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The development and evaluation of a new model for measuring land fragmentation

Demetris Demetriou[1], John Stillwell[2] and Linda See[3]

[1,2] School of Geography
University of Leeds
Leeds LST 9JT

[3] International Institute of Applied Systems Analysis (IIASA)
Schlossplatz 1
Laxenburg, A-2361 Austria

Email: [1]demdeme@cytanet.com.cy;
[2]j.c.h.stillwell@leeds.ac.uk;
[3]see@iiasa.ac.at

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Abstract

Land fragmentation is a major problem in different parts of the world. This paper presents a new land fragmentation index which overcomes the weaknesses of existing indices by integrating a number of land fragmentation factors, allowing the user to select which factors are included and to apply weights to the factors selected. When applied to a case study area in Cyprus, the new 'global land fragmentation index' outperforms the existing indices. The paper also introduces a new 'parcel shape index' and a new transformation process known as the 'mean standardisation method'. Sensitivity analysis is carried out to indicate the impact of changing weights of selected factors under particular scenarios and utilisation of the new parcel shape index versus existing indices.

Keywords

Land fragmentation; land parcels; multi-attribute decision making; fragmentation indices; parcel shape; Cyprus

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1 Introduction

This paper reports on the development and evaluation of a new land fragmentation model called *LandFragmentS* (*Land Fragment*ation *S*ystem) that quantifies the extent of land fragmentation using a new index whose values range from 0 (worst fragmentation) to 1 (least fragmentation). This index measures the efficiency of the existing land tenure system and may assist planners in policy decision making, i.e. it can help to decide whether land consolidation should be applied.

The paper begins with an outline of existing land fragmentation indices in section 2 and a discussion of the data sets that are typically available for the measurement of fragmentation in section 3. Section 4 sets out a methodology for developing a new index as part of an integrated planning and decision support system for land consolidation called LACONISS (LAnd CONsolidation Integrated Support System) whose structure is explained in detail in Demetriou *et al.* (2011a). The interface to the *LandFragmentS* module is also introduced and then section 5 explains how two popular land fragmentation indices are calculated using the module. Section 6 explains how a 'land fragmentation table' is generated and outlines five of the six factors that are used to measure fragmentation. A new 'parcel shape index' (PSI) is discussed separately in the following section and a new standardisation process called the mean standardisation method (mSM) is introduced. Section 8 shows how a 'standardised land fragmentation table' is generated and Section 9 presents the new index called the 'global land fragmentation index' (GLFI), which is the core outcome of the module. Sensitivity analysis provided by the module is presented in section 10 and in section 11, an application of the module is presented using a case study in Cyprus involving the investigation of four weighting scenarios, a comparison of the GLFI with existing indices, a sensitivity analysis focusing on changes to the weights and a comparison of the new PSI with existing indices. Conclusions are drawn in the final section.

2 Limitations of existing land fragmentation indices

Land fragmentation is a spatial problem associated with six relevant factors: the landholding size; the number of parcels belonging to the holding; the size of each parcel; the shape of each parcel; the spatial distribution of parcels; and the size distribution of the parcels (King and Burton, 1982). In Cyprus, land fragmentation has additional complexities including the lack of road access to land parcels and problematic ownership rights (Demetriou *et al.*, 2012). For example, a parcel may be owned in undivided shares, i.e. it may belong to more than one landowner; or a parcel may have dual or multiple ownership, i.e. the land is owned by one person whilst the trees growing on the land are owned by someone else and a third party has ownership rights to the water. In addition, a land parcel may not have a title deed. The existence of all these different factors highlights the complexity of representing and measuring land fragmentation.

There appears to be no standard measurement of land fragmentation (Bentley, 1987; Van Hung *et al*., 2007) and no index takes into account all of the factors mentioned above (Monchuk *et al*., 2010). Most authors have utilised a simple measure such as the average number of parcels per holding or the average holding size or the average parcel size at the regional or national level. Indices were developed in the 1960s and 1970s that incorporate some of the above factors (e.g. Edward, 1961; Simmons, 1964; Dovrin, 1965; Januszewski, 1968; Igbozurike, 1974; and Schmook, 1976). However, existing indices are partial at best as they do not take all of the relevant factors into account. Current indicators ignore non-spatial factors such as the ownership type for each parcel and the existence or absence of road access to a parcel, which may completely prevent parcel exploitation. Furthermore, there is no user flexibility in the selection of the variables that could be contained in the fragmentation index, and the factors are given the same weight or level of importance, which may not always be realistic. For example, in the case of Cyprus, the importance of distance between the parcels of a holding may be less than the shape of the parcels or the number of parcels. Moreover, planners, policy makers and farmers may have different perceptions about the importance of particular factors and would most likely assign different weights to these factors for a given project. These limitations clearly indicate the need for a new methodology for measuring land fragmentation (Demetriou *et al.*, 2012).

3 Data considerations

The study area is a part of the broader region of Chlorakas village in the District of Pafos which is located at an altitude of 70 m above mean sea level and at a distance of 3km north of the town of Pafos (Figure 1). The village administrative boundaries cover a total area of 492 hectares of lowland while the extent of the consolidated area is 195 hectares. The main crops cultivated in the area are citrus, vines, vegetables and bananas. A land consolidation project began in March 1971 and was among the first applied in Cyprus that completed in June 1974. The reasons for selecting this case study area for evaluating LACONISS are noted in Demetriou *et al.*, (2011b).

The Land Consolidation Department (LCD) of Cyprus provided two main types of original data regarding the study area: databases and cadastral maps. In particular, three database files were provided that were initially cleaned and renamed for the purpose of this research. The final structure of the collected databases is shown in Table 1.

Figure 1: Location of the case study in the district of Pafos

Source: The Land Surveys Department of Cyprus

Table 1: The original databases

	Database Fileneme		Database Fields	Field Type	Field Description
1	LandOwnersEN	1	**Owner_ID**	Number	Primary Key; it is a unique number for each landowner
		2	Owner_Code	Text	It is a code for each landowner used by the Department
		3	Owner-Name	Text	Name and Surname of an owner
		4	Total_Old_Area_Owned	Number	The original total area (in sqm) of the property owned by an owner in the study area
		5	Total_Old_Value_Owned	Number	The original total value (in Cyprus pounds) of the property owned by an owner in the study area
		6	Total_New_Area_Owned	Number	The total area (in sqm) of the property received by an owner in the new plan
		7	Total_New_Value_Owned	Number	The total value (in Cyprus pounds) of the property received by an owner in the new plan
2	OriginalParcels	1	**Parcel_ID**	Text	Primary Key;it is a unique number for each original parcel
		2	Parcel_Sheet_Number	Text	The cadastral sheet number in which a parcel belongs
		3	Parcel_Area	Number	The official registered area of a parcel
		4	Parcel_Value	Number	The value (CyP) of a parcel as it has been defined by the Valuation Committee
3	OriginalParcelsOwnership	1	Owner-ID	Number	it is a unique number for each landowner
		2	Owner_Code	Text	It is a code for each landowner used by the Department
		3	Parcel_ID	Text	it is a unique number for each original parcel
		4	Share_Numerator	Number	The numerator of the fraction of a share for a parcel
		5	Share_Denominator	Number	The denominator of the fraction of a share for a parcel
		6	Only_Trees	Boolean	The property includes only trees

In addition, a 1:5,000 cadastral map showing the original cadastral situation before land consolidation was provided, which was digitised and is shown in Figure 2. This digitised map has been split into three GIS layers (shapefiles) named “OriginalParcels”, “ExistingRoads” and “Streams”. The shapefile “OriginalParcels” has polygon geometry created to represent the original parcels. The shapes of the original parcels were digitised on screen with the editing functions of ArcMap using a scanned version of the original cadastral map. This shapefile is interlinked with the noted above three databases. The shapefiles “ExistingRoads” and “Streams” were created in the same way using the same scanned cadastral map and represented as polygon feature classes These data are sufficient for calculating all of the associated parameters and hence for measuring the existing land fragmentation in the case study area as described in section 11.

Figure 2: The digitised case study area

4 A new methodology for measuring land fragmentation

To overcome the deficiencies in existing land fragmentation measures, a new methodology has been developed that is comprehensive, flexible and problem specific. It is comprehensive since it is capable of handling any land fragmentation factor for which there are available data; it is flexible because the user may select which factors need to be taken into account for a particular project; and it is problem-specific since the planner may decide the weighting given to each component factor for a specific project. The method utilised is one that measures how far the existing land fragmentation condition is from the status of being 'perfect', i.e. an ideal condition which in most cases may be theoretical; or conversely how far the existing land fragmentation is from the 'worst' status. The proposed process is based on the Multi-Attribute Decision Making (MADM) and has four main steps as set out in Figure 3.

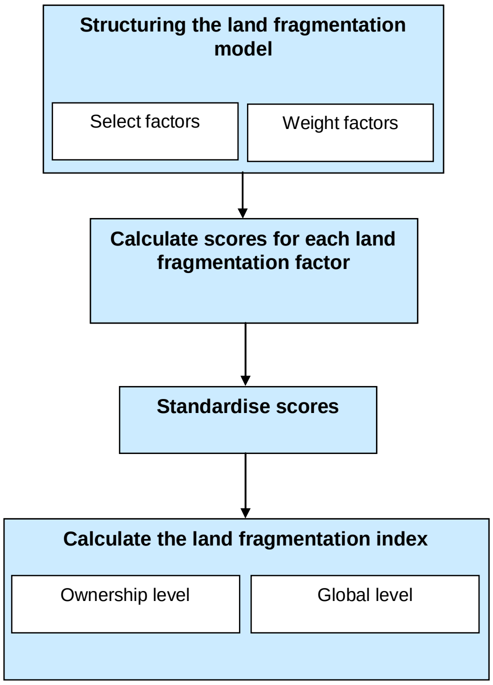


Figure 3: Outline of the *LandFragmentS* model (Demetriou *et al*., 2011a)

Although MADM is conventionally utilised for the assessment of alternative solutions of a problem, in this context it is employed to represent the performance of an existing system (i.e. a land tenure system) compared to the performance of an ideal system. Initially the planner selects the land fragmentation factors to be incorporated into the model and then assigns a relevant weight to each factor, which represents its importance in a given project. The selection of factors is discussed in the next section. Thereafter, the scores associated with each of these factors, e.g. the mean size of parcels and the dispersion of parcels, will be automatically calculated by the system to create a 'land fragmentation table' (Figure 4). Each row represents a holding or ownership and each column a land fragmentation factor (LFF). Each element of the table represents a score of holding *i* and factor *j*. These scores are then standardised (if necessary) using appropriate methods (e.g. using value functions) to create the standardised land fragmentation table. An ownership level land fragmentation index (LFI_i) is computed by multiplying the standardised score of each factor (f_{ij}) by the relevant weight of each factor (w_j) and summing these up for each row or holding as follows:

$$LFI_i = \sum_{i=1}^{m} f_{ij} w_j \qquad (1)$$

	Land fragmentation factors (Weights)							**Index**
	F_1 (w_1)	**F_2 (w_2)**	**F_3 (w_3)**	**..**	**F_j (w_j)**	**..**	**F_m (w_m)**	
Ownership ID of holding								
1	f_{11}	f_{12}	f_{13}	..	f_{1j}	..	f_{1m}	LFI_1
2	f_{21}	f_{22}	f_{23}	..	f_{2j}	..	f_{2m}	LFI_2
3	f_{31}	f_{32}	f_{33}	..	f_{3j}	..	f_{3m}	LFI_3
.	..	..	..	..	.	..	..	..
i	f_{i1}	f_{i2}	f_{i3}	..	f_{ij}	..	f_{im}	LFI_i
.	..	..	..	..	..	..	..	..
n	f_{n1}	f_{n2}	f_{n3}	..	F_{nj}	..	f_{nm}	LFI_n
								GLFI

Figure 4: A land fragmentation table of land fragmentation factors for each holding

Holdings will take values between 0 (full fragmentation or worst system performance) and 1 (no fragmentation or best system performance). A global land fragmentation index (*GLFI*) for the whole study area is then calculated as the mean of the *LFI*s:

$$GLFI = \sum_{i=1}^{n} LFI_i / n \qquad (2)$$

or the mean weighted by the size of the holdings. A median value could be also considered if the distribution of *LFI*s is skewed. A sensitivity analysis should then follow to assess how robust the outcome is regarding uncertainties and potential errors.

4.1 Land fragmentation factors

The following seven factors were initially considered for inclusion in the new index: dispersion of parcels; size of parcels/holdings; shape of parcels; accessibility of parcels; number of parcels per holding; and type of ownership which is twofold, i.e. dual ownership and shared ownership. The factors/criteria involved in any MADM need to satisfy a number of requirements (Malczewski, 1999; Sharifi *et al.*, 2004; Keeney and Raiffa, 1993), the most critical of which is the independence between the factors, i.e. to avoid duplication of associated factors. For instance, the size of a holding and the size distribution of parcels are both directly related to the size of the parcels. In addition, a test for 'preferential independence' was carried out which showed that the number of parcels per holding is preferentially dependent on the mean size of the parcels, which involves the number of parcels per holding in its calculation.

Based on these considerations, the following six variables were chosen:

- the spatial distribution of parcels, i.e. the dispersion of parcels (F1);
- the size of parcels (F2);
- the shape of parcels (F3);
- the accessibility of parcels (F4);
- the type of ownership which is twofold, i.e. dual ownership (the case when land and trees and/or water belong to different landowners) (F5); and
- shared ownership (where the land belongs to different landowners) (F6).

All of these factors are measured per ownership or holding. In particular, the dispersion of parcels by holding is measured by utilising the dispersion of parcels before land consolidation (DoP_b) in metres. The size of the parcels is represented by the ownership size index (with values between 0 and 1), which will be introduced by utilising value functions. The shape of each parcel is represented by a new complex measure called the parcel shape index (PSI), which is associated with six parameters defined by five separate value functions and a new standardisation process called the mean standardisation method (mSM) as discussed in detail in section 9. An overall ownership shape index is then calculated as the mean shape index of all parcels belonging to a holding. The accessibility of parcels is 0 for no road access or 1 for parcels with access to a road. The mean accessibility value of all parcels that belong to a holding represents the overall accessibility of an ownership. Similarly, dual ownership is represented by

0 or 1 if a parcel is owned in dual form or not, respectively; and a mean dual ownership value is then calculated for each ownership. Shared ownership is an index estimated as the mean shared factor (that represents the arithmetical proportion of the area possessed in a parcel by a certain landowner/ownership) of all parcels that belong to a holding.

