

$$l_{ijk} = \frac{X_{ik} W_{ij} L_{jk}}{\sum_{k=1}^n L_{jk}} \quad (5.5)$$

where  $X_{ij} = 1$  if farmer  $i$  receives parcel  $j$ , 0 otherwise, and  $W_{ij}$  as above.

The sum of all  $L_{jk}$  for a parcel will be termed the *perimeter* of  $j$  for brevity. Although, in fact boundaries of parcels which will not be removed through consolidation, such as rivers, are not included in this sum.

With  $l_{ijk}$  established, the sub-problem can be expressed mathematically as:

$$\max z = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n X_{ij} l_{ijk} \quad (5.6)$$

subject to:

$$\sum_{j=1}^n X_{ij} v_j^p \geq (1 - \alpha_-^p) \beta_i^p \quad \forall i, p \quad (5.7)$$

$$\sum_{j=1}^n X_{ij} v_j^p \leq (1 + \alpha_+^p) \beta_i^p \quad \forall i, p \quad (5.8)$$

$$\sum_{i=1}^m X_{ij} = 1 \quad \forall j \quad (5.9)$$

$$X_{ij} \in \{0,1\} \quad (5.10)$$

$$p = 1,2,3,\dots,P \quad (5.11)$$

where in addition to the notation set out above:

$m$  is the number of farmers;

$n$  is the number of parcels to be assigned;

$i$  is an index of farmers;

$j$  and  $k$  are indices of parcels;

$p$  is an index of attributes;

$P$  is the number of attributes;

$v_i^p$  is the value of each parcel in each attribute  $p$ ;

$\beta_i^p$  is the total value owned by farmer  $i$  in each attribute  $p$  before consolidation; and,

$\alpha_+^p$  and  $\alpha_-^p$  are the positive and negative tolerances for each attribute respectively.

Equation (5.6) maximizes contiguity among parcels owned by the same farmer. Equations (5.7) and (5.8) ensure that no one farmer loses more than  $(1 + \alpha_+^p) \beta_i^p$  or gains more than  $(1 - \alpha_-^p) \beta_i^p$  for all  $p$ , respectively. Equation (5.9) ensures that a parcel is allocated to only one farmer.

Solution of the above problem is complicated by the product of integers  $X_{ij}$  and  $X_{ik}$  (included in  $l_{ijk}$ ) in the objective function. The problem can be made linear by removing  $X_{ik}$  from  $l_{ijk}$  and replacing the objective function with:

$$\max Z = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n Y_{ijk} l_{jk} \quad (5.12)$$

and adding two constraints:

$$X_{ij} - Y_{ijk} \geq 0 \quad \forall i, j, k, \quad j \neq k \quad (5.13)$$

$$X_{ik} - Y_{ijk} \geq 0 \quad \forall i, j, k, \quad j \neq k \quad (5.14)$$

where  $Y_{ijk}$  is forced to equal 1 if both parcels  $j$  and  $k$  are assigned to farmer  $i$ , 0 otherwise (Rosing and ReVelle, 1986). However, this formulation adds several additional variables and constraints. While solution times are reduced, determining an exact solution for problems the size of typical consolidation schemes is computationally impractical. Rosing and ReVelle were able to create five clusters from a problem comprising only nineteen parcels in just under eleven hours on a VAX-11/750. Even with substantial improvements in computer processing since 1986, this approach is clearly still inappropriate for a problem consisting of several hundred parcels.

An alternate approach is to use a heuristic algorithm that cumulatively assigns adjacent parcels to farmers until all parcels are assigned. The algorithm proceeds as follows:

1. Determine  $l'_{ijk}$ , the largest  $l_{ijk}$ .
2. If  $l'_{ijk} = 0$ , stop.
3. Assign parcel  $j'$  to farmer  $i'$  if:

$$\sum_{j=1}^n (X_{i'j} v_j^p) + v_{j'}^p \leq (1 + \alpha_+^p) \beta_{i'}^p \quad \forall p \quad (5.15)$$

4. Set  $l_{i'j'k} = 0$  for all  $i$  and  $k$ .
5. Recalculate  $l_{ikj'}$  for all  $k$ , where  $X_{ik} = 0$ .

6. Return to step 1.

Therefore, *ceteris paribus*, a small parcel completely enclosed by another parcel will be assigned before a large parcel with a long common border less than the perimeter of the parcel. Over several assignments, this approach seeks a solution that maximizes the length of boundaries within parcels, and minimizes the length of external boundaries to parcels. This is the surrogate measure for compactness used by Johnston and Rossiter (1983) and Wright *et al.* (1983).

The *Adjacency* algorithm will likely complete the bulk of the assignments. Of the five routines, it alone actually seeks to consolidate parcels. By assigning parcels to the farmer with the longest common border, *Adjacency* attempts to create compact parcels. Parcels are not assigned if contiguity is not possible. The algorithm is similar to Johnston and Rossiter's (1983) approach to political districting. However, *Adjacency* improves on the approach by incorporating compactness directly into the solution algorithm.

### The Deficit Procedure

The *Adjacency* algorithm may not assign all parcels. Some parcels may be completely surrounded by parcels that are now owned by farmers who do not want the remaining parcel. Consequently, another routine is needed. *Deficit* ignores the spatial arrangement of the parcels to concentrate on equity issues. It seeks to minimize the maximum deficit faced by any farmer for a given attribute. Only one attribute can be considered at a time.

The procedure is that of a 'greedy add'; steps that result in the greatest improvement in the objective function are completed first. The routine proceeds as follows:

1. Prompt the user to select an attribute  $p'$ .
2. Find  $i'$ , the farmer with largest value of  $D_{i'}$ , where

$$D_{i'} = \beta_{i'}^{p'} - \sum_{j=1}^n X_{i'j} v_j^{p'} \quad (5.16)$$

3. Find parcel  $j'$ , the parcel that satisfies the following:

$$\min \beta_{i'}^{p'} - \left[ \sum_{j=1}^n (X_{i'j} v_j^{p'}) + v_{j'}^{p'} \right] \quad (5.17)$$

subject to:

$$\sum_{i=1}^n X_{ij'} = 0 \quad (5.18)$$

$$W_{i'j'} = 1 \quad (5.19)$$

4. Assign parcel  $j'$  to farmer  $i'$ .
5. Repeat until,

$$\sum_{i=1}^n X_{ij} = 1 \quad \forall j \quad (5.20)$$

or

$$\sum_{j=1}^m W_{i'j} = 0 \quad (5.21)$$

Constraint 5.18 ensures that parcel  $j'$  is not already assigned. Ensuring that the farmer wants the parcel is accomplished by constraint 5.19. Other equity constraints are not considered. The algorithm proceeds until all parcels are assigned (5.20) or farmer  $i'$  does not want any more parcels (5.21).

The *Deficit* procedure simply assigns a parcel to the farmer with the largest deficit in one attribute. The chances of attaining a feasible solution (one within the equity constraints) is dependent on the number and value of parcels. A few parcels, all worth the same value present much fewer options for assignments. It is then less likely that combinations can be determined that result in all farmers being within their equity constraints.

## CONCLUSIONS

The routines described in this chapter provide a powerful and flexible set of tools for producing land consolidation plans. Collectively, the constraints imposed and the assignment routines account for many of the objectives associated with the consolidation problem. Table 5.1 repeats Table 4.1, but now the algorithmic approach taken for each objective is provided.

The tessellation strategy is an indirect method of respecting several difficult objectives. In this model, new roads and irrigation canals are specified before any assignments occur. Therefore, they can be incorporated into the solution algorithm

<b>Objective</b>	<b>Relevant Model Component</b>
<i>Parcel Efficiency</i> Shape Access to common facilities Parcel access	Adjacency Communal equity constraints Tessellation strategy
<i>Spatial Efficiency</i> Contiguity Proximity Diversity	Adjacency Pre-consolidation survey Communal equity constraints
<i>System Efficiency</i> Development Retain existing boundaries	Tessellation strategy Tessellation strategy
<i>Equity</i> Communal Personal	Communal equity constraints Pre-consolidation survey

**Table 5.1** Objectives and solution approaches to land consolidation.

through the tessellation. The density of these features introduced and the configuration of the cells created, partially determine the potential for parcel access. In the extreme case, if each cell is adjacent to a road, all parcels created from amalgamating those cells will also be adjacent to a road. Similarly, the maintenance of existing boundaries is dependent on the tessellation strategy. A strategy of using the existing parcels will result in all new boundaries coinciding with the old. If the difference between the interactive tessellation and the existing boundaries is great, few existing boundaries will be retained.

Equity objectives are well represented through the stringent constraints imposed on the model. Communal equity objectives are better represented in this model through a series of constraints on each parcel attribute. These same constraints also enable planners to consider access to common facilities and diversity of land types. Both of the latter objectives can be formulated as an attribute of a parcel. The model does not seek to maximize either of the two, but identifies the effects of consolidation and can ensure

that no farmer loses in either objective. Personal perspectives on equity are considered by incorporating a pre-consolidation survey of farmers into the solution process. Planners still implement the farmers' wishes in the way they see fit; however, with this information they are making more informed decisions.

The *Adjacency* routine considers two of the remaining objectives. *Adjacency* seeks to optimize shape and contiguity between parcels. By specifying shape as compactness, and using length of internal boundary as a surrogate measure of compactness, these objectives can be combined into one. This single objective problem can be solved heuristically by assigning parcels based on the length of common boundary.

One objective remains. Specific proximity objectives are simply too complex and require too much farmer-specific information to be properly modelled. Part of this objective may be embodied in the parcels wanted by each farmer. Otherwise, it has to be considered by the decision maker in evaluating plans created by the system.

From this discussion, it appears that all but one objective is considered. However, several of the metrics do not completely represent the objective. A significant portion of the solution is dependent on the tessellation strategy and other subjective steps in the model. Consequently, it is important that the system provide the interactive capabilities necessary to override improper assignments resulting from previous assumptions. The following chapter describes the implementation of the algorithms into a system that furnishes this interactive capability.

## Chapter Six

### Implementing the Model

This chapter describes the implementation of the model into a spatial decision support system. Because of the importance of decision maker interaction in the proposed model, its implementation requires much more than coding the solution algorithm. The system must also provide extensive tools for interaction. This necessitates developing routines for cartographic display, graphical user interface, reports and database management.

Creating advanced routines for these functions from scratch would require an impractical amount of software development. Therefore, a commercial GIS is used as a platform for the SDSS. The spatial interface, display and database of GIS provide an excellent foundation for SDSS development. However, incorporating the analytical procedures needed can be problematic. The first section of this chapter explains these obstacles and describes some existing attempts to overcome them.

Application program interfaces (API) offer a more promising method of integrating spatial analysis into GIS. API provides a powerful and flexible method for skilled programmers to tailor the GIS to meet their needs through the use of standard programming languages. The use of API in implementing the proposed model into a GIS is described in section two.

The third section describes the database developed for this SDSS. Database management is a major component of the model, as all of the routines require frequent database access. Consequently, devising an efficient, comprehensive and flexible database model is vital to the successful operation of the system.

The ability of the system to interact with the user is also a key determinant of the system's effectiveness. The fourth section of the chapter describes how the user interacts with the system.

## **GIS AND SPATIAL ANALYSIS**

As described in Chapter Two, current GIS do not have the spatial analysis functions needed for decision support. While vendors have provided cartographic analysis tools, such as buffering and topological overlay, spatial analysis tools are still lacking. Despite several calls for their provision (Densham and Goodchild, 1989; Fotheringham, 1991; Rhind, 1988), statistical and mathematical tools for analyzing and modelling spatial data, such as spatial optimization, simulation models, and spatial pattern measures, are as yet not well represented in current commercial GIS.

There are two primary reasons for this deficiency. First, vendors of GIS often lack staff with additional expertise in spatial analysis, as well as more typical skills in computer programming and GIS. A greater impediment, however, relates to the very nature of spatial problems. Rarely can these problems be represented in generic formulations. Consequently, spatial solution procedures are likely to be applicable to only a very small set of problems. Therefore, the market for these procedures is often too small for commercial ventures.

Vendors have attempted to overcome these impediments through several strategies. For those problems that can be formulated in a generic solution strategy and have wide application, vendors have provided standard solution routines. For example, a number of GIS offer solution routines for the shortest path problem.

Developers have also created links to external database management systems or statistical analysis packages. These packages provide a wealth of powerful analysis functions. However, they are not oriented towards spatial data. Spatial analysis requires very different set of analytical functions.

A third approach is to provide the user with a modelling language specific to the GIS. Vendors conceptualize and implement a new proprietary language that enables users to create their own analysis procedures. Users sequence commands provided by the vendor into a script that performs the desired function. However, this approach always limits users. Not only does it require substantial development by the vendor, it

compels users to learn a complete programming language, and restricts them to one vendor's language.

### **CODING THE SYSTEM USING AN API<sup>3</sup>**

The above options, although striving for spatial analysis, still do not empower users with a powerful and flexible programming language. To create truly functional analytical modules, users will need to have access to more advanced languages. Application programming interfaces (API) attempt to provide that functionality without requiring too much development by the user. An API consists of a library of routines for specialized functions. These routines are called by and incorporated into programs written in standard programming languages, such as C or Fortran.

An API for GIS consists of routines for managing and displaying spatial and attribute data, and building a user interface. In essence, users of an API are recreating a GIS from its essential elements. However, now developers are free to omit those routines of the GIS that they do not require, and add unsupported routines they need. The analytical functions specific to the problem are likely unsupported. Therefore, while the platform for a system is created using the database management and user interface routines of an API, programmers are free to concentrate on building specialized analytical functions.

At this point in the evolution of GIS, the API concept is still in the 'beta' stage — meaning only a few GIS vendors are testing preliminary versions of an API. These beta releases lack cohesion and complete documentation, and are therefore, difficult to use. Consequently, any use of APIs in their current state presents challenges to the programmer. The format for many routines must be learned through trial and error, and the integration of the routines is not well documented.

Despite these initial deficiencies, the API approach to spatial analysis integration offers tremendous potential. To illustrate this potential, the proposed model was implemented on a PC-type microcomputer using an application program interface for the

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<sup>3</sup>For further details on the potential of API for spatial analysis see Strapp and Keller (1992).

TerraSoft<sup>4</sup> GIS. TerraSoft, by Digital Resource Systems (DRS) is a full featured GIS for the personal computer. DRS will soon release an API compatible with its GIS. Their API offers C language routines to manipulate spatial data directly, build a user-interface containing both graphical and textual screens, and access attribute data contained in an external database management system. In accordance with a British Columbia Science Council grant, DRS provided their API for this project to obtain an independent review of its features.

Using the API reduced the source code needed for the model to less than 2000 lines in 21 source files. Reproducing the code in the thesis would offer little to the reader. Much of the source code is calls to API functions that are not understandable or usable without the TerraSoft API. The source code therefore, has not been included in the thesis, but is available by contacting the Department of Geography.

The completed system consists of an executable file, three TerraSoft system files, data files containing the map and theme information, and several database files. The database is described in detail in the next section.

## **DATABASE MODEL**

Database management is a fundamental component the proposed model. Unfortunately, the TerraSoft API does not supply the necessary database functions for a model of this complexity. For instance, indexing and database relationships are not supported. The TerraSoft GIS translates routines to access attribute data into Code Base<sup>5</sup> API routines. Code Base is a C function library. It replicates dBASE<sup>TM6</sup> commands and enables data to be stored in dBASE compatible databases. Code Base offers more powerful functions for database management than TerraSoft. Therefore, the system manages much of the information in the model with routines written using the Code Base API directly. This illustrates another major advantage of using APIs for software development; programmers are able to use several specialized APIs in concert.

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<sup>4</sup>Digital Resource Systems, Nanaimo, B.C.

<sup>5</sup>Sequiter Software Inc., Edmonton, Alberta

<sup>6</sup>Borland International Inc.

In order to store and manage the information necessary for the model, a database must be established and furnished with the necessary data. The SDSS contains seven tables: *Topo*, *Farmers*, *Parcels*, *Values*, *Equity*, *Wants*, and *Sums*. The tables were integrated into a network database containing all the necessary information for the system (Figure 6.1). Each table is constructed to store a different component of the dataset.

Some of the information needed must be extracted from the internal TerraSoft database manager. For instance, TerraSoft stores topology for every arc in the system. One common boundary between two parcels may be composed of several arcs. Therefore, determining all adjacent parcels can be a time consuming operation as the program has to process all the arcs that make up the polygon. This needs to be accomplished several times in the model. To improve this query, topological data were extracted from the TerraSoft, reformatted and stored in dBASE files. A table called *Topo* was created with one row for each adjacent parcel of every parcel. A third column contains the length of the common border between the two parcels as a ratio of the parcel's perimeter i.e.

$$\frac{L_{jk}}{\sum_{k=1}^m L_{jk}} \quad (6.1)$$

The *Farmers* table lists the name of every farmer. Unknown to the user, the system gives each farmer a number. This number is used to identify farmers in all other tables. Users assign each farmer a colour, shading pattern and shading spacing. These patterns give each farmer a unique graphical identifier. After background and property lines are considered, fourteen colours remain. Combining these colours with the six shading patterns supported by TerraSoft creates eighty-four possible different graphical identifiers. This can be augmented by including different spacing widths. Assignments are displayed by shading parcels with the graphical identifier of the farmer receiving the parcel. An unassigned parcel is filled with solid black. Therefore, provided with a graphical legend and reasonable number of farmers, users can very quickly identify which parcels have been assigned to which farmers.

In the *Parcels* table each parcel comprises a row. Parcels are known to the user by the label, but given numbers by the system. A binary column indicates whether the

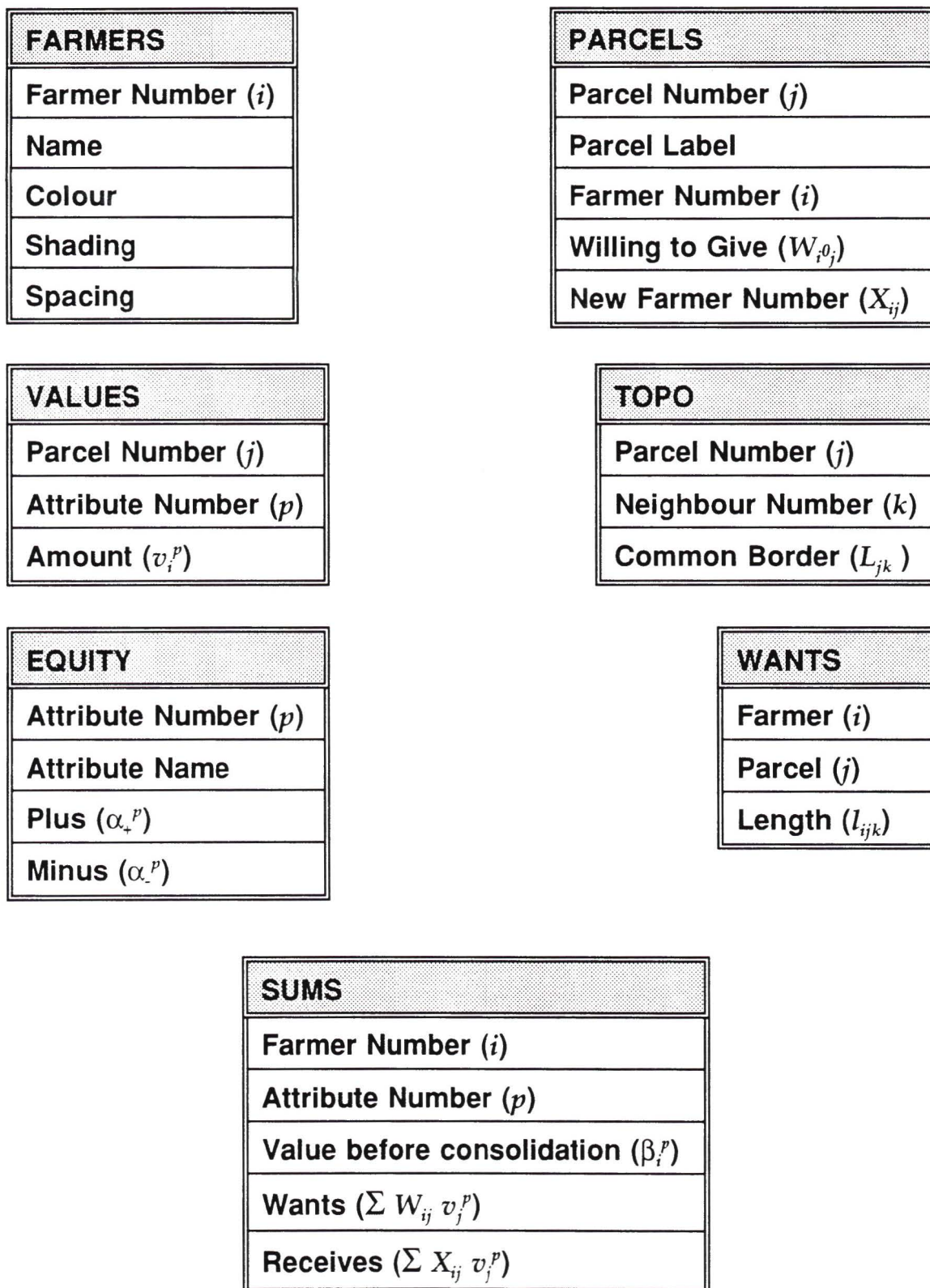


Figure 6.1 Database model for the SDSS

original owner requested to keep the parcel or not. Two other columns indicate the owner before and after consolidation by farmer numbers. The assignment of a parcel to a farmer is stored by entering the farmer's number into the new farmer column. Finally, the numbers used by TerraSoft to identify polygons are included in the table. The TerraSoft numbers are used to more quickly retrieve a parcel from the internal spatial database so that it can be shaded. These numbers must be extracted from TerraSoft through a custom program.