These six factors satisfy all the relevant requirements. In particular, each factor is comprehensive in terms of clearly representing a part of the associated problem and each is measurable, i.e. objectively estimated. Moreover, the whole set of factors is complete since all of the main aspects of the problem are covered. The factors are operational because they have clear content. The number of factors is kept as small as possible although they provide adequate and reliable representation of the problem and they are non-redundant, i.e. independent so as to avoid duplication.

4.2 Module interface

The *LandFragmentS* module is operationalised as a toolbar (Figure 5) consisting of seven icons: 'Existing LF indicators'; 'LF factors'; 'LF table'; 'LF value functions'; 'Standardised LF table'; 'LF indices' and 'Sensitivity analysis'. Each icon, which represents a stage of the MADM process, launches a separate window with one or more functionalities. With the exception of the 'Existing LF indicators' and the 'LF function' icons, the remaining icons are in the order in which they must be executed. The functionality of each icon will be described separately in the sections that follow.

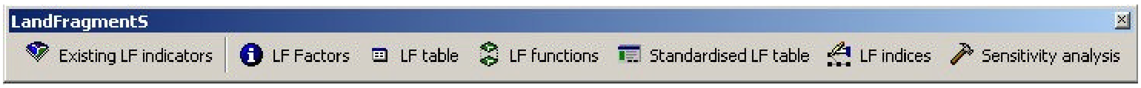


Figure 5: The *LandFragmentS* toolbar

5 Calculation of existing indices of land fragmentation

The most popular land fragmentation indices are those of Simmons (1964) and Januszewski (1968) in which a value of 0 indicates the worst possible land fragmentation situation while a value of 1 indicates no land fragmentation. To calculate these indices, the first icon on the toolbar shown in Figure 3 is selected, launching the window shown in Figure 6.

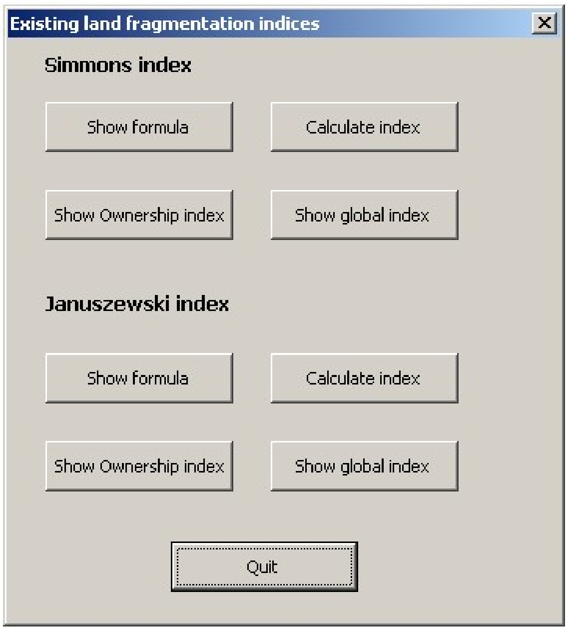


Figure 6: The window for calculating the Simmons and Januszewski indices

The formula for calculating Simmons index can be displayed by clicking on the 'Show formula' button. The remaining buttons are used to calculate the index and display its values by ownership ID in a column called 'Simmons' in the LandOwnersEN table, or globally as the mean index of all ownerships. The same options are available for calculating the Januszewski index.

6 Generation of the land fragmentation table

6.1 Factor Selection and weighting

The user may select which factors are to be included in the model via the 'LF Factors' menu item that launches a window as shown in Figure 7. Selection is made by checking the appropriate boxes or all of the factors can be selected at once. After selection, the structure of the LF table is created. Clicking the OK button completes the process. This window also allows the assignment of weights to factors. In particular, weighting can be carried out by utilising the direct ranking and the qualitative rating methods described in Demetriou *et al.* (2011c).

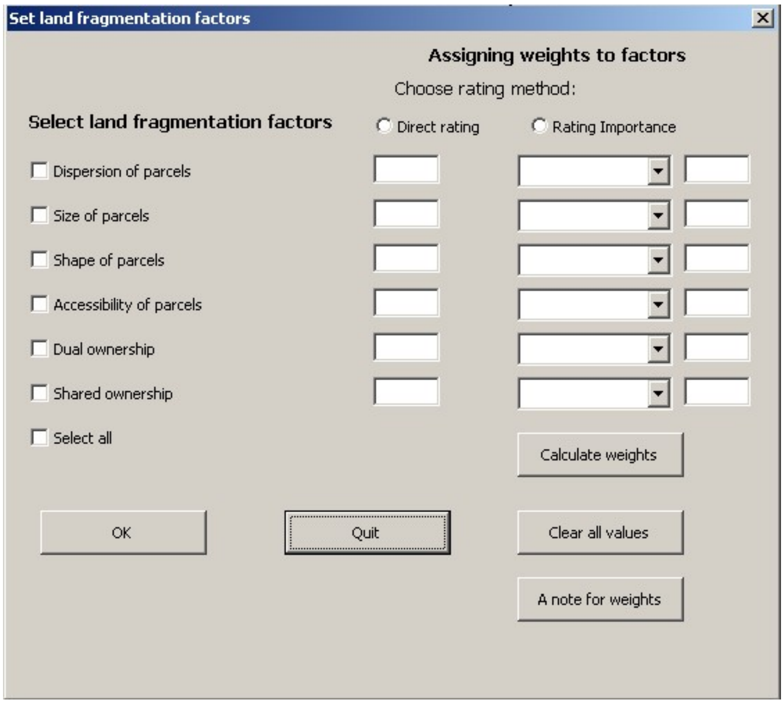


Figure 7: The window for selecting and weighting factors

The user may then select the 'LF table' menu item, which appears as a button on the dialogue box shown in Figure 8. In fact this window provides four main functions (with corresponding buttons): the 'Show LF table structure' (Figure 9) with no scores (a score represents the performance of an ownership associated with a particular factor); 'Pre-calculations' regarding shape analysis factors discussed in a later section; calculation of the scores f_{ij} via the 'Calculate Scores' button; and the final LF table with scores (via the 'Show LF Table' button).

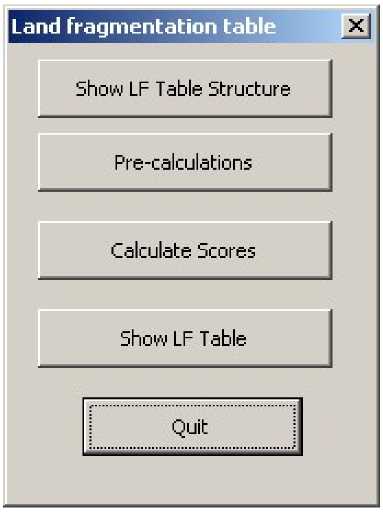
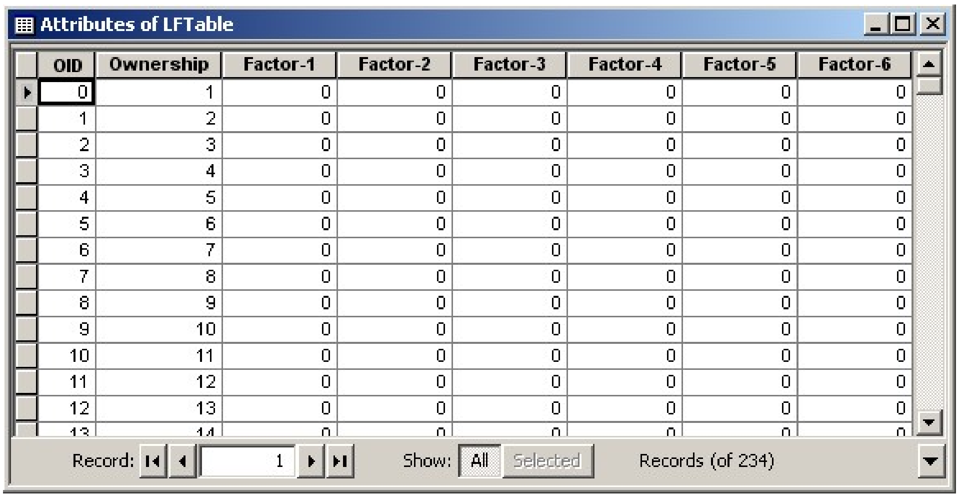


Figure 8: The 'LF Table' window



Attributes of LFTable

OID	Ownership	Factor-1	Factor-2	Factor-3	Factor-4	Factor-5	Factor-6
0	1	0	0	0	0	0	0
1	2	0	0	0	0	0	0
2	3	0	0	0	0	0	0
3	4	0	0	0	0	0	0
4	5	0	0	0	0	0	0
5	6	0	0	0	0	0	0
6	7	0	0	0	0	0	0
7	8	0	0	0	0	0	0
8	9	0	0	0	0	0	0
9	10	0	0	0	0	0	0
10	11	0	0	0	0	0	0
11	12	0	0	0	0	0	0
12	13	0	0	0	0	0	0
13	14	0	0	0	0	0	0

Record: 1 Show: All Selected Records (of 234)

Figure 9: The structure of the LF Table

6.2 Calculation of factor scores

Dispersion of parcels (F1)

The dispersion of parcels can be calculated for the original cadastral situation (DoP_b), i.e. before applying land consolidation as follows:

$$DoP = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{hmc})^2 + \sum_{i=1}^{n}(y_i - y_{hmc})^2}{n}} \qquad (3)$$

where x_i and y_i are the co-ordinates of the centroid of parcel i and x_{hmc} and y_{hmc} are the coordinates of the holding's mean centre. This is the only factor that needs standardisation as all of the others have values between 0 and 1.

Size of parcels (F2)

The size of parcels is represented by an ownership size index which is calculated as the mean value of the size of all parcels belonging to a holding based on the value functions shown in Figures 10 and 11 for arid and irrigated areas respectively. Value functions have been created by a group of five experts (including the principal author) based on the methodology described in Demetriou *et al.* (2011c). Figure 10 presents a fifth-order polynomial function:

$$V(x_i) = -1.71(10^{-20} x_i^5) + 6.83(10^{-16} x_i{}^4) - 9.97(10^{-12} x_i^3) + 6.36(10^{-8} x^2{}_i) - 7.37(10^{-5} x_i) + 5.58(10^{-3}) \qquad (4)$$

This function can be divided into two parts represented by a smooth S-shaped function and a straight line, respectively. The first part begins from a score of 1,338 m² (1 donum) that corresponds to the value 0 which is the lowest minimum size of a parcel that may be allocated after land consolidation (if the parcel is irrigated); up to a value of 6,689 m² (5 donums), which corresponds to a value of 0.5, which is the lowest minimum size of a parcel that may be allocated after land consolidation (if the parcel is arid). The latter is decided by the Head of the Land Consolidation Department (LCD) in Cyprus who may decrease the minimum size to half, i.e. from 13,338 m^2 (10 donums) to 6,690 m^2 (5 donums). The second part begins from the last value of the first part up to a value of 13,338 m^2, which corresponds to a value of 1.

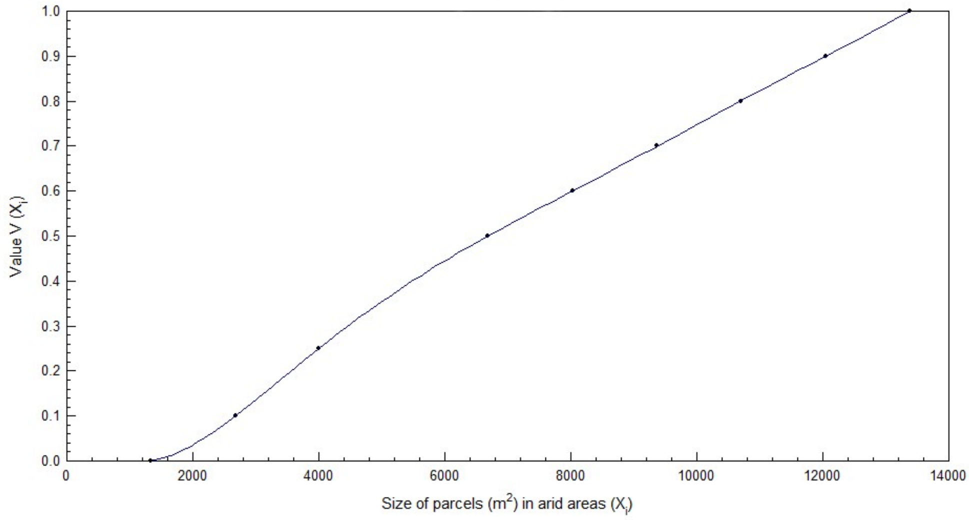


Figure 10: The value function for the size of parcels in arid areas

Figure 11 shows a concave benefit fourth-order polynomial function:

$$V(x_i) = -3.24(10^{-17} x_i^4) + 1.10(10^{-12} x_i^3) - 2.74(10^{-8} x_i^2) + 2.82(10^{-4} x_i) - 9.68(10^{-2}) \qquad (5)$$

which gradually increases from the lowest to the highest score, i.e. 334m^2 (a quarter of a donum) (value 0) to 7,700m^2 (value 1), which corresponds to the maximum of the mean parcel size based on five censuses carried out between 1946 and 2003. The value of 0.5 corresponds to a score of 2,676m^2 (2 donums) which is the minimum size of a parcel that may be allocated after land consolidation for irrigated areas according to the legislation.

The mean value for each holding does not require standardisation since the values are already between 0 and 1 due to the pre-processing of input factors via the value functions. In both functions, scores lower than X_{min} are standardised to 0, while scores higher than X_{max} are standardised to 1.

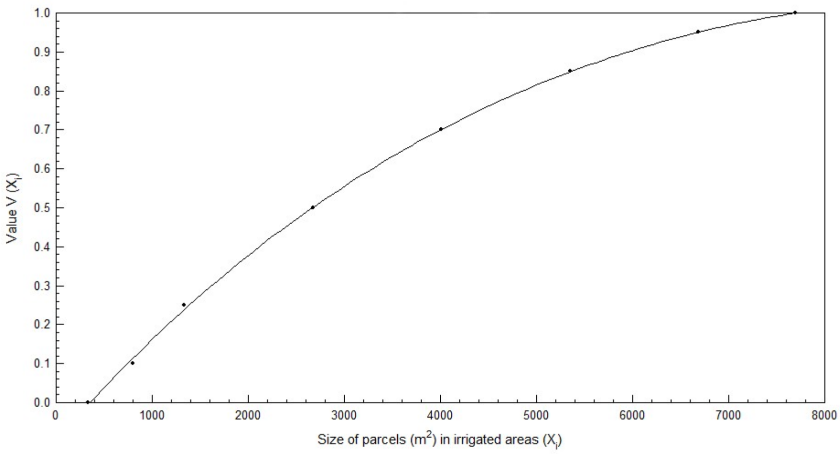


Figure 11: The value function for the size of parcels in irrigated areas

These and the other value functions will be described later regarding the parcel shape index and can be shown via the ‘LF function’ icon on the toolbar in Figure 3.

Shape of parcels (F3)

The shape of parcels is represented by a new parcel shape index (PSI) which takes into account six factors that are outlined in detail in section 6.

Accessibility of parcels (F4)

The system automatically detects if a parcel has access to a road or not. This is possible by employing the appropriate topology rule. In particular, the esriSpatialRelTouches rule of ArcObjects is utilised to check if a parcel ‘touches’ a road or not. If this is positive, then 1 is assigned to a special field for the relevant parcel while 0 is assigned if it is negative. The ownership accessibility index is calculated as the average value of assigned 1s and/or 0s for the parcels that belong to a holding. A potential weighting of the average accessibility index using the size of a parcel, given that it is more important to have access for a large parcel than a small parcel, is not appropriate because the size of the parcels is a separate land fragmentation factor in the model, which would mean duplication of factors.

Dual ownership (F5)

Similar to the accessibility of parcels, dual ownership is represented by a binary function that takes values of 1 (dual ownership) or 0 (not dual ownership). This information is included in the original data. Thus, a dual ownership index is calculated as the average value of assigned 1s and/or 0s for the parcels that belong to a holding. Potential weighting of the average ownership index by the size of the parcels is prone to the same limitation as noted earlier.

Shared ownership (F6)

Similar to the two previous factors, shared ownership is represented by a binary function that takes values of 1 if a parcel is possessed by more than one landowner or 0 if it is not. This information is also included in the original data. Thus, a shared ownership index is calculated as the average value of assigned 1s and/or 0s for the parcels that belong to a holding. Similar to the last two factors, the potential weighting of the average shared ownership index is prone to the same limitations as noted earlier.

7 Parcel shape

7.1 Outline

Shape measurement has been one focus of geographical study for many years (Boyce and Clark, 1964). Several authors have attempted to develop generic methods for measuring shape (e.g. Boyce and Clark, 1964; Lee and Sallee, 1970). MacEachren (1985) identifies four approaches: perimeter area ratios; direct comparison to a standard shape; dispersion of elements of an area around a central point; and single parameters of related circles. There are problems with each of the methods and it is sometimes hard to explicitly understand the differences or similarities in index values between various shapes. As a result, there is still no satisfactory method for measuring shape in a standard and explicit manner because of the variety of factors involved for each specific spatial context such as political geography, ecology, agriculture or urban geography.

Therefore, efforts for developing a new method should be focused on analysing shapes in the context of each particular problem (MacEachren, 1985) and satisfying the following requirements pointed out by Lee and Sallee (1970): (i) each shape should be represented by a unique number. Although this is in general reasonable, two or more different shapes may have very similar values compared to a 'standard shape'; (ii) no two shapes can be represented by the same number unless they are completely the same; the remark made in the previous requirement is also appropriate for this statement; (iii) two similar shapes should be assigned close numbers. Two other requirements are as follows: (iv) a shape index should take values within a predefined dimensionless range so that there is an explicit definition of what is the best and worst shape for the problem concerned, i.e. 1 and 0, respectively; and (v) a shape index needs to be comprehensive, i.e. take into account all possible factors (not only compactness and/or regularity as with generic methods) that are associated with the problem concerned. Moreover, the precision of an index should be chosen for ease of understanding and interpretation by planners. Practice shows that the optimal number of decimal digits to satisfy these conditions is three.

Based on the above considerations, a new shape index should be incorporated as a factor in the land fragmentation model. What is a good shape for land parcels for agricultural purposes? Several studies have dealt with this issue, some many years ago such as Barnes (1935); Lee and Sallee (1974); Johnson (1976); Witney (1995); Landers (2000); Gonzalez *et al*. (2004, 2007); Aslan *et al*. (2007); Amiana *et al*. (2008); Libecap and Lueck (2009). Despite these studies, there is not yet an index that reliably represents the impact of parcel shape on the effectiveness of cultivation (Amiana *et al*., 2008) and, more generally, on agricultural development.

Parcels with irregular shapes present many disadvantages in terms of parcel cultivation, crop yields, land wastage, conservation works (e.g. fencing), boundary disputes, *et cetera*. Therefore, most existing studies have shown the advantages provided by rectangular parcels (Barnes, 1935; Lee and Sallee, 1974; Johnson, 1976; Landers, 2000). In particular, Witney (1995) and Gonzalez *et al*. (2004) showed that the most optimal rectangle in terms of cultivation has a length:breadth ratio of 4:1. However, this finding is based on the maximum ploughing area, i.e. minimum dead ground, which is a factor relating to cultivation and not on other factors such as irrigation techniques utilised, the kind of crop or the potential future status of a parcel such as further subdivision or change of land use, for example. Thus, in Cyprus, where a mixed land-use development is permitted in agricultural areas (although with limitations), the optimal parcel shape utilised in practice (at least in land consolidation areas) is a rectangle with a length:breath ratio of 2:1 or alternatively something between 1:1 and 3:1.

7.2 Existing parcel shape indices

Whatever rectangle is considered as optimum, a shape index should be capable of explicitly defining how far any shape is from this optimum standard shape. However, existing studies have shown that this is not an easy task. Thus, in practice, simpler indices have been utilised for describing shapes. In particular, Aslan *et al*. (2007) have utilised indices that take into account the perimeter (p) and area (a) of parcel i. Such indices are the shape index (SI) shown in equation 8 (McGarigal and Marks, 1995) and the fractal dimension (FD) shown in equation 9 (Krummel *et al*., 1987; O'Neill *et al*. 1988; Milne, 1991):

$$SI = \frac{p_i}{2\sqrt{\pi a_i}} \tag{8}$$

$$FD = \frac{2\ln p_i}{\ln a_i} \tag{9}$$

Both indices have been developed to represent ecosystem fragmentation, i.e. splitting up contiguous ecosystems into smaller areas called ‘patches’ (Rutledge, 2003). Patches may be classified based on land cover and land use, habitat and vegetation. Thus, these indices are focused on landscape and they are not appropriate for use individually for land parcel shape analysis. In particular, both indices do not meet any of the requirements set out above except for that noted in (iii).

Figures 12 and 13 show the SI and the FD for various shapes. Index values are located within parentheses while the number above these values represents the number of the parcel concerned. These examples have been picked up from the case study area in Cyprus. As illustrated in Figures 12e and 13c, the shapes are alike and they have similar indices, i.e. requirement (iii) is satisfied. In contrast, requirements (i) and (ii) are not met as illustrated in Figures 12a-d and 13a-c, respectively. In particular, the SI for all rectangles equals 1.128 (and not 1 as noted by Aslan *et al.,* 2007). Figure 12a shows that shapes significantly different from a rectangle may have exact or very similar SI values. Similarly, Figures 12b-d indicate that considerably dissimilar shapes may have the same SI value when compared to a regular or near regular shape.

Even worse, the FD gives different values for different sizes of rectangles (Figure 13a) while similar to the SI, the same values emerge from significantly dissimilar shapes with apparent varying quality (Figure 13b). Requirements (iv) and (v) are also not met by either index.

Another index that takes into account the perimeter and area of a parcel is that utilised by Gonzalez *et al*. (2004, 2007) and earlier by Witney (1995), which is called the areal form factor (AFF) shown in equation 10:

$$AFF = \frac{a_i}{p_i^2} \tag{10}$$

It is a differentiation of the simple area/perimeter ratio that has the advantage of being independent of parcel size. Gonzalez *et al*. (2004) demonstrated that the optimal AAF for

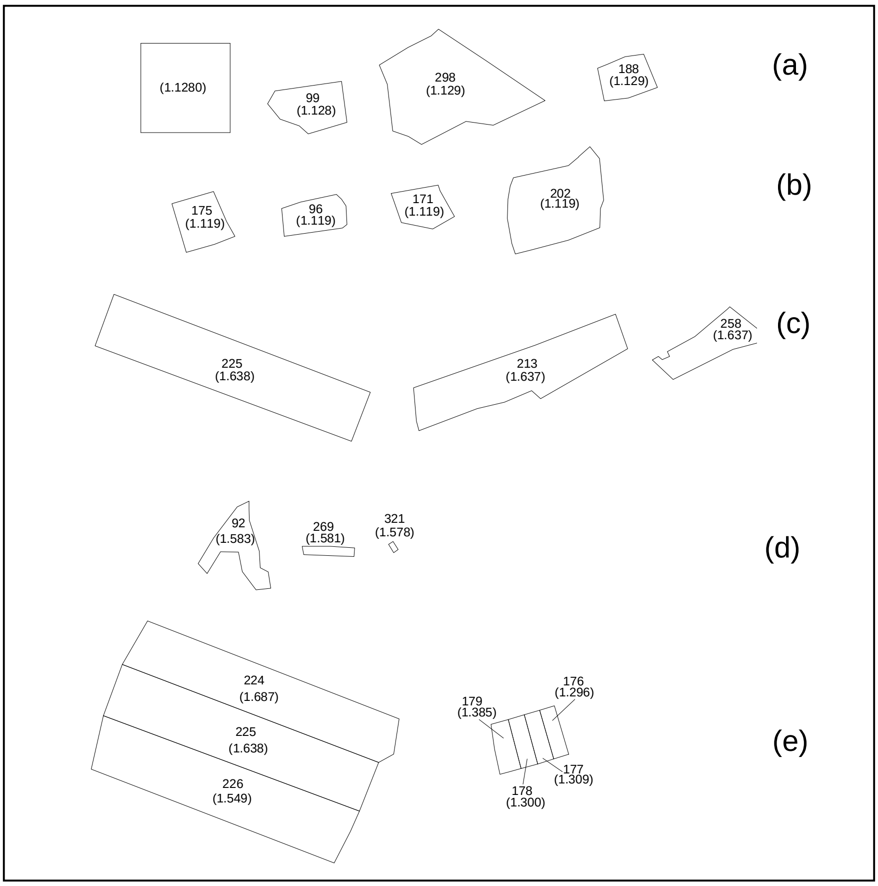


Figure 12: Shape index (SI) for various shapes taken from the Cyprus case study

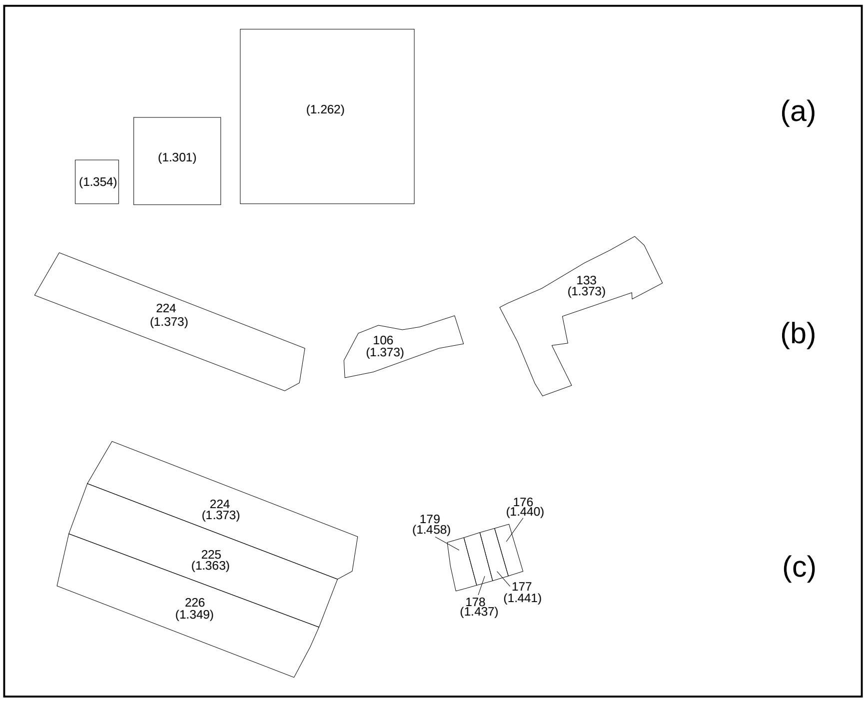


Figure 13: Fractal dimension (FD) for various shapes taken from the Cyprus case study

agricultural purposes based on the maximum useful area (i.e. the area that can actually be exploited) is 0.04 and corresponds to a rectangle with a length:breadth ratio of 4:1. This index has been incorporated into a broader measure called the combined size and shape index (CSSI), which is an estimate of tillage time per useful area based on a predefined set of 36 standard parcel shapes.

Similar to the SI and FD noted above, the AFF only fulfils requirement (iii) as shown in Figure 14f. In contrast, Figures 14a-e indicate that completely different shapes, which are clearly very bad for agricultural purposes, may have very close AAF values with orthogonal shapes (of various length:breadth ratios) and thus requirements (i) and (ii) are not fulfilled.