Different consolidation programs will have a different number of attributes. To allow the system to manage a variable number of attributes the *Values* table is carefully constructed. It consists of three columns: parcel number ( $i$ ), attribute number ( $p$ ) and value ( $v_i^p$ ). Each row in the table contains the value for one parcel in one attribute. Additional attributes can be added to the model by simply appending rows. No changes to the structure of the table are required.

Attribute names are referenced in the *Equity* table. One row in the equity table is required for every attribute being considered. Additional columns in *Equity* contain the tolerances for each attribute ( $\alpha_+^p$  and  $\alpha_-^p$ ).

The preferences of farmers are stored in the *Wants* table. For an individual farmer, the parcels they wish to acquire are listed ( $W_{ij} = 1$ ). A third column contains  $L_{ijk}$ . The value of  $L_{ijk}$  will be zero for parcel-farmer combinations not in the *Wants* table because  $W_{ij}$  equals zero.

The final table is *Sums*. *Sums* provides a sub-total for every farmer in every attribute. Information is collected on the value of land owned before consolidation ( $\beta_i^p$ ), and the sum of the values of parcels acquired by each farmer through consolidation is calculated after each parcel assignment.

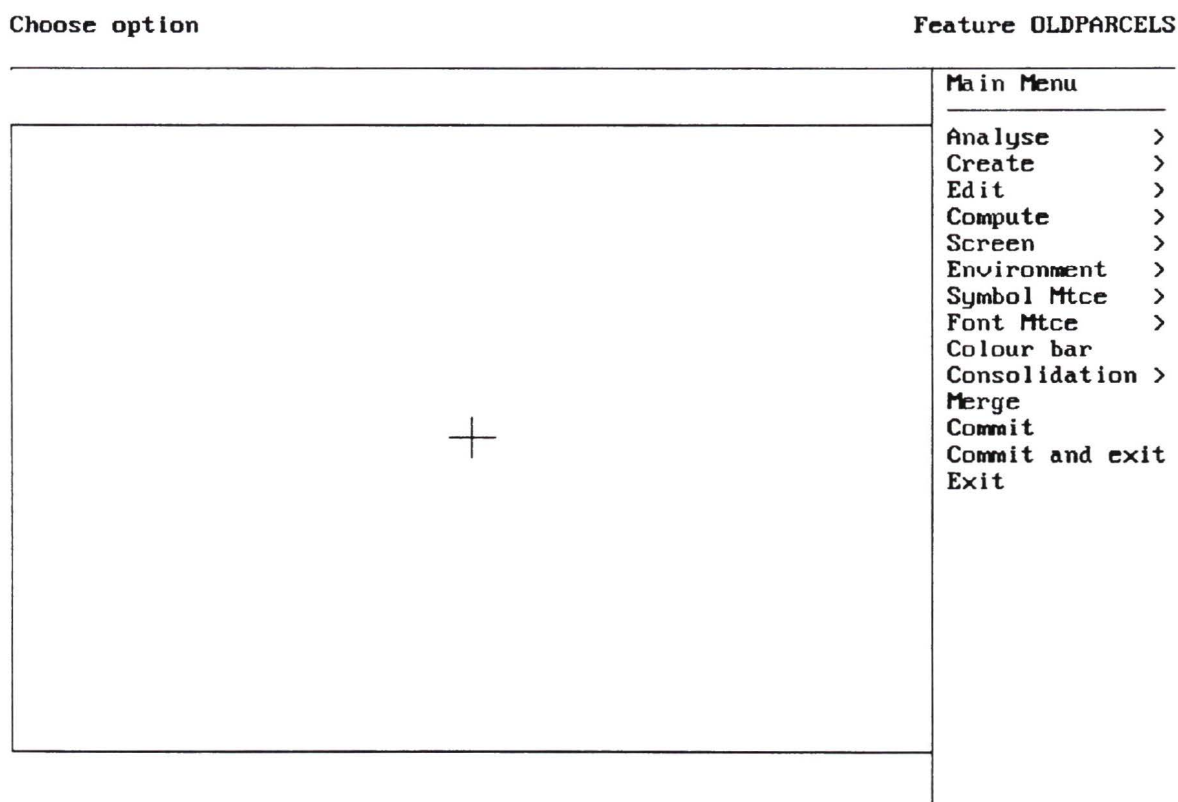
Storing the information as above has several advantages. First, several different reports can be produced from the same database. Relationships between tables can be established to provide all of the necessary information. Second, using a standard storage format allows the use of third-party software packages for generating reports, graphing the data and writing custom programs. Several software packages exist that access dBASE format databases. Finally, the database has the flexibility to adapt to a different number of attributes without changing table structures. Changing the number of attributes only requires changing the number of rows in the *Values*, *Equity* and *Sums*

tables. Changes of this nature can be accomplished much more easily than changes to the columnar structure of the table.

Once the necessary information has been entered directly into the above tables or extracted from information entered into TerraSoft, planners are ready to run the program.

## RUNNING THE SYSTEM

Upon loading the program the user is presented with a graphical screen comprised largely of a map, topped by two lines for messages, and bounded on the right side by a menu of items (Figure 6.2). Users specify locations on the map and select menu items by using a mouse or digitizer puck. *Consolidation* has been added as a sub-menu onto the standard TerraSoft main menu. All other functions of TerraSoft are also available to users. These functions enable users to create, edit, analyze and output maps using standard GIS functions. All of the data management components of a GIS, so valuable in consolidation, are maintained through this integration. However, now with the consolidation routines added, the system can also directly assist in developing solutions.



**Figure 6.2** Main TerraSoft graphics screen with Consolidation added to the menu on the right.

The *Consolidation* sub-menu consists of eighteen commands (Figure 6.3). The first, *Select Theme*, is a TerraSoft command to specify which cartographic features combine to create the parcel polygons. For example, existing parcels are likely composed of features such as river banks, roads, and property lines. Users need to create themes within TerraSoft. Once they select the theme for the land parcels, they are free to run the other routines at any time. Each of the five procedures outlined in chapter five: *Reassign*, *Unwanted*, *Uncontested*, *Adjacency*, and *Deficit*, is present in the menu, as are standard TerraSoft utilities to zoom in and out of an area, redraw the screen, and display specific features.

Choose option	Feature OLDPARCELS
	<b>Consolidation</b>
	<b>Select theme</b>
	<b>Query Before</b>
	<b>Query After</b>
	<b>Reset</b>
	<b>Reassign</b>
	<b>Unwanted</b>
	<b>Uncontested</b>
	<b>Adjacency</b>
	<b>Deficit</b>
	<b>Direct</b>
	<b>Reshade Parcels</b>
	<b>Redraw Parcels</b>
	<b>Redraw screen</b>
	<b>Window</b>
	<b>Draw features</b>
	<b>Entire map</b>
	<b>Use key map</b>
<b>Return to Terra</b>	

**Figure 6.3** The Consolidation main menu

In addition, four application specific routines are provided. *Reset* clears all assignments, and sets all  $I_{ijk}$  to zero. The screen is then redrawn without any parcels shaded. Two standard queries — *Query Before* and *Query After* — shade the parcels owned by a specified farmer before and after consolidation, respectively. *Query Before*

Direct Assignment of Parcel			
Parcel: 113		Original Owner: Juan Antonio Sanchez	
# Attribute	Value	Upper %	Lower %
1. Composite land value	100.4	10.0	10.0
2. Class I ha	34.1	5.0	5.0
3. Class II ha	12.1	5.0	5.0
4. Total distance from home	8.2	25.0	999.9
Assigned To: Antonio Fernandez			
	Originally	Tolerance	vs. Assigned Parcel
1.	1539.4	- 1385.5	440.1 - 339.7 *
2.	342.2	325.1	365.4 331.3
3.	14.4	13.7	12.2 0.1
4.	87.3	0.0	44.3 36.1 *
Change To: Jorge Bell			
1.	2012.4	+ 2213.6	1930.4 + 2030.8
2.	554.1	581.8	574.2 608.3 *
3.	640.1	672.1	340.4 352.5
4.	143.2	179.0	104.2 112.4
Cntl End - Save and Exit; Esc - Abort; Enter - Change Assignment			

**Figure 6.4** Tabular data presented for the *Direct* routine. The owner of parcel 113 before consolidation was Juan Sanchez. Previous routines have assigned the parcel to Antonio Fernandez. If the parcel is taken from Fernandez and assigned to Jorge Bell, Fernandez will no longer be allotted his minimum quota in two of the attributes, and Bell will exceed his maximum quota in a Class I land (attribute 2).

also shades the parcels wanted by the farmer. Users can create custom queries through the TerraSoft *Query* command.