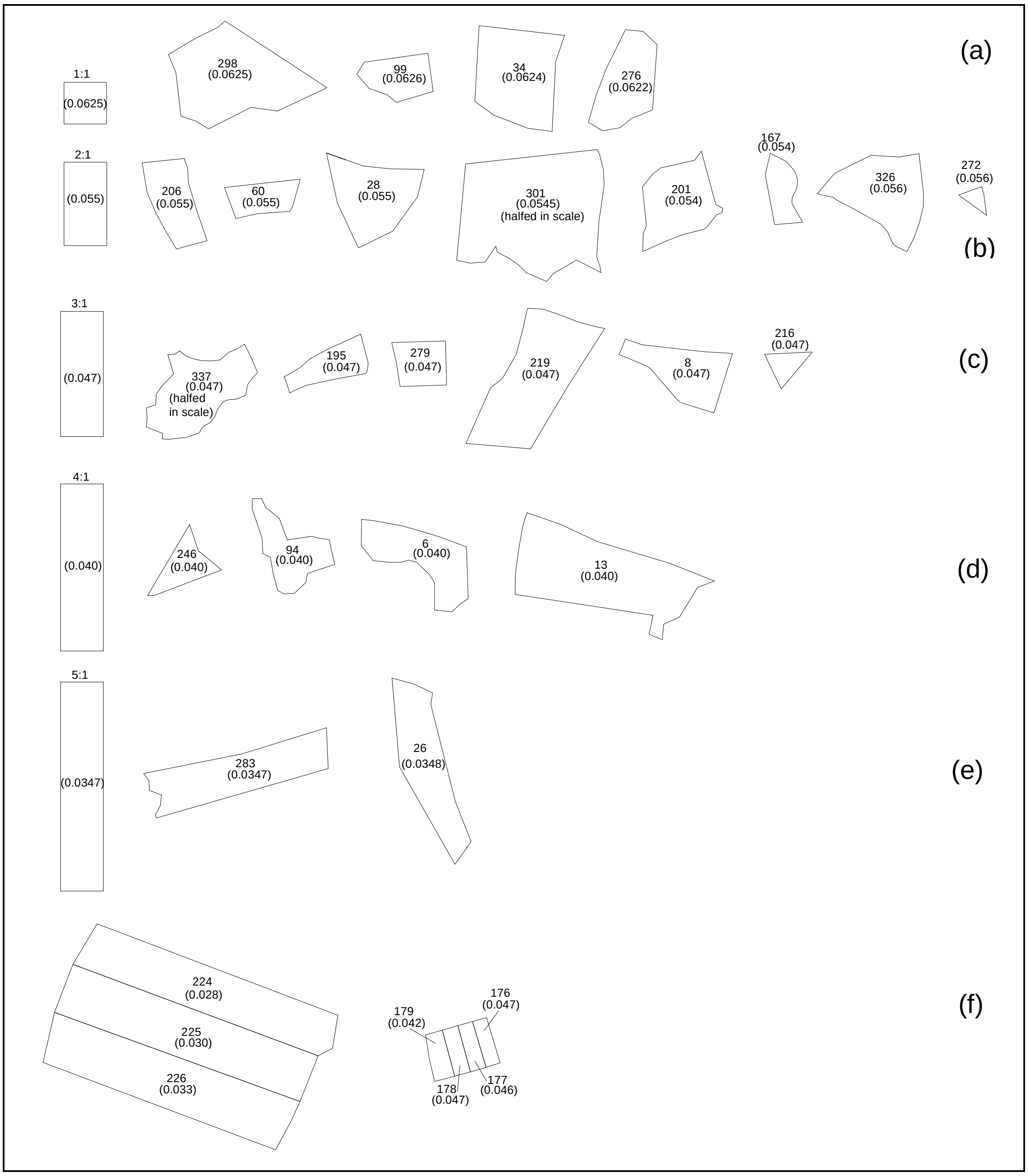


Figure 14: AAF values for various parcel shapes taken from the Cyprus case study

In other words, while the AAF gives certain numbers for rectangular shapes of different length:breadth ratios, the same numbers represent considerably irrelevant and irregular shapes. This is also obvious in the AAF values of the 36 standard parcel shapes defined by Gonzalez *et al*. (2004), which is a serious disadvantage of this methodology. Similar to the previous indices, requirements (iv) and (v) are not satisfied.

In addition, the AAF is poor at representing shapes appropriate for agriculture because it actually measures only the compactness of a shape (MacEachren, 1985; Amiama *et al*., 2008). In particular, if the relation between the area and the perimeter of a shape is in 'harmony', then the AAF takes a value of greater than 0.04; otherwise a shape with a tailed or complex form takes a value of less than 0.04 as shown in the thematic map with AAF values for all the parcels in the case study area (Figure 15).

To overcome the deficiencies of existing shapes indices, more factors must be taken into account that will be capable of comprehensively representing all shape parameters, and are able to collectively define what are good and bad shapes for a land parcel. Efforts in this direction have been made by Amiama *et al*. (2008) who proposed two new indices to overcome the deficiencies of the AAF. The first index is quadrilateral with orthogonal sides that best circumscribe the analysed parcel and the second index is an expansion of the first one by applying a correction factor resulting from comparing the parcel perimeter with the perimeter of the quadrilateral that circumscribed the parcel. This correction penalises the shape index depending on the number of vertices and the number of acute vertices. The second index is measured on a scale between 0 and 1.

Amiama *et al*. (2008) argue that the two proposed indices were slightly better than using the AAF. Thus, as they are only slightly better, both new indices will most likely present similar weaknesses to those of the AAF noted earlier although insufficient details are provided in the paper to carry out a proper comparison. In another recent attempt, Libecap and Lueck (2009) utilised a variation of the area perimeter ratio ($p_i / \sqrt{a_i}$) and the number of sides to assess parcel shape. This latter index should present similar deficiencies to those of the SI, FD and AAF since it belongs to the same family, i.e. area:perimeter ratio. Therefore, the latest indices are not good enough for the purpose of determining land fragmentation and hence further research is needed to produce a more comprehensive and accurate parcel shape index.

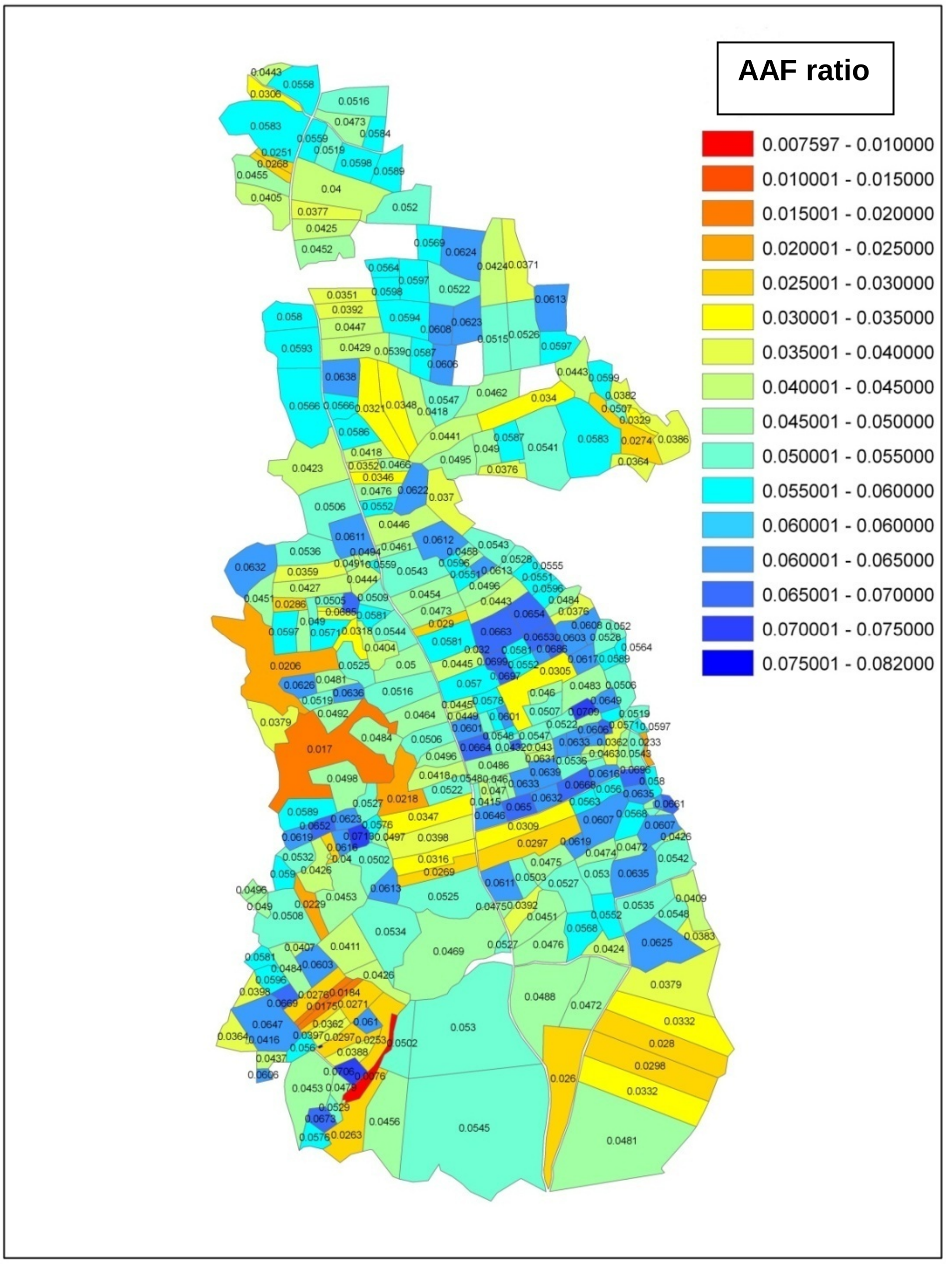


Figure 15: Thematic map classifying AAF for the parcels of the case study area

7.3 A new shape analysis index for land consolidation

A new parcel shape index (PSI) has been developed which involves six significant parameters that comprehensively describe the shape of a land parcel compared with an optimum-standard shape. This index explicitly defines the best and worst shape for agricultural development, i.e. the shape index equals 1 and 0 respectively. The PSI for parcel ID*i* consists of six functions of shape properties:

$PSI_i = f\,(\text{length of sides}) + f\,(\text{acute angles}) + f\,(\text{reflex angles}) + f\,(\text{boundary points})$
$+ f\,(\text{compactness}) + f\,(\text{regularity})$ (11)

As noted earlier, an irregular parcel shape has significant disadvantages regarding its current and future exploitation. Thus, five land consolidation experts have set out various geometrical rules through value functions to define optimum parcel shape. The rules are based on the empirical assumption that the most effective parcel shape (at least those created in land consolidation areas) is a rectangle with a length:breadth ratio of 2:1 for which the PSI will result in a value of 1, i.e. the best value. Other acceptable shapes such as a square or a rectangle with a length:breadth ratio of 3:1 are also assigned values very close to 1, namely, 0.931 and 0.889, respectively. As the length:breadth ratio continues to increase, i.e. to 4:1 and 5:1, the value of the PSI decreases to 0.598 and 0.315 respectively, indicating that the shapes are less desirable for land consolidation. These shapes and their PSI values are shown in Figure 16. The six geometric parameters involved in the calculation of the PSI are described below.

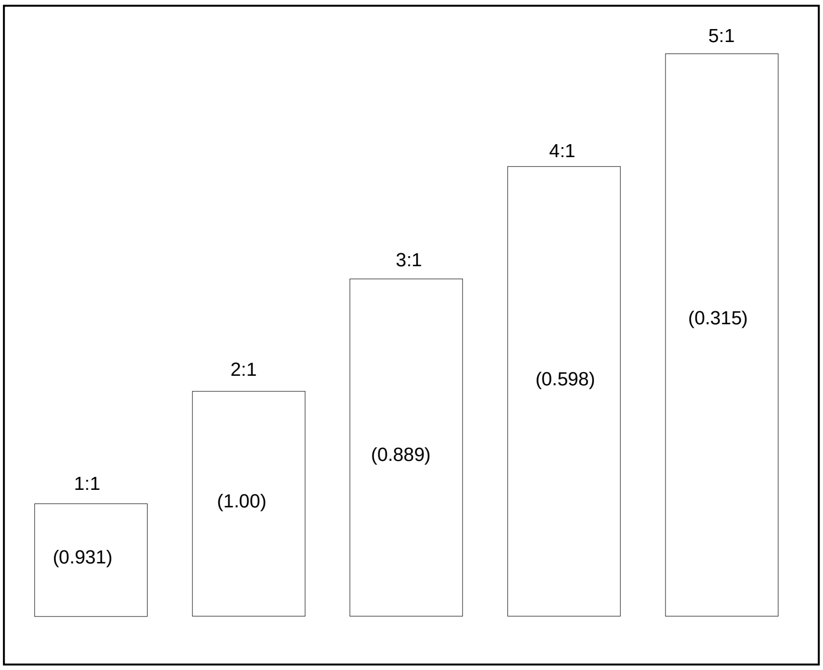


Figure 16: PSI values for rectangles with various length:breadth ratios

Length of sides

The length of a side of a land parcel should exceed some minimum (especially in the frontage) and theoretically may reach any value depending on the length of the other sides and the area. The minimum size of parcels based on Cypriot legislation is 1 donum (1,338 m^2) for irrigated parcels, and the minimum acceptable length of a side (especially in the frontage) as defined by the experts is 25 metres. Thus, the number of sides with a length of less than 25 metres will be penalised through a value function. Sides that form angles that are close to a straight line (i.e. between 175° and 185°) are considered by the algorithm to be a straight line.

Acute angles

An acute angle is an angle that is less than 90°. Acute angles constitute a weakness for a land parcel and the more acute angles there are in a shape, the worse this becomes. Experts judged that an acute angle less than 80° should be penalised because it is a significant disadvantage of parcel exploitation (Figure 17).

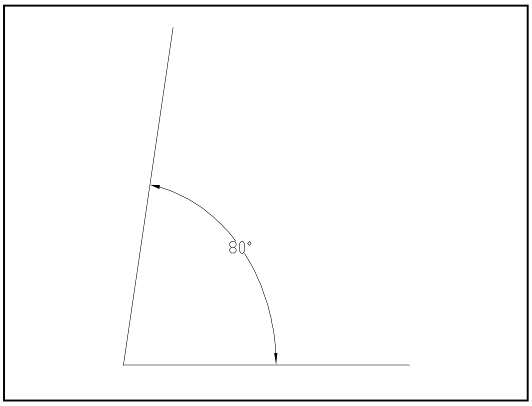


Figure 17: An acute angle of 80°

Reflex angles

A reflex angle is more than 180° but less than 360°. Experts judged that a reflex angle of greater than 215° (Figure 18) should be penalised for the same reason noted earlier. Thus, the number of reflex angles that exceed this limit will be penalised based on a value function.

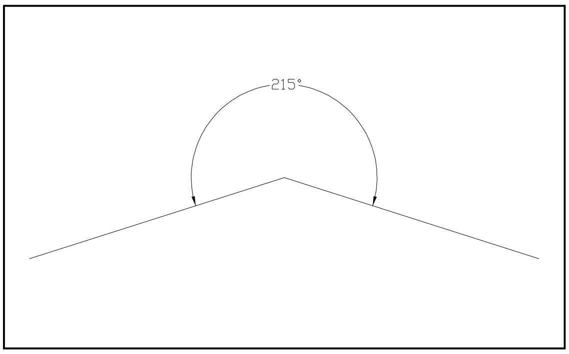


Figure 18: A reflex angle with 215°

Boundary points

The number of corners of a parcel defines the density and complexity of a polygon. Thus, clearly the desirable number of boundary points for a land parcel is four while a slightly higher number of points may not worsen a shape if all other factors are satisfied. In contrast, a polygon with three points, i.e. a triangle, is not an acceptable shape for a land parcel. Similar to the length of sides, the algorithm ignores points where two joined line segments form angles between 175^{o} and 185^{o}.

Compactness

Compactness represents the degree to which a shape is compact in terms of morphology. Symmetrical shapes are compact in contrast to shapes that are fragmented, elongated, perforated and protruded. MacEachren (1985) compared and evaluated eleven different measures of compactness with varying levels of accuracy. As noted earlier, the most popular index which has been utilised in practical problems for evaluating parcel shape is the AAF which measures compactness. Although problematic for the reasons outlined before, it is necessary to include this factor in the new shape index because it ensures that a shape has an appropriate area:perimeter ratio.

However, the incorporation of the AAF into the PSI calculation introduces some bias, i.e. it favours all regular polygons such as triangles or pentagons over rectangles even though these regular polygons are bad shapes for land parcels. Experiments were undertaken in which the AAF was excluded from the PSI calculation but this resulted in favouring shapes with a non-proportional area:perimeter relationship. Thus, the AAF has been included and regular polygons of a poor shape for land consolidation are simply penalised.

Regularity

Any regular polygon has a rotational symmetry; thus, all of its points lie on a common circle (the circumscribed circle) as shown in Figure 19.

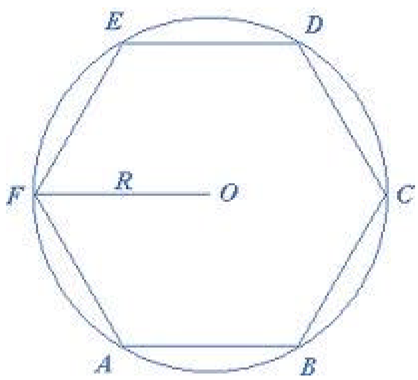


Figure 19: Rotational symmetry of a regular polygon

In addition, a regular polygon has all sides and angles equal. Therefore, this factor is used to check if a parcel has a regular shape like that of the optimum shape. With the exception of a square, all other regular polygons (such as a triangle, a pentagon, a hexagon) are undesirable shapes for a land parcel and as a result are erroneously favoured. As with compactness, these undesirable polygons are penalised. Regularity is measured as the standard deviation of the radials, i.e. distances between the centroid of a parcel and all the boundary points of a parcel. A zero standard deviation means a completely regular shape with increases in irregularity as the standard deviation increases.

7.4 Standardisation

The first five shape parameters are standardised using value functions while regularity is standardised by employing the mSM described later in section 8. In addition, it is noted that in all of the value functions that follow, scores lower than X_{min} are standardised to 0, while scores higher than X_{max} are standardised to 1, which is the optimum or best shape for a given geometric factor.

Length of sides

Figure 20 presents a convex cost function, i.e. the higher the score (axis Y), the worse the factor becomes, as represented by equation 12:

$$V(x_i) = 0.99 + 1.49(10^{-2} x_i^{1.5}) - 0.46(x_i^{0.5}) \qquad (12)$$

The value function begins from a score of zero parcel sides that corresponds to the maximum value of 1 (Y axis) and falls relatively sharply to a value of 0.5 that corresponds to a score of 1 (X axis). The function then gradually decreases until a value of 0.1 corresponds to a score of 5 and afterwards slowly decreases until a minimum value of 0 corresponds to a score of 10. This function favours shapes with 0 sides with less length than the minimum limit and then gradually penalises shapes with 1 to 10 (including more than 10) sides of this type.

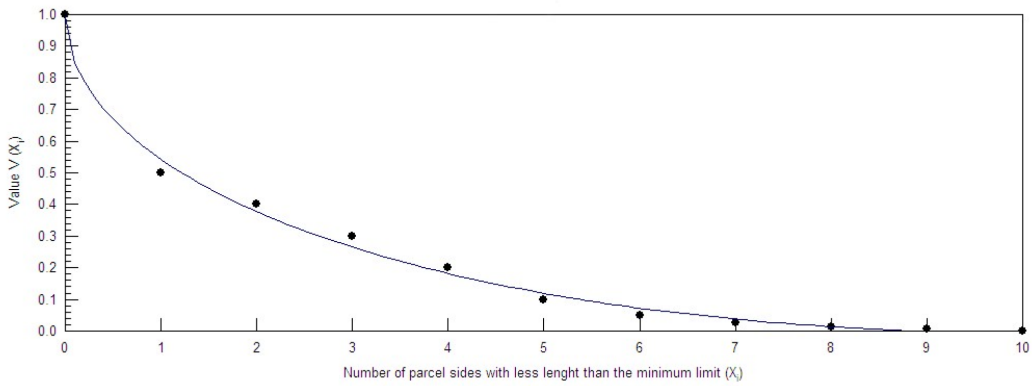


Figure 20: The value function for the number of parcel sides with length less than the minimum limit

Acute angles

Figure 21 presents a convex cost function:

$$V(x_i) = \frac{1}{(1 + 6.05x_i + 2.71x_i^2)} \tag{13}$$

which very rapidly drops from the maximum value, that is 1 (corresponding to a score of 0 on the X axis) to a value of 0.1, which corresponds to a score of 1. Then the function slowly bottoms out to a value of zero at 10 acute angles. This function significantly favours shapes with no acute angle being less than the minimum limit of 80^o, whilst in contrast, it considerably penalises (by assigning a value around 0) those shapes having one or more acute angles with less than the minimum limit.

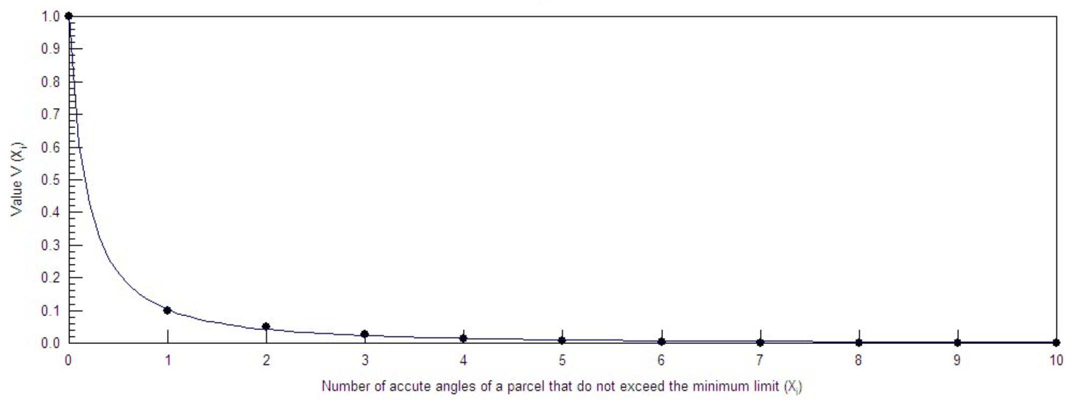


Figure 21: The value function for the number of acute angles that do not exceed the minimum limit

Reflex angles

The value function for the number of reflex angles that exceeds the maximum limit (215^o) is represented by the same function and equation for acute angles as illustrated in Figure 22 and equation 14, respectively.

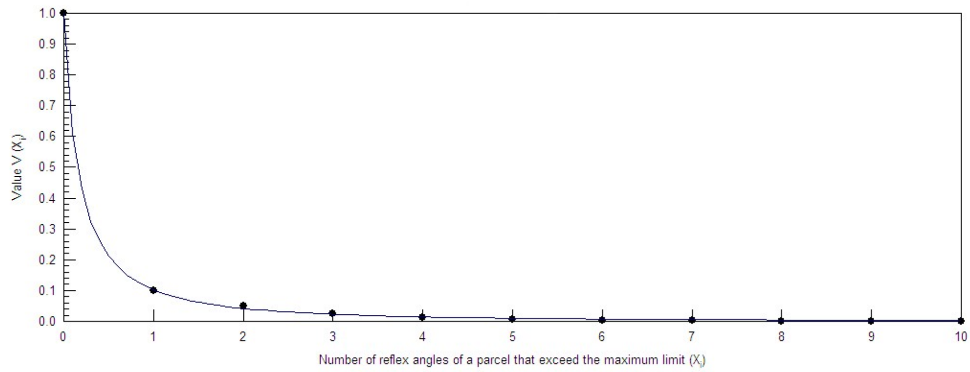


Figure 22: The value function for the number of reflex angles that exceed the maximum limit

$$V(x_i) = \frac{1}{(1+6.05x_i + 2.71x_i^2)} \tag{14}$$

Boundary points

Figure 23 presents a concave value function represented by equation 15:

$$V(x_i) = 14.45 - 407.76/x_i + 4280.97/x_i^2 - 20959.323/x^3{}_i + 49414.25/x_i^4 - 45677.80/x_i^5 \tag{15}$$

that begins with a score of three boundary points, representing a triangle that corresponds to the worst value of 0 because the triangle is a very bad shape for a land parcel. The function then reaches a peak with a score of 4 which represents the number of points of the optimum shape and afterwards gently decreases as the number of points increases. Finally, the function bottoms out at 10 boundary points that corresponds to the worst value of 0. If a land parcel does not have the ideal number of boundary points (4), then it can still be considered as acceptable with five (with a value of 0.9) or even six (with a value of 0.65) boundary points as expressed by the experts. After six boundary points, shapes are significantly penalised so that land parcels with more than seven points correspond to the worst value of around 0.

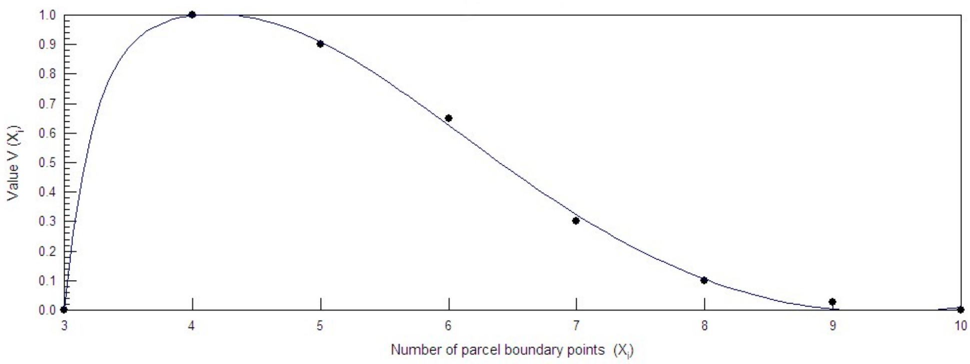


Figure 23: The value function for number of parcel boundary points

Compactness

The value function is shown in Figure 24 and is represented by equation 16:

$$V(x_i) = -1467298744.97x_i^6 + 4133386014.178x_i{}^5 - 45406553.82x_i^4 + 2435303.92x^3{}_i \\ - 65445.193x_i^2 + 831.98x_i - 3.91 \tag{16}$$

The function can be divided into two parts. The first part is an S-shaped curve that begins from a minimum value of zero that corresponds to scores of less than or equal to 0.02 and then swiftly increases to a peak value of 1 that corresponds to a score of 0.055 which represents the optimum shape. The second part goes from a maximum value of 0.95 (corresponding to a score of 0.06) and then gradually levels off to a value of 0.9 corresponding to a maximum score of 0.075 as specific to the case study. This value function has been defined based on the assessment of the thematic map shown in Figure 15.

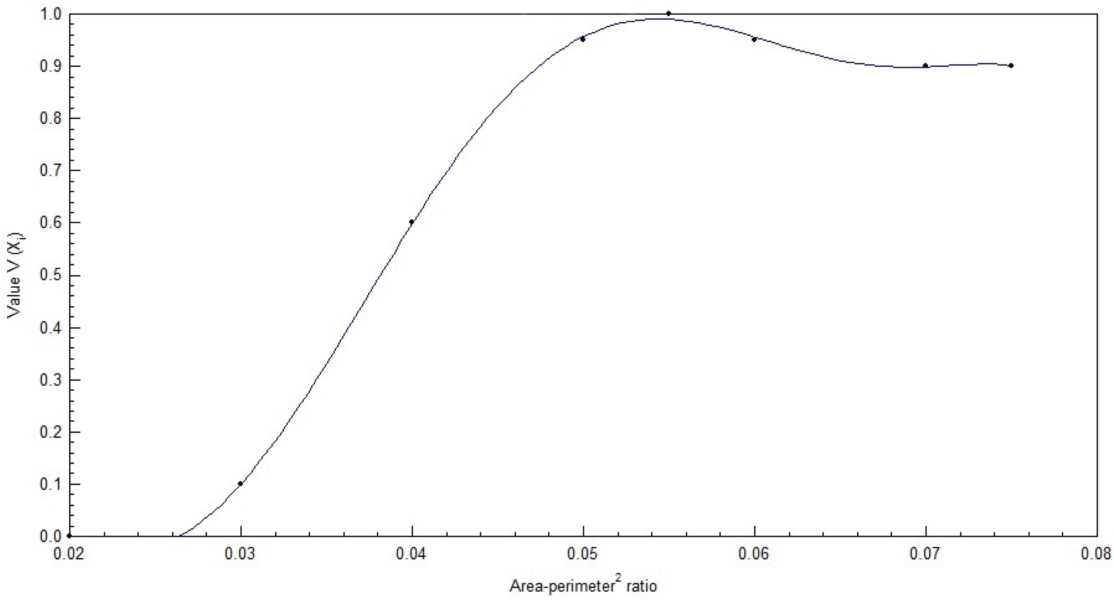


Figure 24: The value function for the area: perimeter^2 ratio

Based on this thematic map, the experts found that the best compactness ratio is found in concentrated shapes which are not tailed or prolonged. Such shapes have a compactness value between 0.050 and 0.060 with the best value of 0.055 which corresponds to the optimum shape. Values between around 0.05 and 0.025 present a gradual reduction in the quality of compactness, while values of less than 0.025 represent tailed, elongated and protruded shapes. At the other end of the spectrum, values greater than 0.060 represent good shapes that are close to rectangles.