In order to offer the user more immediate control over the assignments another routine was added. *Direct* asks the user to select a parcel by pointing at it with the mouse or digitizer puck. The parcel selected is determined through a point-in-polygon routine provided in the TerraSoft API. The screen clears, and tabular information about the selected parcel is presented (Figure 6.4). The user is provided with information about the value of the parcel in each attribute, the original owner before consolidation, and the owner to which the parcel is currently assigned. By pressing the 'Enter' key the user is able to select a farmer from a pick-list. Included in this list is an option to 'unassign' a parcel. Information about the result of assigning the parcel to the farmer chosen is presented in the bottom portion of the screen. The user may then choose to abort the procedure and leave the parcel as is, assign the parcel to the new farmer, or select

another farmer. Once the user selects a farmer or aborts the routine, the system clears the tabular information and the map and menu reappear. Any changes to the assignment are then reflected in changes to the shading of the parcel.

## CONCLUSIONS

These functions form the core of a spatial decision support system for land consolidation. To comprise a full decision support system, additional queries and reports would have to be included. Development of these components of the system would involve no more than simple database management programming with little algorithmic complexity. Therefore, they are not considered an important element of the research.

The system created is a fully functional decision support system. Users are able to initiate assignment routines, monitor their progress, stop the procedure, and change inputs, execute another routine, or continue. Users can accomplish all of this within a 'user-friendly', graphical user interface.

The use of the TerraSoft and Code Base APIs greatly facilitated development of the SDSS. Creation of such a robust and advanced systems as this would not have been possible in a reasonable time frame without them. API offers tremendous potential for the advancement of GIS. New applications and users of GIS are likely to appear as GIS are customized to meet their needs using an API. Despite the very immature status of APIs for GIS, this implementation provides an illustration of its potential.

The next step in development of such a system for consolidation is thorough testing of the routines and evaluation of the solution algorithms. The following chapter describes the testing procedure in detail.

## **Chapter Seven**

### **Evaluating the Model**

This thesis concentrates on the conceptualization and implementation of a model of agricultural land consolidation. For reasons that will become apparent in this chapter, a comprehensive evaluation of the system is beyond the scope of the project. Nevertheless, the performance of the system can be assessed against certain criteria.

The first section of the chapter examines the general issues in evaluating a decision support system, including the inherent difficulty in establishing the evaluation criteria and methods of conducting evaluation.

The second section evaluates the proposed system using concepts from the first section. Evaluation was aided by sample data from a recent consolidation project in Spain. These data were used as a base to examine the algorithmic validity, user interaction, and practical considerations of the system. While evaluated on a project from Spain, it is important to note that the system was intended to be useful in any program that meets the consolidation definition.

#### **EVALUATING A DSS**

There are two steps to evaluating a DSS. First, reviewers must determine the appropriate evaluation criteria. Once criteria have been established, they must develop a method of assessing the system against these criteria. This section explores both of these stages in DSS evaluation in detail.

## Evaluation Criteria

Assessing the effectiveness of a decision support system is made difficult by the very nature of the problem they are to solve. As Keen and Scott Morton note:

a DSS is designed to address a relatively unstructured problem with — by definition — no clear criteria for assessing performance or definition of *exactly* how the decision is to be supported (Keen and Scott Morton, 1978: 214).

Therefore, unlike the case of pure optimization models, generic, quantitative criteria for evaluating a DSS cannot be established. Standard tests of the system's algorithmic efficiency and execution time are not more important than the effect of the system on the decision making process. In other words, one DSS is not 'better' than another simply because it produces a solution faster, or one that is closer to the defined optimum. The true effect of the system in supporting decision makers must be evaluated more directly.

Additional complexity is created by the variability of DSS. The benefits of a DSS are different for different applications. One set of criteria useful for a particular problem are not necessarily applicable to another problem. Even within the same problem category, implementation differences may require a different set of evaluation criteria. Consequently, developing criteria that are applicable to all systems is unlikely.

The evolutionary nature of DSS is another concern. A DSS continues to mature over time, and thus lacks clear completion dates. Therefore, is it unclear at what point in its evolution a system should be evaluated.

Because of the uniqueness of each DSS, each warrants a different set of standards. Nevertheless, to standardize DSS evaluation, generic categories of evaluation criteria can be established. Based on Adelman (1982) and Armstrong *et al.* (1990), three categories of criteria were identified:

- algorithmic validity;
- human factors; and,
- practicality.

Each of these categories is discussed in detail below.

***Algorithmic Validity:***

It is important that the system provide the variety of functions required by the decision maker. Information returned by these functions must be logically correct. Solutions ought to follow from the specified logic sequence and therefore be reproducible.

To be worthwhile, the quality of the solution produced by the DSS must be an improvement over previous methods. DSS do simply seek quick solutions to simple tasks. They are oriented towards effective decision making. Therefore, no matter how well the problem is modelled or implemented, if solutions are not improved as a result of the DSS, it is unlikely that they will be deemed beneficial.

A final algorithmic consideration of DSS concerns its responsiveness to the needs of the decision makers. A DSS should be flexible enough to allow users to create their own solution strategy (Densham, 1991). This entails routines that are independent from one another, and do not require a fixed sequence of steps to reach a solution.

***Human Factors:***

Systems must interact with the user in an effective manner. The system should respond from each command within reasonable time, so as to not subject users to the frustrations of unexpected delays. Textual information must be concise, but informative. Graphical display of data eases interpretation, but also increases system demands and introduces possible erroneous interpretation. Graphs and maps must be legible while portraying all of the information necessary.

***Practical Concerns:***

DSS are practical systems. The concept recognizes that systems and solutions must be politically acceptable to be useful. Systems must overcome institutional constraints and justify the organizational changes they dictate.

Included in these concerns is the system's efficacy. The system should be evaluated on the time it takes to produce a final solution, its training requirements, the reliability of the system, the documentation provided, and its ability to adapt to new settings (Armstrong *et al.*, 1990).

**Methods of Evaluation**

The demands of the above evaluation criteria are significant. Methods of assessing the system against these criteria have not been standardized. Ideally, evaluation entails the on-going interaction with the users of the system. Not only must the system produce a

good solution; organizational and procedural changes must also be noted. Three potential evaluation strategies can be identified:

- analogue solution comparison;
- analogue system comparison; and,
- decision maker evaluation.

Analogue solution comparison involves contrasting a solution developed without the DSS with a solution from the system. This makes two assumptions. First, that criteria for evaluating a solution can be formed. The unstructured nature of these types of problems complicates this process. Analogue solution comparison also requires an identical problem application to compare. This can either be two applications of the same instance or two comparable instances. Data availability and objectives need to correspond closely.

Even with the suitable solution evaluation criteria, and an appropriate case study, comparing solutions is an indirect way of comparing systems. The procedure for obtaining the solution is not evaluated. Without assessing the system itself, the practical aspects of the system, and the potential of the system to assist in solving instances other than the case study, are unknown. As an alternative, the system can be evaluated directly through comparison with another existing system. The existing system may be another DSS, but is more likely an optimization model, simulation model, or manual method. Through direct comparison, the system can be evaluated in each step in the solution process. The costs and benefits — both monetary and non-monetary — can be determined, and organizational effects of the system be ascertained.

The final form of evaluation involves those using the system directly. If an impartial person with extensive knowledge of the particular problem is available, he or she can provide expert consultation about the system (Keen and Scott Morton, 1978). This may prove to be the simplest and most cost-effective method of evaluation. An impartial expert in the field is able to evaluate both the system itself and the solutions it produces.

Ideally, each of the above methods would be employed to evaluate a DSS. Unfortunately, this is not always possible. The following section describes the evaluation of the SDSS presented in this thesis and outlines the limitations encountered.

## SYSTEM EVALUATION

Evaluating a system for a problem as significant as land consolidation entails significant logistical burdens. Consolidation planning involves dozens of people and is active over several years. Consequently, complete evaluation of a system throughout the lifetime of a consolidation plan is impossible without several years of research. In addition, evaluation of the consolidation solutions is limited by the lack of suitable program evaluation criteria.

Other limitations are specific to this research project. Analogue system comparison to existing software is not possible as a comparable system for consolidation does not exist. Therefore, opportunity for comparison is limited to manual methods and the cartographic routine written by Digital Resource Systems (Figure 3.5).

Second, it is impossible to directly compare consolidation plans created with this model and an actual plan, based on quantitative information alone. There is a significant amount of knowledge that is not, or cannot be included in sample data. First, this model requires additional material that is likely not available. Attribute information about each parcel is usually lost early in the process of valuation, and details on the parcels desired by farmers is not collected. Even if this information were acquired, first hand knowledge of the area, input from the community representatives, and an appreciation for system objectives is necessary to compare the solutions of the model versus the manual plans.

Finally, the lack of suitable cooperation from anyone directly involved in a consolidation program means that expert evaluation of the system is not possible. Nevertheless, with the addition of sample data from an actual consolidation, it is possible to evaluate the system in many of the key evaluation criteria.

### Sample Data

Data were obtained from a recent consolidation in Huesca province in central Spain. The information included digital maps of the 296 parcels before consolidation (Figure 7.1) and the 135 parcels after consolidation (Figure 7.2). A map of six land use classes (Figure 7.3) was also included.

Unfortunately, ownership of parcels was not available. To compensate, it was assumed that there were fifty farmers. This results in an average of almost six parcels



**Figure 7.1** Cadastre in the sample area of Huesca, Spain before consolidation.



**Figure 7.2** Cadastre after actual consolidation. Notice the new roads (double lines) and drainage ditch (single line parallel to right map boundary)



Figure 7.3 Agricultural land classification in sample area.

per farmer, approximately equal to the 1959 average for Huesca (Naylon, 1961). Original ownership was assigned randomly. The resulting distribution is portrayed in Figure 7.4. Prior to consolidation, the average area per farmer was 15.0 ha. with a standard deviation of 8.4. The largest farm contained 44.5 ha, the smallest 0.2 ha. This information provided the basis for all case study evaluation.

Because topographic information was unavailable, the original parcels were used as the basic unit of assignment. This limits the solution to a combination of the 296 parcels. Given the number, shape, and configuration of the existing parcels the resulting parcels will not be very regularly shaped, and a reasonable constrained solution may be infeasible. To provide the initial assignments necessary for the *Adjacency* procedure, it was assumed that farmers would wish to retain their largest parcel.