Regularity

Regularity, which is represented by the standard deviation of radials of each parcel, may take any score. Thus, while it is clear that the best score is 0, i.e. the parcel shape is absolutely regular or more precisely symmetrical, the worst score is unknown and it will be necessary to set an arbitrary upper limit for the worst regularity score. For this reason, the mSM is utilised to transform the original regularity scores as explained in more detail in section 8.

8 Generation of a standardised land fragmentation table

As noted earlier, the only land fragmentation factor that needs standardisation is the dispersion of parcels (DoP) since it may take any positive value (in metres). There are factual data available on this index so it is hard for experts to define a value function based on their judgement. In addition, the DoP is measured on a ratio scale, i.e. values are real and may vary considerably from project to project. Thus, a more generic standardisation method is recommended.

The DoP could be standardised using a linear cost function, i.e. the higher the DoP, the worse it is. This function presents a proportional increase of standardised values from 0 to 1 based on the minimum and maximum DoP scores, respectively. Sharifi *et al*. (2007) review a series of linear standardisation methods. The maximum standardisation appears to be the most appropriate for this factor because the DoP is measured on a ratio scale; thus the relative differences must be preserved and hence the standardised values are proportional to the original values. However, maximum standardisation may present a disadvantage in the situation when the minimum and maximum values of the sample are extreme. For example, a holding with one parcel has a DoP of zero while a holding with several parcels may have a DoP of several kilometres. Thus, we introduce the so called mean standardisation method (mSM) by adding 1 to the formulae similar to that undertaken for the calculation of PPI (Demetriou *et al*., 2011c), which balances the potential extreme minimum and maximum values by taking into account the mean of the sample. Therefore the modified formulae are:

$$E_i = 1 - \left(\frac{(S_i - \min S) * 0.5}{meanS - \min S} \right) \text{ (if } S_i \leq meanS \text{)} \tag{6}$$

and

$$E_i = 1 - \left(\left(\frac{(S_i - meanS) * 0.5}{\max S - meanS} \right) + 0.5 \right) \text{ (if } S_i > meanS \text{)} \tag{7}$$

where E_i is the standardized value of score S_i and $\min S, \max S, meanS$ are the corresponding statistical values for all the scores in the dataset.

Table 2 presents an example of standardisation of values obtained using both methods. This example includes ‘extreme’ values i.e. three 0s and one value of 10000 so as to show the difference between the two methods. It is apparent that the maximum SM assigns a value of 0.75 for the mean score of the sample i.e. 2,500, whilst the mSM assigns the value of 0.5 for the same score which is exactly half, i.e. the mean of the standardization range from 0 to 1. The latter outcome indicates that the mSM balances the standardisation process by precisely assigning values based on the original scores. In accordance with this, the mSM assigns smaller values to the other scores compared to those assigned by the maximum SM. As a result, large scores are not favoured over small scores when standardised because of the way the mSM operates.

Table 2: Results obtained by the maximum and mean standardisation methods

Values	Maximum standardisation	mSM
10,000	0.00	0.00
5,000	0.50	0.33
3,000	0.70	0.47
2,500	0.75	0.50
2,000	0.80	0.60
1,500	0.85	0.70
1,000	0.90	0.80
0	1.00	1.00
0	1.00	1.00
0	1.00	1.00
The minimum, maximum and mean values of the sample are 0, 10,000 and 2,500, respectively.		

It is worthwhile noting that the median is not an appropriate measure for this case because usually there are many holdings that include only one parcel, i.e. the DoP is 0. Thus, the DoP is skewed towards small values and this fact will bias the standardisation. The mSM will overcome this limitation by using the mean value and therefore produce better results. Standardisation is carried out via the ‘Standardised LF table’ menu item that launches a window as shown in Figure 25.

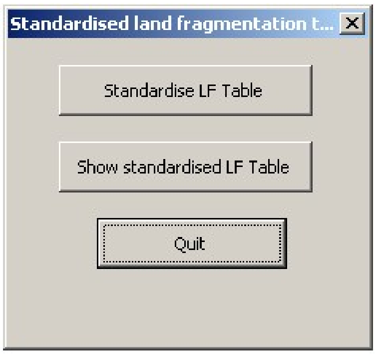
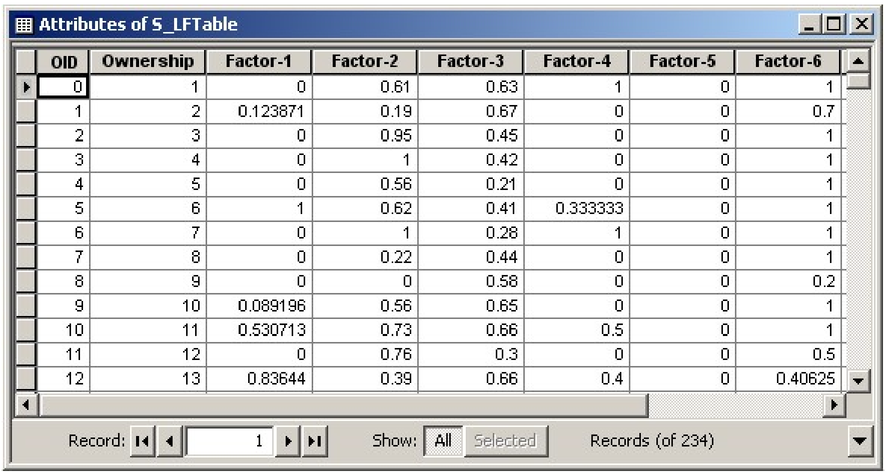


Figure 25: The window for standardising the LF table

This window provides two operations, i.e. standardise and show the LF table where an example of a standardised LF table is shown in Figure 26. As expected, all values of the factors range between 0 and 1.



Attributes of S_LFTable

OID	Ownership	Factor-1	Factor-2	Factor-3	Factor-4	Factor-5	Factor-6
0	1	0	0.61	0.63	1	0	1
1	2	0.123871	0.19	0.67	0	0	0.7
2	3	0	0.95	0.45	0	0	1
3	4	0	1	0.42	0	0	1
4	5	0	0.56	0.21	0	0	1
5	6	1	0.62	0.41	0.333333	0	1
6	7	0	1	0.28	1	0	1
7	8	0	0.22	0.44	0	0	1
8	9	0	0	0.58	0	0	0.2
9	10	0.089196	0.56	0.65	0	0	1
10	11	0.530713	0.73	0.66	0.5	0	1
11	12	0	0.76	0.3	0	0	0.5
12	13	0.83644	0.39	0.66	0.4	0	0.40625

Record: 1 Show: All Selected Records (of 234)

Figure 26: An example of a standardised LF table

9 Calculation of land fragmentation indices

Land fragmentation indices can be calculated by the 'LF indices' icon, which launches a window like that shown in Figure 27 and provides six buttons for calculating and showing: the LFI for each ownership; the GLFI; and the contribution of each factor to land fragmentation at both the ownership and global levels.

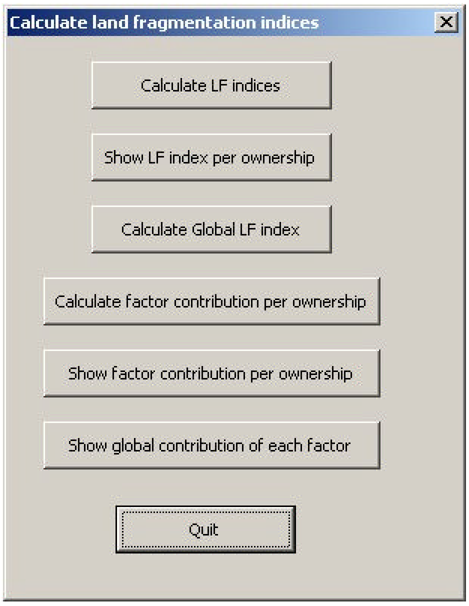
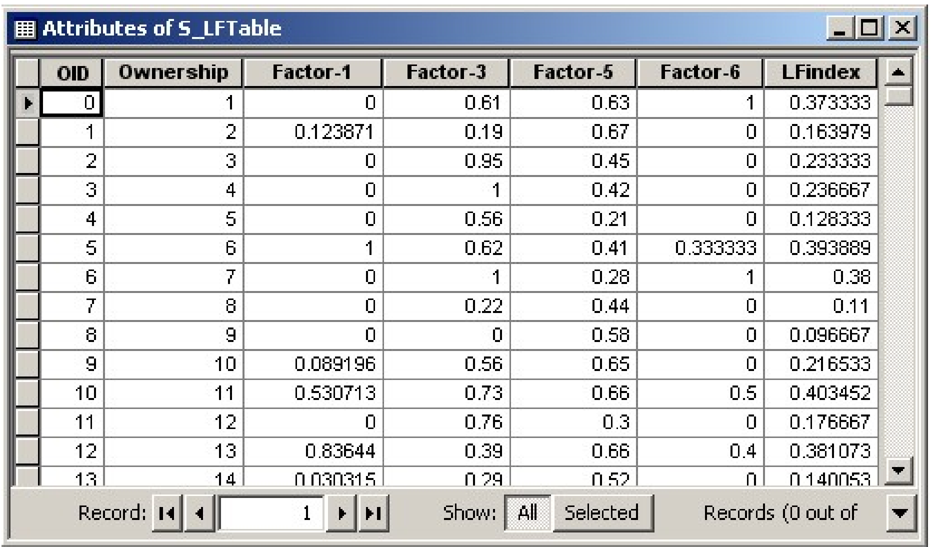


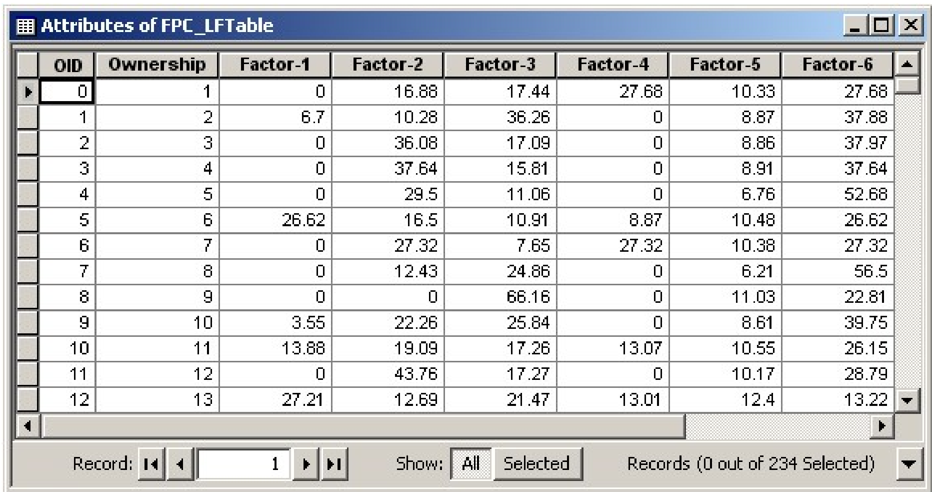
Figure 27: The window for calculating land fragmentation indices

As noted in section 3, an ownership level LFI is computed and stored in the field 'LFindex' in the S_LFTable (standardised land fragmentation table) as shown in Figure 28. The contribution of each factor to the ownership level of land fragmentation is calculated as the percentage of the value $f_j w_j$ relative to the whole $\mathrm{LF_i}$ value and stored in the FPC_LFTable (factor percentage contribution land fragmentation table) as shown in Figure 29. The global contribution of each factor is estimated as the mean value of these percentages for all ownerships.



OID	Ownership	Factor-1	Factor-3	Factor-5	Factor-6	LFindex
0	1	0	0.61	0.63	1	0.373333
1	2	0.123871	0.19	0.67	0	0.163979
2	3	0	0.95	0.45	0	0.233333
3	4	0	1	0.42	0	0.236667
4	5	0	0.56	0.21	0	0.128333
5	6	1	0.62	0.41	0.333333	0.393889
6	7	0	1	0.28	1	0.38
7	8	0	0.22	0.44	0	0.11
8	9	0	0	0.58	0	0.096667
9	10	0.089196	0.56	0.65	0	0.216533
10	11	0.530713	0.73	0.66	0.5	0.403452
11	12	0	0.76	0.3	0	0.176667
12	13	0.83644	0.39	0.66	0.4	0.381073
13	14	0.030315	0.29	0.52	0	0.140053

Figure 28: The LFindex field in the S_LFTable


Attributes of FPC_LFTable

OID	Ownership	Factor-1	Factor-2	Factor-3	Factor-4	Factor-5	Factor-6
0	1	0	16.88	17.44	27.68	10.33	27.68
1	2	6.7	10.28	36.26	0	8.87	37.88
2	3	0	36.08	17.09	0	8.86	37.97
3	4	0	37.64	15.81	0	8.91	37.64
4	5	0	29.5	11.06	0	6.76	52.68
5	6	26.62	16.5	10.91	8.87	10.48	26.62
6	7	0	27.32	7.65	27.32	10.38	27.32
7	8	0	12.43	24.86	0	6.21	56.5
8	9	0	0	66.16	0	11.03	22.81
9	10	3.55	22.26	25.84	0	8.61	39.75
10	11	13.88	19.09	17.26	13.07	10.55	26.15
11	12	0	43.76	17.27	0	10.17	28.79
12	13	27.21	12.69	21.47	13.01	12.4	13.22

Record: 1 Show: All Selected Records (0 out of 234 Selected)

Figure 29: An example of a factor percentage contribution land fragmentation table

10 Sensitivity analysis

In the case of MADM, two important elements need to be examined in the context of sensitivity analysis (SA): the weights of the criteria and the criterion scores (or performance measures) (Triantaphyllou, 1997; Malczewski, 1999). Triantaphyllou's methodology allows investigation of both elements regarding altering the ranking order of alternative solutions. Similarly, this model inherently involves two sources of uncertainty: the weighting of land fragmentation factors by the planner and the estimation of the performance scores of ownership for three out of six factors (F1, F2 and F3) because of the utilisation of standardisation methods, namely, the mSM and value functions which are defined by experts. The model provides an SA operation for the former and not for the latter source of uncertainty.