### **Practical Tests**

With data from an actual consolidation plan the system is ready to be evaluated in each of the three categories described above. Initially, routines were developed and tested on a small, irregular grid composed of sixteen cells. Once each procedure was performing the expected task accurately on this small dataset, the larger Spanish dataset was established. To provide practical experience with the system four formal tests were devised. Tests were undertaken on the Spanish consolidation data. Each test was stricter and more realistic than the previous test. These tests evaluate the solutions of the algorithms, the speed of the algorithm, and the ability of the system to reach solutions for a problem of realistic size and complexity. Each test was designed to investigate different components of the model. All were completed on a 33 MHz 486 personal computer.

To provide more information on the results of each test, one farmer was chosen randomly to represent the change in land ownership. José Rebled's original land holding is portrayed in Figure 7.5.

#### ***Test One:***

In test one, only one attribute — area of the parcel — was used. To concentrate on the *Adjacency* procedure, each farmer was assumed to want all parcels. Therefore, a *Wants* table containing 14,800 rows (50 farmers × 296 parcels) was constructed. To remove the equity constraints a tolerance of 999 percent was placed on the only attribute. Therefore, farmers are able to acquire land totalling virtually any value.



**Figure 7.4** Random ownership assignment. The shaded parcels represent the largest parcel of each farmer. They were re-assigned to their original owner.

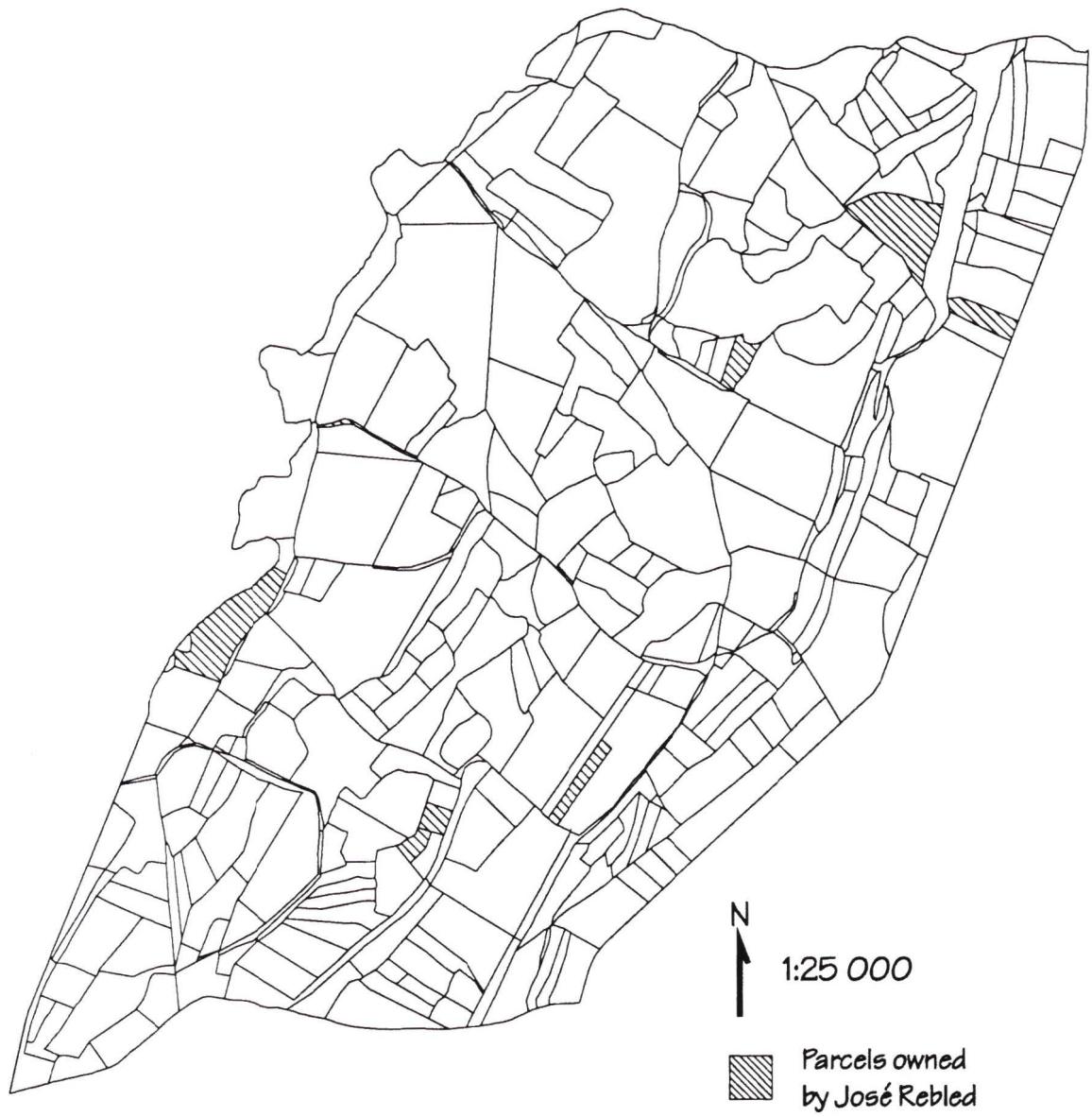


Figure 7.5 Parcels owned before consolidation by sample farmer.

First, the *Reassign* procedure was used to assign parcels to farmers wishing to retain them. This left 244 of 296 parcels to be assigned. The *Uncontested* and *Unwanted* procedures would not make any assignments in this case, as all parcels are wanted by farmers. The *Adjacency* routine was executed next.

As expected, this resulted in complete consolidation, meaning all farmers received one parcel (Figure 7.6). How much a farmer received was based solely on the location and incidence of his or her reassigned parcel. If the initial parcel had many adjacent parcels or was relatively isolated from others, a farmer could acquire more parcels before being surrounded by parcels already assigned.

*Test Two:*

To evaluate a single equity constraint, in test two a tolerance of five percent — consistent with the actual Spanish program — was specified. All other parameters are identical to test one. After thirteen minutes the routine stopped with 50 parcels yet to be assigned. At that point none of the farmers in a deficit situation owned a parcel adjacent to an unassigned parcel. Therefore, all  $I_{ijk}$  equalled zero and *Adjacency* could not make any more assignments. The *Deficit* procedure was implemented. This procedure took four minutes to assign the rest of the parcels.

This resulted in 296 parcels being reduced to 101. In equity concerns, no farmers received more than five percent of their original. However, three farmers lost 24, 16 and 11 percent of their land area. Each of these were small farmers, owning less than four hectares. The *Deficit* procedure uses the absolute deficit to determine the worst-off farmer. Consequently, small farmers rarely have the largest deficit. However, constraints are specified as percentages specifically to not discriminate against small farmers. Therefore, the *Deficit* procedure was changed to search for the farmer with the largest percentage deficit. The test was rerun with the new *Deficit* procedure resulting in a maximum loss to one farmer of seven percent. Figure 7.7 illustrates the resulting parcel boundaries and shades José Rebled parcels.

*Test Three:*

Test three increased the number of equity constraints to eight. The map of seven land classes (Figure 7.3) was overlaid on the map of original parcels and the area of each class for each parcel was calculated. Attribute one is the relative value of land calculated

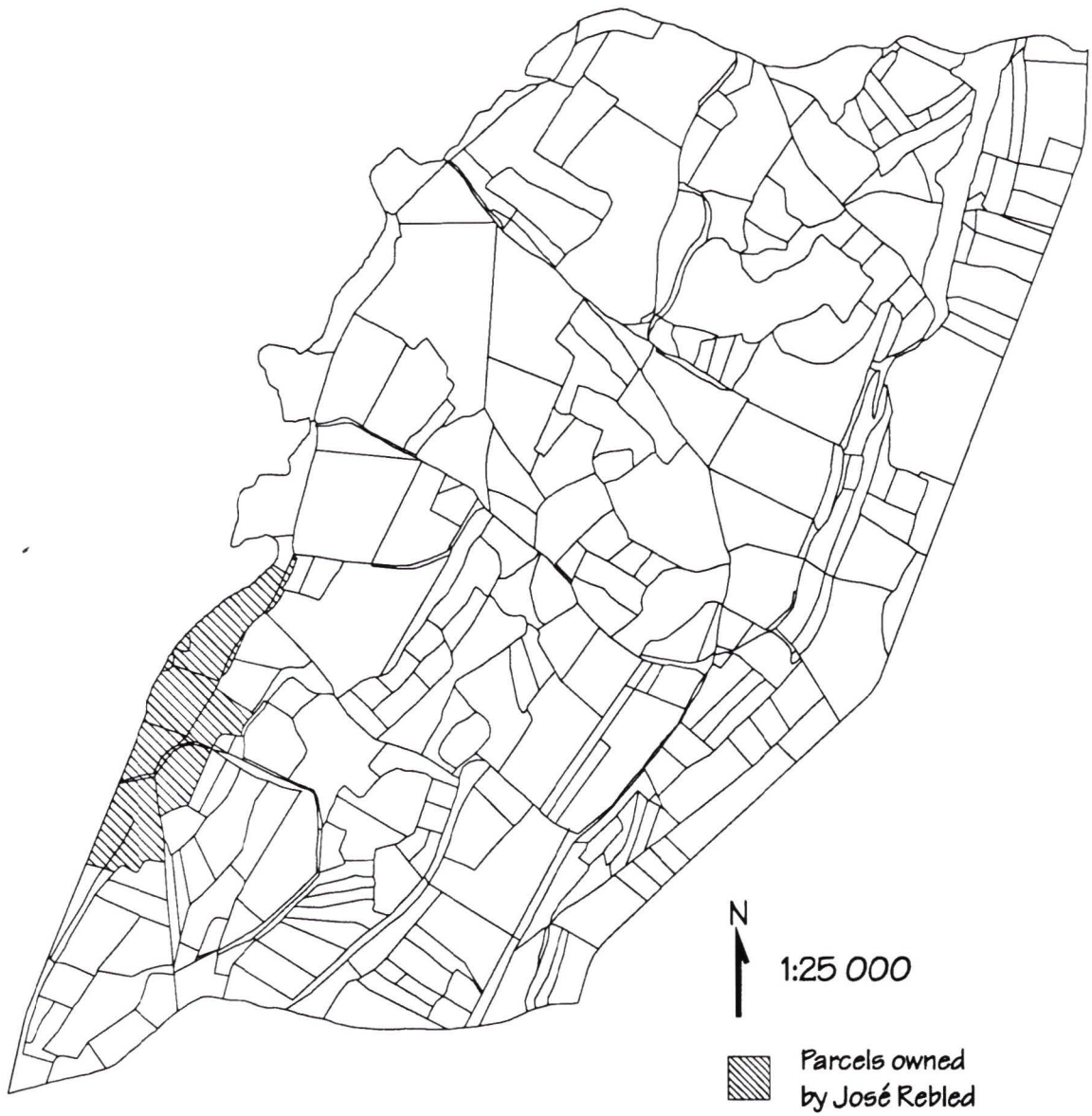


Figure 7.6 Parcels owned by sample farmer after test one.

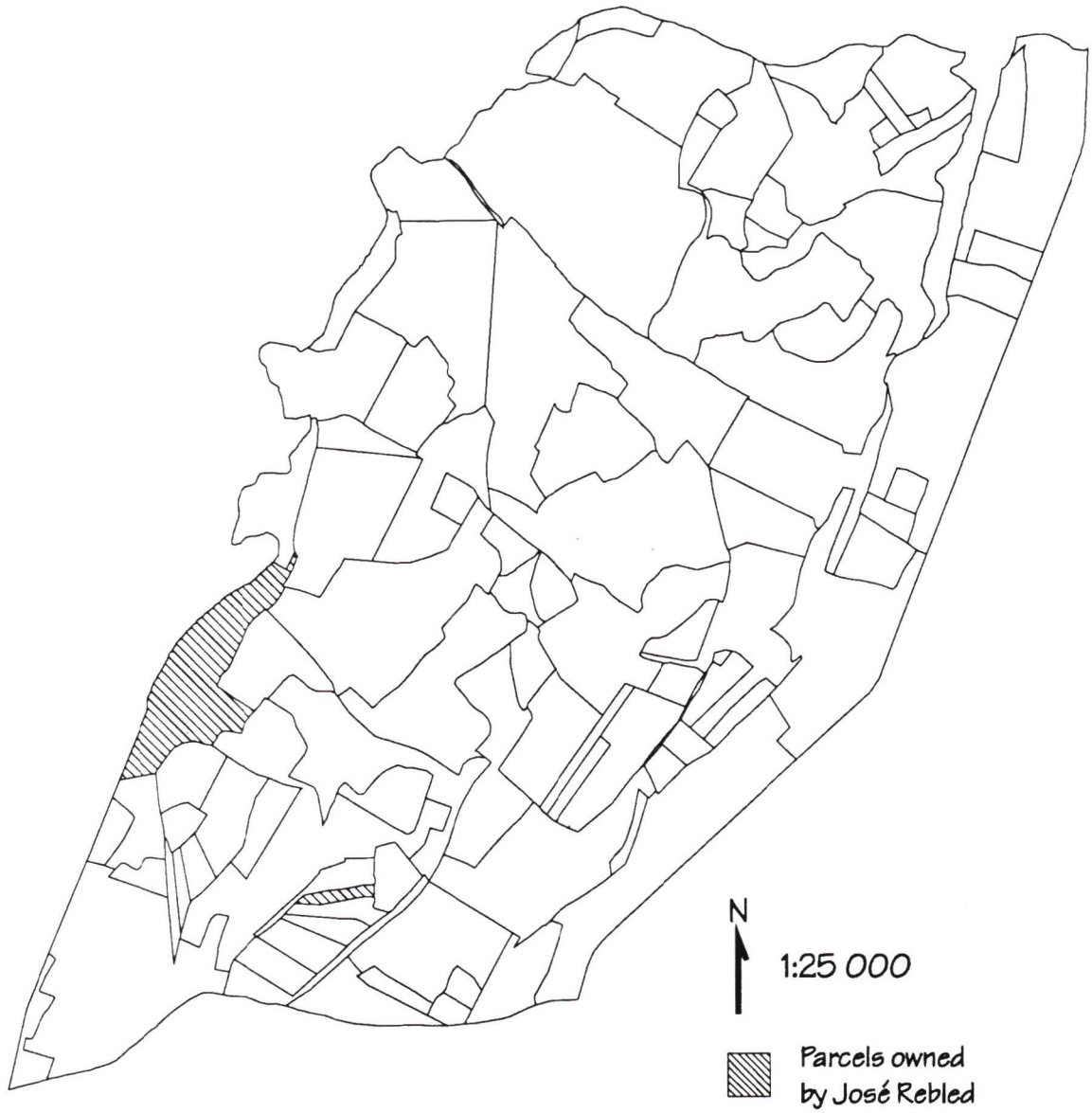


Figure 7.7 Parcels owned by sample farmer after test two.

using the formula from the actual Spanish consolidation:

$$P_1 = 1.0C_1 + 0.9C_2 + 0.8C_3 + 0.65C_4 + 0.3C_5 + 0.05C_6 \quad (7.1)$$

where  $C_i$  is the area of land in class  $i$ . The parameters are the relative values of each land class.

A five percent tolerance was maintained for attribute one. The seven land classes were assigned a less strict tolerance of fifteen percent. As in the previous tests, a complete *Wants* table was used and each farmer's largest parcel was retained.

Parcels were assigned using the *Reassign*, *Adjacency* and *Deficit* routines. The *Deficit* routine was executed with attribute one as the key attribute. *Deficit* ignores the other attributes in assigning parcels to the worst-off farmer. Consequently, the effect on other attributes is entirely dependent on the distribution of land classes comprising attribute one.

At this point another difficulty in the system was realized. When measuring parcels in several different attributes, it is very likely that a farmer will not have any value in one attribute (area of ranch land for a gardener for example). As a result, *no matter how high the tolerance*, many parcels assigned to the farmer with a total worth of zero in one attribute will exceed his or her upper bound in that attribute. Therefore, that farmer can receive very few, if any, parcels. To alleviate this problem a check was added. A potential assignment is not declared to exceed the equity constraint for attribute  $p$  if  $\beta_i^p = 0$ . This enables farmers to receive parcels until the total value assigned exceeds  $\beta_i^p + \alpha_i^p$ , in another attribute. Further discussion of the use of tolerances is provided below.

The test was re-executed with the alteration to the *Deficit* procedure producing 105 parcels (Figure 7.8). Several farmers received land containing more than twice or less than half the area they owned before consolidation in one or more land classes. However, no farmer exceeded the five percent tolerance in the most important attribute, attribute one, the relative value. Therefore, any farmer that lost land in one land class, gained land in another class. This information is readily available to planners in the *Sums* table.

#### **Test Four:**

Test four was the most realistic and constrained of the tests. In addition to the inputs of test three, the *Wants* table was reduced. Farmers were randomly assigned parcels

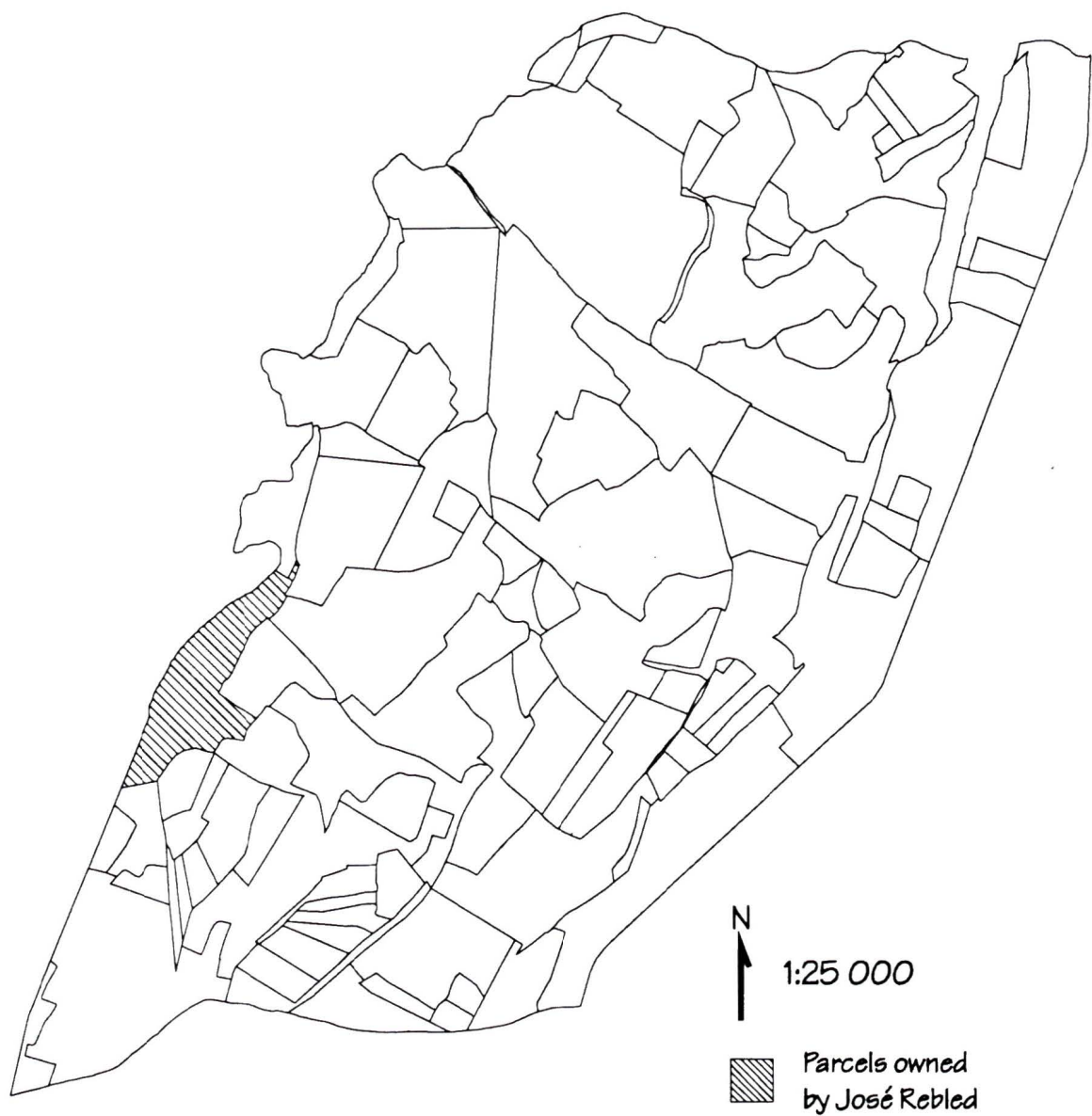


Figure 7.8 Parcels owned by sample farmer after test three.

they desire. Each farmer was given wants numbering three times the number of parcels they previously owned. This resulted in 888 rows in the *Wants* table, as opposed to the previous 14,800.