In particular, the model incorporates a SA operation for investigating predefined weighting alterations for various percentages from 10 to 100% (at increments of 10%) provided by the 'Sensitivity analysis' menu bar, which launches a window like that shown in Figure 30. On the other hand, it is impossible to investigate systematically the potential sensitivity of performance scores because any standardisation method, especially a different value function, may result in considerably different scores with an irregular pattern. Therefore, standardisation methods need to be applied with awareness. Value functions in particular need to be carefully considered by experts by analysing their behaviour, i.e. the sensitivity of each function during the process of its definition.

The SA window provides new outcomes regarding the land fragmentation indices defined in the previous section, based on selected increases or decreases in the value of a particular weight and the proportional readjustment of the value of the rest of the weights. Thus, a planner may compare the results for various changes of weights and assess the sensitivity of each factor for all land fragmentation indices.

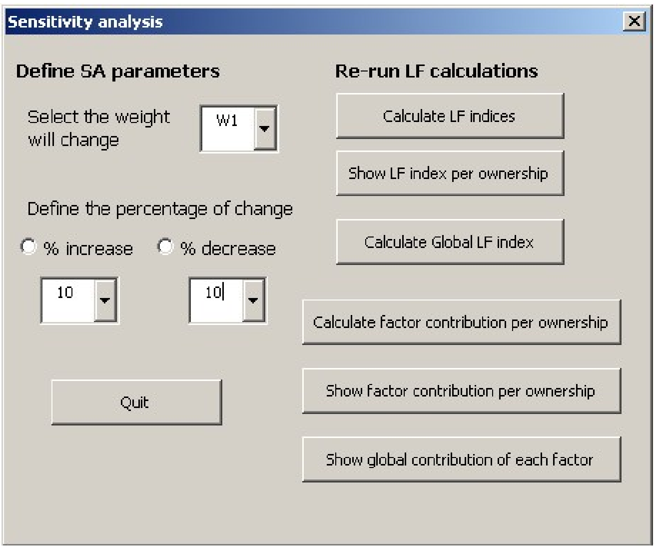


Figure 30: The window for carrying out SA on the weights of the factors

11 A case study

In this section, LandFragmentS is applied to the case study area. Four issues are investigated: the four weighting scenarios; the comparison of the GLFI with existing indices; a sensitivity analysis focused on changes to the weights; and a comparison of the new PSI with existing indices.

11.1 The effect of changing the weights of the factors

Land fragmentation at both levels, i.e. ownership and global, has been calculated based on four scenarios. In scenario 1, all six criteria have been given the same weight. In scenario 2, weights were assigned to each of the first five criteria in the following descending order of importance: extremely high, very high, high, intermediate, moderate and low. In contrast, the weights in scenario 3 have been assigned in ascending order of importance, whilst in scenario 4, they were assigned based on the judgement of the author as: very high, high, extremely high, extremely high, intermediate and high.

Table 3 reveals firstly, that there is no combination of weights that results in a considerably different picture regarding existing land fragmentation. The maximum difference, i.e. between the minimum and maximum GLFI (scenarios 2 and 3, respectively) is not significant, i.e. 13.03%. As a result, there is no issue regarding the existence of a land fragmentation problem for the case study area since the GLFI is around 0.50 in all scenarios. That is, the current situation is around 50% from the optimum situation and this suggests a significant deficiency in the tenure system. Land fragmentation is therefore a problem in this area. Empirically, it could be said that a GLFI of greater than 0.70 could imply a satisfactory situation where 1 means no land fragmentation problem at all and 0 suggests very serious land fragmentation. This assumption could be investigated in more detail by considering other economic indices regarding agricultural production, farmer income, *et cetera*.

Table 3: The GLFI and the impact of each factor for four weighting scenarios

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
GLFI	0.512		0.555		0.491		0.515	
	Weight	Contribution	Weight	Contribution	Weight	Contribution	Weight	Contribution
F1	0.167	26.34	0.303	42.18	0.061	10.98	0.182	28.32
F2	0.167	15.69	0.242	21.25	0.091	9.1	0.136	13.06
F3	0.167	18.92	0.182	18.95	0.121	15.23	0.227	25.33
F4	0.167	6.94	0.121	5.03	0.182	7.66	0.227	9.14
F5	0.167	8.45	0.091	4.38	0.242	13.03	0.091	4.58
F6	0.167	23.66	0.061	8.21	0.303	44.00	0.136	19.57
Sum	1.00	100	1.00	100	1.00	100	1.00	100

F1: Dispersion; F2: Size; F3: Shape; F4: Accessibility; F5: Dual ownership; F6: Shared ownerships

Secondly, although the impact of each factor in the land fragmentation problem is influenced by the weight assigned to each factor, it seems that some factors achieve the highest or among the three highest contributions to this problem, independent of the weight. In particular, F1 (the dispersion of parcels) has the highest negative impact in three out of four scenarios followed by F6 (shared parcels) with the highest, second highest and third highest contribution in scenarios 3, 1 and 4 respectively; F3 (parcel shape) has the second highest contribution in scenarios 3 and 4 and the third highest contribution in scenarios 1 and 2. Other factors have less influence. This outcome suggests that factors F1, F6 and F3 magnify and are responsible for the land fragmentation problem in the case study area compared to factors F2, F4 and F5 that have less influence in this particular context.

11.2 Comparison of the *LandFragmentS* indices with existing indices

The Simmons and Januszewski indices present very similar patterns as shown by their distributions in Figures 31 and 32, respectively. As a result the correlation coefficient is very high indeed ($r = 0.98$). The difference between the indices is that the Januszewski index gives higher values with a minimum of 0.364, an average of 0.841 (maximum value is 1 for both indices) and a narrow spectrum of values (standard deviation of 0.186). Many values of this index are 1 (as shown in the scatter plot in Figure 34). In contrast, the Simmons index gives lower values with a minimum of 0.160, an average of 0.785 and a wider range of values (standard deviation equals 0.262), as shown in Figures 32 and 34.

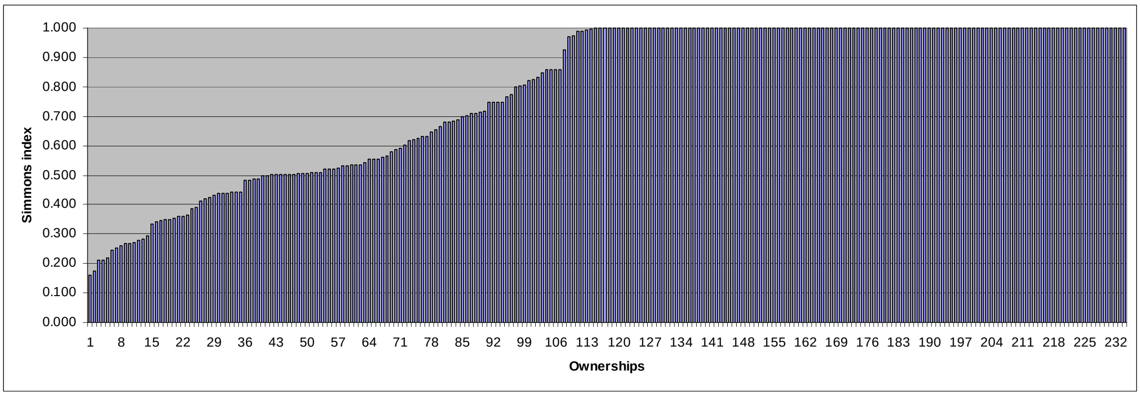


Figure 31: Distribution of Simmons index across holdings

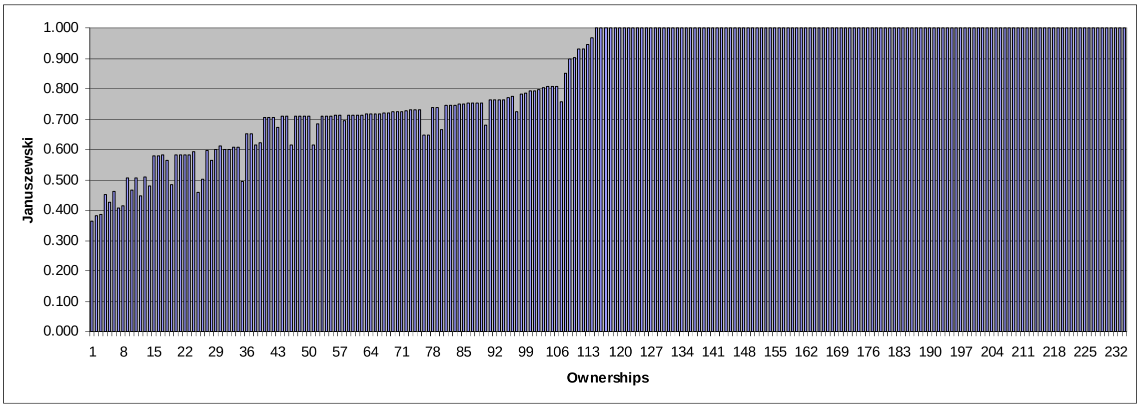


Figure 32: Distribution of Januszewski index across holdings

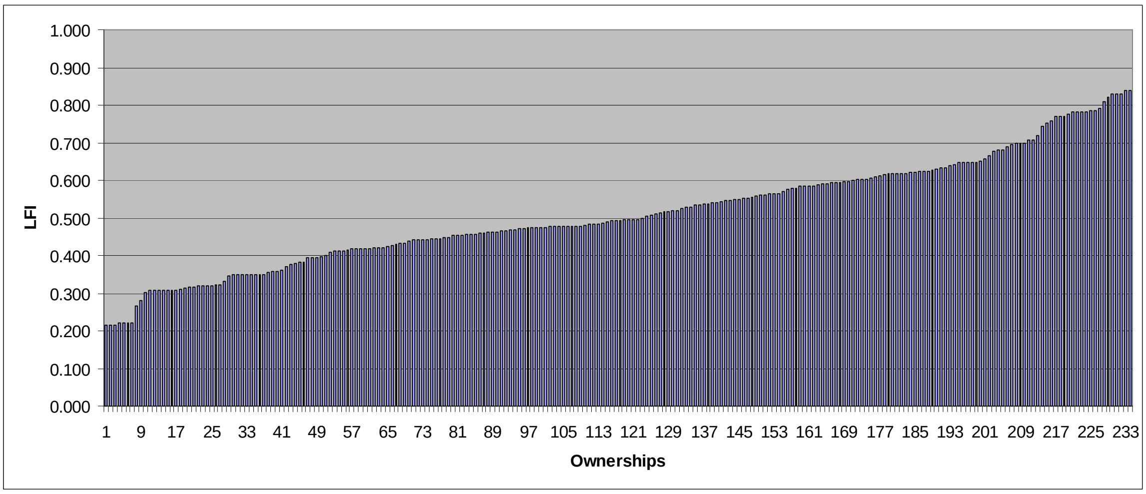


Figure 33: Distribution of the new LFI index across holdings

On the other hand, the new index (LFI) clearly results in considerably lower values compared to both existing indices (although the minimum value of the Simmons index is lower) as shown by the distribution in Figure 33 and revealed by the values of the basic statistics:

minimum 0.216; maximum 0.839; and average 0.512. It is also noteworthy that no holding achieves the maximum LFI value of 1. The lower spectrum of values of this index (with standard deviation equal to 0.143) compared with the other two indices is obvious from the dispersion of points in Figure 34.

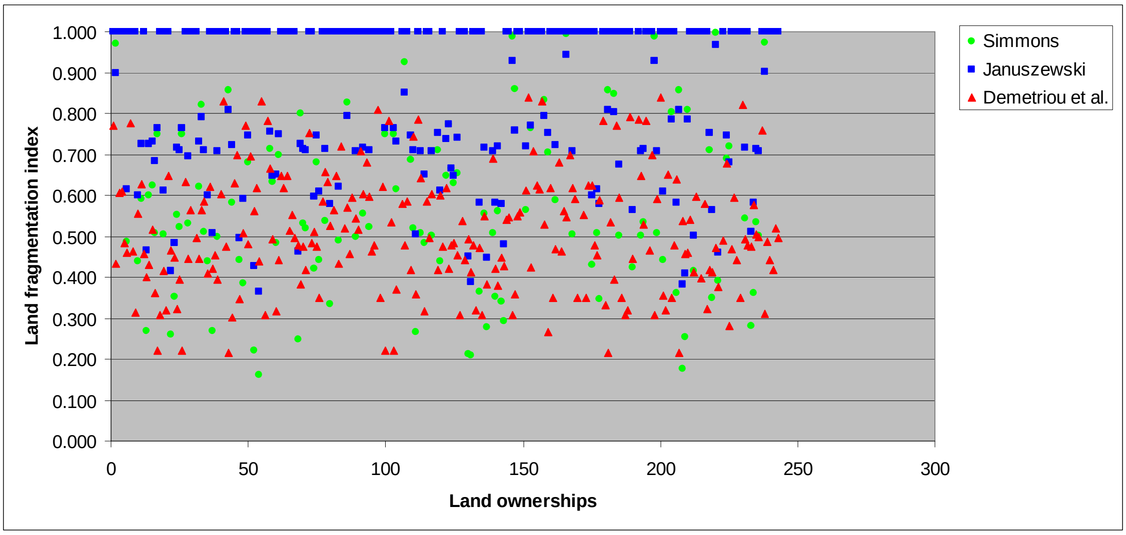


Figure 34: Comparison of the values of the three land fragmentation indices

Whilst the Simmons index takes into account only two interrelated factors (the size of each parcel and the size of each holding), the Januszewski index only measures the size of each parcel. In contrast, the LFI and GLFI indices rely on the six independent factors noted above. Both of the existing indices underestimate the problem of land fragmentation with higher average values, i.e. around 0.8 in both cases. As a result, the policy decisions made from these indices will be wrong. In contrast, the GLFI outcome of around 0.5 suggests that the area concerned has a significant land fragmentation problem since the global value is a little more than half that compared with the results of the existing indices. It is interesting to note that land consolidation was carried out in this study area which is a decision closer to the GLFI and not to both existing indices. However, decisions for applying land consolidation at the time of the case study were based on feasibility studies that focused on economic indices which directly related to land fragmentation compared to the current situation in which environmental impact assessment studies are carried out.