After running each routine, including *Unwanted* and *Uncontested*, in sequence only 178 of the 296 parcels were assigned to farmers. A feasible solution could not be found because of the strict constraints. The addition of one parcel will exceed every farmer's capacity in one or more attributes. Because of the large units used as assignment blocks in this example this outcome is quite likely. A finer tessellation would be more appropriate. It would provide more possible solutions and, therefore, is more likely to produce a feasible plan.

There are four possible strategies to modify the problem in order to create a complete solution from a partially completed plan. The *Direct* procedure can be used interactively to assign parcels to farmers whether they want them or not. Secondly, the tolerances on key attributes can be increased. Standard reports inform the user which constraints are being met the most frequently. Thirdly, the length of the *Wants* table can be increased. The less desirable parcels of each farmer are added to the list of wants. A fourth strategy involves starting again with no assignments. A tessellation strategy that creates more units to be assigned increases the number of possible solutions. Therefore, a feasible solution is more likely to be found.

The third strategy was undertaken in this example. Each farmer was allowed to select as wanted five times the number of parcels he or she currently owns. Running the *Adjacency* and *Deficit* procedures with the new *Wants* table resulted in an additional 64 parcels being assigned. This still left 54 parcels unassigned. Even with the unassigned parcels no farmer had received less than ten percent of the original allotment in attribute one.

As with test three, because attributes other than number one were not specified in the *Deficit* procedure, the values obtained by farmers in each land class were highly variable. For example, some farmers lost up to fifty percent of the land in class one (attribute two). Therefore, if the *Wants* table is increased further and the *Deficit* procedure is used to assign more parcels, it may be advisable to select another attribute. Every farmer is within the tolerance for attribute one already.

These four tests provided a demonstration of the system on a realistic case study. Numerous other combinations could be specified and used as test data. However, given the arbitrariness of the sample data the incremental benefits from additional tests are modest. It is clear that the formulation is quite strict. Planners need to create small enough cells to provide the necessary flexibility. They also must be prepared to relax some of the constraints at appropriate stages in the solution process.

### **Algorithmic Validity**

From the above tests, conclusions about the logical soundness of each algorithm can be established. Each routine produced the expected result. Compact shapes were created with the *Adjacency* procedure and equity constraints were maintained by all routines where applicable and possible. However, small problems with the solution approach were identified.

In routines *Adjacency* and *Deficit* ties may occur. A generic, objective method of resolving ties is not provided. The first farmer to be temporarily assigned a parcel, acquires it, regardless of other farmers just as deserving. A log of all assignments may be provided which would highlight ties and enable users to retrace their steps. Other logical concerns are related to the use of tolerances and including farmers' preferences.

### **Tolerances:**

The second improvement relates to the use of tolerances in the model. The use of percentage tolerances on each attribute is problematic. In test two the *Deficit* procedure was changed from one that found the farmer with the largest absolute deficit to the one with the greatest percentage deficit. This was done to avoid the large percentage losses experienced by small farmers. However, in test three it was discovered that percentage tolerances were negating appropriate assignments due to trivial equity constraint violations. While percentage tolerances are more equitable (owners of small and large farms are considered equal), the system can be hampered by insignificantly small transgressions of one equity constraint. Farmers were about to receive a parcel that was beneficial in all other attributes, but placed them over their allotted value in one attribute of which they owned little. Therefore, despite the other benefits, the parcel could not be assigned to them because of a small violation in one attribute.

This problem could possibly be alleviated by using both a percentage and small absolute tolerance. A percentage tolerance is used for all farmers; however, a minimum

absolute tolerance predominates. In other words, if the absolute difference between the assignment and the tolerance is less than a certain value, ignore the transgression. Therefore, a farmer with little or no land in one attribute can obtain a parcel with a small value in that attribute, despite exceeding an inappropriate percentage constraint.

It is also possible to assign each farmer his or her own tolerance for each attribute. Then, allowances can be made for differences in original allotments. Establishing and changing these tolerances, however, would be tedious. The approach does offer the possibility of allowing farmers to specify their own tolerances. The restrictions that are needed for this process would have to be defined.

Additional difficulty in the use of tolerances is evident in the proximity attribute. In proximity and other similar measures, there is no direct detriment to other farmers if one farmer benefits substantially. Therefore, a positive tolerance on that attribute is not warranted. However, the system currently does not have a mechanism to ignore a tolerance. Instead, a large tolerance, say 999.9 percent must be specified. This is not only awkward, without the above adjustment; it is conceivable that it may be exceeded for very small values. A mechanism to ignore positive tolerances for certain attributes is advisable.

***Wants Table:***

The final improvements identified concern the specification of parcels farmers wish to acquire. The first three tests ignored the parcels desired by individual farmers. However, to accomplish this, a *Wants* table comprising every farmer wanting every parcel was constructed. In this approach the program spends an inordinate amount of time answering the obvious question of whether a farmer wants a parcel. If the 'wants' constraint is not to be considered, a more efficient approach to a problem with this condition would be to simply ignore the 'wants' of each farmer. No option for this is offered by the system at present. If this were implemented, the database would have to be reformulated so that information on length of common border ( $l_{ijk}$ ) is moved from *Wants* to another table.

Additional problems with incorporating the desires of participants concern the changing nature of the problem. The list of wants does not automatically change as the solution is created. The user may select a different level of desire to constrain the assignments, but no routine automatically change the list of wants. Therefore, the

*Unwanted* and *Uncontested* procedures can only be run once for a given wants list. This presents a slight problem. Suppose farmer A has been assigned enough parcels to reach his or her limit in all attributes. Therefore, no further parcels should be assigned to that farmer. However, farmer A's wants are still 'active'. If farmer A and farmer B both desire an unassigned parcel, *Uncontested* will not be able to assign it to farmer B, despite the apparent rationale for such an assignment. The same is true for parcels where only farmer A wants the parcel. *Unwanted* will not reassign the now, for all intended reasons, unwanted parcel to its original owner. An improvement would be to deactivate the 'wants' constraint of a farmer temporarily once they have reached their upper tolerances.

The above tests have shown that despite minor problems, the system can produce reasonable solutions to the multiple objective problem of land consolidation. However, further evaluation of the effectiveness of the system in interacting with the user is required. The next section describes how well the system interacts with the user and decision maker.

### **Human Factors**

It is of obvious importance that algorithms produce valid results. However, in a SDSS it is of equal importance that the system provide the tools for the decision maker to interact with the system.

The system consists of all the technological needs to provide a very effective user interface. A graphical display is provided for a powerful user interface and an accurate portrayal of cartographic data. The shading of parcels upon assignment graphically portrays the solution as it emerges. The approach is limited in the number of farmers and parcels that users can reasonably be expected to interpret.

Another concern is the provision of the large amount of data needed by planners in a concise and accurate manner. The system needs to provide more information to the user as the assignments are occurring. Often, assignments of a small parcel cannot be detected from the shading of the parcel alone. No on-going information about the status of the system or individual farmers is provided.

The major impediment to furnishing this information is a lack of screen space. All of the monitor is filled with the map and menu; no room for tabular information remains. This can be overcome by providing a second monitor. Ideally, a SDSS consists of two monitors, one to display the spatial information, another for tabular data (Cooke,

1991; Ferland and Guenette, 1990). This provides the user with both forms of information without frequent screen flips. However, the TerraSoft API does not yet support a dual monitor system. Hence, the system is forced to clear the spatial data before displaying any tabular information beyond the two message lines. An inferior alternate is to provide several different screens of paper reports. Each report must be requested by the user by stopping the assignments and selecting a menu item.

### **Practical Concerns**

In order to be beneficial to those undertaking a consolidation program the system must meet certain practical standards. The use of a commercial GIS package running on PC hardware is a major determinant in its practical success. In fact, even without the decision support module, the GIS has proven beneficial to consolidation planners in Europe.

One of the disadvantages of a PC platform is computational speed. While the system can produce solutions in a reasonable time, the users would benefit from faster execution. A complete run of the *Reassign*, *Adjacency* and *Deficit* procedures with a full *Wants* table takes about 25 minutes on 33 Mhz, 486. A more realistic *Wants* table speeds up the process by about 10 minutes. Some technical measures to improve the speed of the system could be undertaken without excessive effort or modifications. Improved indexing techniques are available, and other database managers have been shown to be significantly faster.

Additional improvements would require more substantial changes. The TerraSoft API requires a tremendous amount of overhead. Only 64 kilobytes of random access memory (RAM) are available for the additional code. Seeking and shading the parcel for each assignment significantly slows the program.

Other impediments to faster execution are related to the database implementation. Using a longitudinal approach for the *Values* and *Sums* tables promotes flexibility, but also introduces an extra search step into every query. Fixing the number of constraints, or using a data dictionary would decrease the execution time.

There are two arguments against producing quick programs at the expense of functionality and flexibility. First, there is little advantage to producing ineffective solutions quickly. Second, with the tremendous advancements in computer hardware expected in the next decade, many argue that one should develop programs for

tomorrow's technology. In fact, if the execution of the program was fast enough that the user could not monitor the process, opportunities for interaction would be restricted. Controls over the speed of the assignments would have to be provided.

## CONCLUSIONS

While several small improvements are possible, particularly in the algorithmic components of the model, the fundamentals of the approach have been shown to have several benefits over existing manual methods.

The most obvious improvement over manual methods is the automation of tedious tasks. Planners no longer have to do numerous repetitive calculations to assess the impact of giving one farmer one parcel of land.

The true strength of the system, however, is in automating the process. Planners lose little control over the solution process, and are provided with more information about the consequences of their decisions. Planners are therefore able to use the automatic assignment routines to create several alternative solutions, while including their judgement to make sure the alternatives are suitable solutions.

By automating the solution process, the system is able to manage more complex consolidation problems. Therefore, planners are able to include more information directly into the model. A mechanism for including the preferences of the participants is provided whereby planners are able to allocate parcels to those farmers that really desire them. Also, the value of a parcel can more properly be represented through the use of several non-commensurate attributes.

With these improvements to the inputs and process of consolidation, planners are more likely to develop a solution that satisfies the diverse players in land consolidation.

## Chapter Eight

### Conclusions

The chapter summarizes the thesis, highlighting the research justification, the decision support approach, the development, and the implementation of a model of the consolidation process. The second part of the chapter emphasizes the research contributions of the thesis and outlines further research needs.

#### SUMMARY

##### *Research Rationale:*

Recent consolidation programs have been undertaken in several countries, particularly in Europe, despite the misgivings of many. While policy makers have cited the benefits of consolidation for many years, other researchers are now documenting its costs. They argue the net price of consolidation is often greater than any costs attributed to fragmentation.

While many problems are endemic to imposed programs such as consolidation, some of the costs can be attributed to inadequate methods used by consolidation planners. Current procedures do not allow those directly affected by consolidation to have meaningful input into the decision making process. Participants' input is limited to persuasion and representation. Consequently, their perceptions may not be properly realized by consolidation planners. This leads to farmers misunderstanding the rationale for the final plan when it is presented to them. From their perspective, land appears to be allocated based on chance or narrow, simplistic goals of regular, square fields. The

resulting land has little to do with their holdings before consolidation or their desires of consolidation.

*Approach:*

The input of participants has been avoided, however, because the problem is currently at the limits of manual solution methods. In developing a consolidation plan there are numerous data sources to consider and objectives to attain. Planners using manual methods have been unable to consider all of the possible data sources or objectives, and instead strive simply to create one feasible solution to a more simply defined problem.

The traditional response to such complex problems is to develop an optimization model. In an optimization model planners must formulate the problem into a set of formal objectives and constraints. These objectives are encoded into a solution algorithm. Planners input data on land ownership and value into the system, and it returns a completed consolidation plan.

This approach, however, suffers from fundamental flaws. The consolidation problem is much too complex, political and important to be left solely to a mathematical optimization algorithm. The simplifications inherent in a model of this type are too great as several crucial objectives of consolidation cannot be modelled in the concise mathematics needed for optimization. For this reason, past attempts to express other complex spatial assignment problems in optimization models have not proven to be of practical success.

In response to limitations of the optimization approach, spatial decision support systems (SDSS) have been developed. SDSS enable decision makers to interact and control the solution to account for unstructured objectives. In past geographical research, this has been primarily accomplished by using two forms of SDSS. Reactive SDSS offer only passive support. They enable users to see the results of an action they initiate. Proactive systems offer more active support. They produce a draft solution, and then enable the user to edit the solution. While proactive systems offer the decision maker more support, they tend to allow the user little control over the solution procedure itself.

To overcome this limitation, the model presented in this thesis follows an interactive framework. Interactive SDSS attempt to find a balance between reactive and proactive systems. The focus is on algorithmic development that allows the user to interact directly with the solution as it emerges. Decision makers are able to understand

the solution algorithm better, are offered more control of the process, and are able to eliminate inappropriate solution paths sooner.

*Model Development:*

A model of consolidation was created that follows the interactive SDSS framework. From reviewing similar multiobjective spatial assignment problems, a solution strategy was devised. The model operates by assigning discrete parcels of land to farmers based on a series of rules. It begins by requiring a tessellation of the study area. A method is developed that separates the land into discrete parcels whereby planners are still able to create well-shaped parcels, but without losing inappropriate amounts of accuracy or resulting in computational intractability. While the tessellation strategy employed will have profound effects on the number of feasible solutions and the shape of the parcels created, the actual assignment routines are tessellation independent.

The next feature of the model is the ability to use several measures of parcel value. A parcel's value need not be reduced to a single monetary figure. Innate measures of value, such as area, soil, terrain, and location can be expressed in their native format. The model manages the additional complexity this entails by using a flexible network database model.

The model also improves the ability to incorporate the preferences of the participants of consolidation. Farmers are able to select which parcels they wish to retain, and of the parcels they do not own, which they would like to acquire. These preferences are used as constraints. Ideally farmers should only acquire parcels they have selected as preferred, unless planners explicitly deem otherwise. Preference of parcels can be ranked and grouped to give planners more information about preferences and more flexibility in assigning parcels.

Parcels are assigned to farmers using a set of assignment procedures. Simple routines handle trivial cases where a parcel is wanted by less than two farmers. When there is a conflict over a parcel, more complex routines assign parcels based on contiguity or equity. The *Adjacency* routine assigns parcels based on contiguity. It seeks to assign adjoining parcels to the same farmer so that their amalgamation creates compact parcels. The *Deficit* procedure ignores spatial criteria to concentrate on equity. Parcels are assigned to farmers experiencing the greatest deficit in one attribute.

These routines can be implemented without significant changes to data needs. Planners are able to use data already collected for manual consolidation plans. Much of that information is being increasingly managed in a GIS, but GIS does not offer special functions needed for consolidation.

***Implementation:***

The underuse of existing digital data is common in GIS installations. GIS have proven invaluable for data management in land consolidation and other spatial concerns. However, the development of spatial problem solving systems has been hindered by the lack of suitable tools. Application program interfaces (API) are a new approach to GIS customization borrowed from other software applications. They offer potential for problems that warrant the investment in time, training and programming. A commercial API was used to implement the proposed model into a GIS. While the present API presented some limitations (primarily documentation and cohesiveness) a complete system was created without extensive coding. Only a few years ago development of a comparable system would not have been possible within the research time period.

The system developed includes:

- a graphical user interface;
- routines to display, edit and query a map;
- a standard database management system; and,
- reporting routines.

Each routine is designed to interact with the user at all times. The user is provided with information about each step in the procedure and is able to interrupt and alter the parameters and assignments as the solution is determined. Assignment procedures are implemented so that assignments were reflected on the map by shading the parcel with a farmer's unique shading pattern and colour combination. Information on the current status of farmers is made available to a user through on-screen reports.

***Evaluation:***

Evaluation of a SDSS for a problem as comprehensive as consolidation is difficult. Sample data from a consolidation program in Spain aids in the evaluation; however, all of the knowledge needed to allocate land parcels cannot be represented in a database. Consequently, direct comparisons between the actual plan and those created by the model are not possible. Also, an analogous system does not exist. Therefore, comparison

of the features of the system with another is not possible. Instead, the system must be tested against manual methods and SDSS for other problems.

Algorithmic validity is the most definite test of the system. The system was shown to produce reasonable plans without losing interactive capabilities. The routines of the model created the desired solutions. The *Adjacency* procedure created compact, consolidated farms. The *Deficit* procedure ensured equitable assignments. However, more flexibility is required. Planners need to be able to ignore the wants of farmers and tolerances placed on each attribute if desired. Also, the parcels chosen by farmers should be adjusted once equity constraints are reached.

Just as importantly, the routines were shown to be practically implemented into an integrated system. Planners are given immediate information about the consequences of an assignment as solutions are portrayed on the screen as they emerge. They are free to stop and start routines at any time. More reports are needed to give planners information about the emerging solution, but the standard format database facilitates the use of additional software to create the desired reports.

## RESEARCH CONTRIBUTIONS AND FUTURE RESEARCH

This thesis has contributed to the geographical research in three areas. It has examined and improved land consolidation methods, developed an interactive algorithm for a SDSS, and used new tools for GIS customization. Nevertheless, however innovative the research, additional inquiry is required in each area.

The primary focus of the research has been on modelling agricultural land consolidation. Explicit statements of the objectives and constraints of consolidation are not present in the English literature. Therefore, to provide a more formal definition of the problem, objectives of consolidation were enumerated and classified into precise declarations. Once the problem has been formalized, solution strategies can be developed. Existing solution procedures are primarily manual and do not take advantage of sophisticated mathematics or computer technology. By exploiting the latter tools this research presents an innovative approach to an old problem.

To continue the advancement of consolidation methods beyond this research, the research agenda should be focused on developing more flexible and comprehensive solution procedures. Metrics for shape and distance, for instance, are well defined, but

are not included directly into this system. Users should be provided with more options as to which constraints and objectives they wish to consider at any time. Finally, fresh approaches and alternative solution procedures may prove more appropriate and should be encouraged.

One advantage of the solution algorithms developed, that is not present in most other approaches, is their ability to be incorporated into a more interactive solution procedure. In assuming a more prescriptive role in consolidation, the research presents an ideal example of new directions for geography and GIS. The system does more than simply examine the consequences of, or manage the data needed for implementing a consolidation plan; it takes an active role in an attempt to improve the plan itself. However, in accepting this role it is important that the GIS not lose its strength in information exchange. A complete movement to an operations research framework to solve spatial problems would result in a loss of control to the model itself. Spatial decision support systems are an attempt to overcome this dichotomy by marrying the information dialogue between user and system with the prescriptive modelling techniques of operations research. Existing proactive SDSS have accomplished this union by simply appending interactive capabilities onto the end of traditional optimization models. This offers the decision maker little more than two segregated tools under one title. True interactive spatial decision making can only be accomplished through the complete integration of solution procedure and decision maker. The system presented in this thesis is one of the few examples of an interactive SDSS. That in itself is a meaningful contribution to the literature. However, further, more general study of approaches to solving spatial problems is required if more examples are to be forthcoming. In order to promote interactive spatial decision making, in addition to the items outlined by Densham and Goodchild (1989), the SDSS research agenda should seek to answer questions about:

- alternate solution algorithms that better facilitate interaction;
- the computation costs of these more spatially oriented algorithms;
- the best methods of cartographically portraying partial and evolving solutions;  
and
- how best to enable users to input their spatial decisions into the system.

The final contribution of the research concerns the implementation of the system. In order to offer a viable platform for interactive decision making, GIS must be able to move beyond its current limitations. Until recently, GIS has occupied a very passive position in decision making contexts. Only through the provision of analytical tools can it mature into a more active role. In this thesis, the use of an API to implement the model demonstrated the potential of this type of toolkit to help GIS meet this goal.

As the number of GIS applications grows, users are calling for more flexible and diverse functions from GIS. Many, if not most, commercial GIS vendors are moving to some form of customization within their product. API portends to offer the most sophisticated form of customization without requiring too much development from the user. However, further efforts in software design and analytical routines are needed if API is to fulfil this potential.

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