11.3 Sensitivity analysis

Table 4 shows the GLFI values and percentage changes (compared with the GLFI when the weights are equal) for either an increase or decrease in the weight of each factor by 10 to 100%. The last row of the table shows the maximum percentage difference of the GLFI values for the minimum to maximum change, i.e. 10 to 100%.

Table 4: Sensitivity analysis of the weights of the factors

Weight change (%)	W1				W2				W3			
	Increase		Decrease		Increase		Decrease		Increase		Decrease	
10	0.517	-0.77	0.507	-0.986	0.512	0.00	0.512	0.00	0.513	0.19	0.512	0.00
20	0.523	0.38	0.502	-1.992	0.512	0.00	0.512	0.00	0.513	0.19	0.511	-0.20
30	0.528	1.33	0.497	-3.018	0.512	0.00	0.512	0.00	0.513	0.19	0.511	-0.20
40	0.533	2.25	0.492	-4.065	0.512	0.00	0.512	0.00	0.514	0.39	0.51	-0.39
50	0.538	3.16	0.487	-5.133	0.512	0.00	0.512	0.00	0.514	0.39	0.51	-0.39
60	0.543	4.05	0.482	-6.224	0.512	0.00	0.512	0.00	0.515	0.58	0.51	-0.39
70	0.549	5.10	0.477	-7.338	0.512	0.00	0.512	0.00	0.515	0.58	0.509	-0.59
80	0.543	4.05	0.472	-8.47	0.512	0.00	0.512	0.00	0.516	0.78	0.509	-0.59
90	0.537	2.98	0.467	-9.64	0.512	0.00	0.512	0.00	0.516	0.78	0.508	-0.79
100	0.531	1.88	0.462	-10.82	0.512	0.00	0.512	0.00	0.516	0.78	0.508	-0.79
Max change (%) of GLFI	2.71		-8.88		0.00		0.00		0.58		-0.78	

Weight change (%)	W4				W5				W6			
	Increase		Decrease		Increase		Decrease		Increase		Decrease	
10	0.507	-0.99	0.517	0.97	0.507	-0.99	0.517	0.97	0.517	0.97	0.508	-0.79
20	0.502	-1.99	0.522	1.92	0.502	-1.99	0.522	1.92	0.521	1.73	0.503	-1.79
30	0.497	-3.02	0.527	2.85	0.497	-3.02	0.528	3.03	0.526	2.66	0.499	-2.61
40	0.492	-4.07	0.532	3.76	0.492	-4.07	0.533	3.94	0.53	3.40	0.494	-3.64
50	0.487	-5.13	0.537	4.66	0.487	-5.13	0.538	4.83	0.535	4.30	0.49	-4.49
60	0.482	-6.22	0.542	5.54	0.482	-6.22	0.543	5.71	0.539	5.01	0.485	-5.57
70	0.477	-7.34	0.547	6.40	0.477	-7.34	0.548	6.57	0.544	5.88	0.48	-6.67
80	0.472	-8.47	0.552	7.25	0.472	-8.47	0.553	7.41	0.548	6.57	0.476	-7.56
90	0.467	-9.64	0.557	8.08	0.467	-9.64	0.558	8.24	0.553	7.41	0.471	-8.70
100	0.462	-10.82	0.562	8.90	0.462	-10.82	0.563	9.06	0.558	8.24	0.467	-9.64
Max change (%) of GLFI	-8.88		8.70		-8.88		8.90		7.93		-8.07	

A general outcome is that the GLFI is not significantly sensitive to changes in the weights because even for a 100% weight change, the maximum change in the index is around ±8.90%, e.g. the GLFI equals 0.462 and 0.563 in the case of an increase and decrease in the weight for F5. This reveals stability in the outcomes and hence reliable policy decisions can be taken based on these indices. The percentage is shown in the bottom row of each panel of the table and reveals that factors F4 and F5 are equally the most sensitive for both increases and decreases in weight; F6 is a little bit less sensitive; F1 is sensitive only to a decrease and F2 and F3 are not sensitive. Hence, factors F4, F5 and F6 are the most critical. However, in this case the sensitivity has two opposite directions, i.e. factors F4 and F5 have a positive impact on the problem; hence, by increasing their importance, the global index GLFI is reduced and vice versa. On the other hand, factors F1, F3 and F6 present a negative impact because, by increasing their importance, the GLFI is increased and *vice versa*. The GLFI for F2 does not change under any change of weight, indicating an independence of this factor from the weights. This finding is in accordance with the finding in section 7.9.1 that factors F1, F3 and F6 have the highest negative impact in this case study context (although they may not be sensitive, e.g. F3), whereas F2, F4 and F5 have less influence.

11.4 Shape analysis

Shape classification

The thematic map in Figure 35 presents a classification of the PSI based on 10 categories and provides an overview of the evaluation of the shapes. In particular, going from category 1 with values around 0 to category 10 with values around 1 represents the worst (irregular-complex shapes) and best (i.e. regular rectangles) parcel shapes respectively. An overall visual inspection of each category reveals that there are common geometric characteristics of the parcel shapes that belong to each category, indicating that the index offers good consistency, reliability and accuracy. For a deeper investigation, parcels that belong to each class have been isolated in separate maps (Figure 36 for PSI categories 1-6 and Figure 37 for PSI categories 7-10).

Category 1 includes the parcels with the worst shape. All shapes are highly irregular and complex. It seems that there is a consistency in the value of the index since all shapes have similar geometric features. Similarly, categories 2 to 5 comprise highly irregular shapes in varying grades. The grade of irregularity or more precisely how far a shape is from the optimum varies and different shapes may have a similar PSI because of different undesirable geometric characteristics. However, it should be noted that it may seem that some shapes which are not irregular along the whole of their perimeter (namely a couple of their sides are straight lines) are disfavoured compared to shapes that are completely irregular along their whole perimeter. This happens because the model examines each shape as a whole compared to the optimum shape. Thus, even a shape with a few (or even all) straight sides is essentially irregular with many disadvantages for agricultural purposes. In addition, in classes 2 to 5, it seems that the accuracy of the PSI is very sensitive since a shape may be in one of these four groups because it is better or worse than another in just one geometric feature.

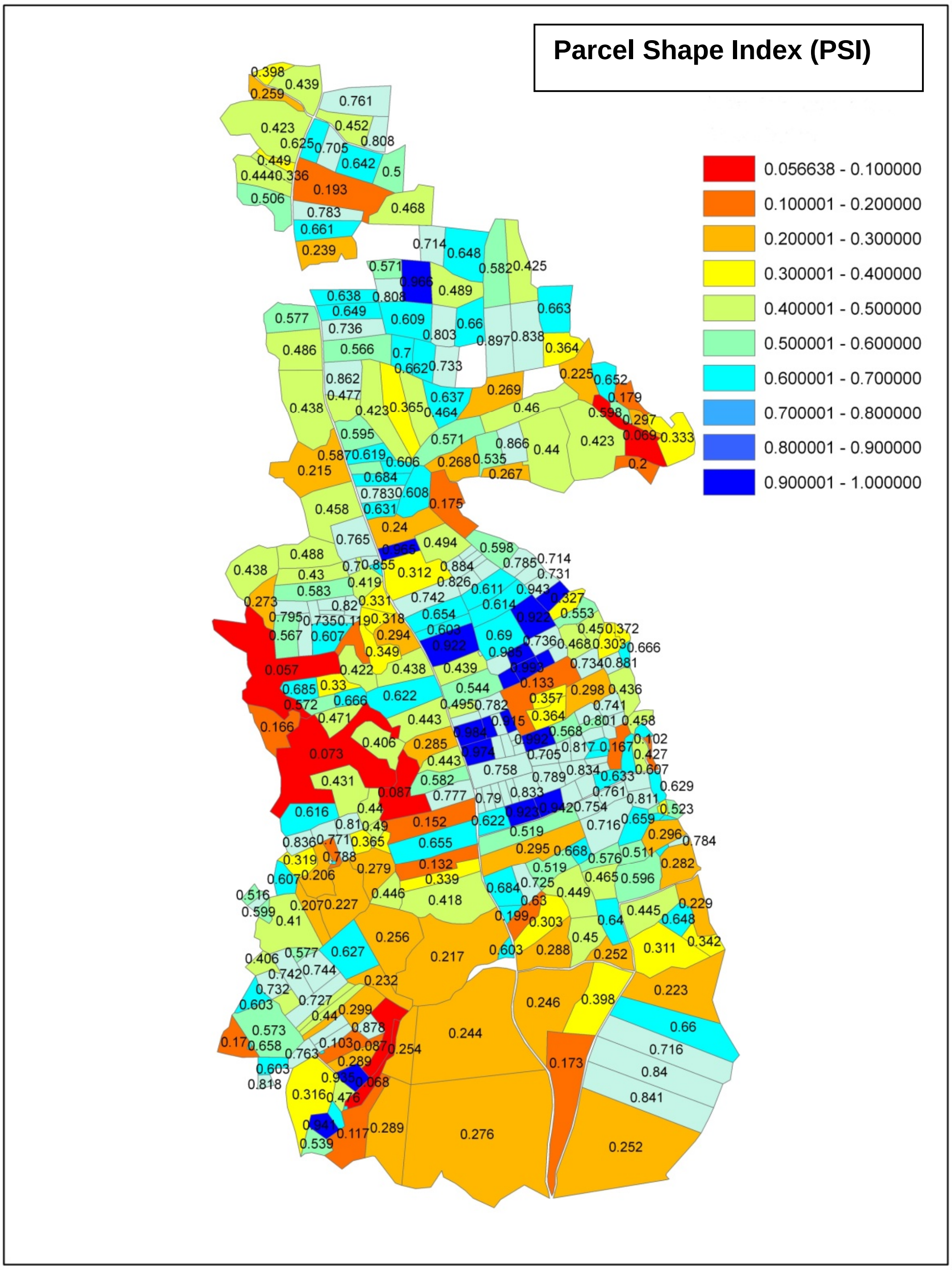
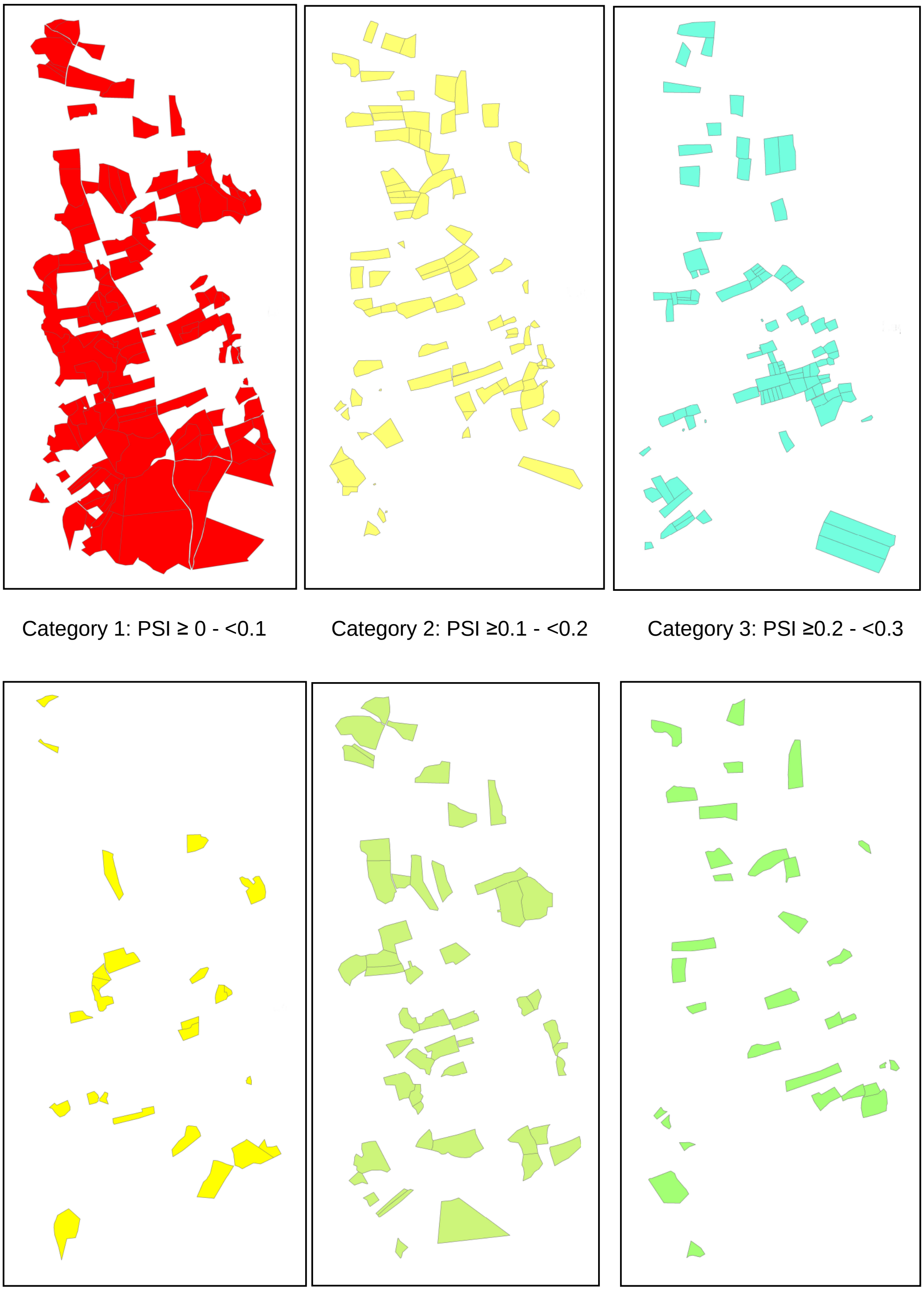


Figure 35: Classification of the PSI based on ten categories



Category 1: PSI ≥ 0 - <0.1

Category 2: PSI ≥0.1 - <0.2

Category 3: PSI ≥0.2 - <0.3

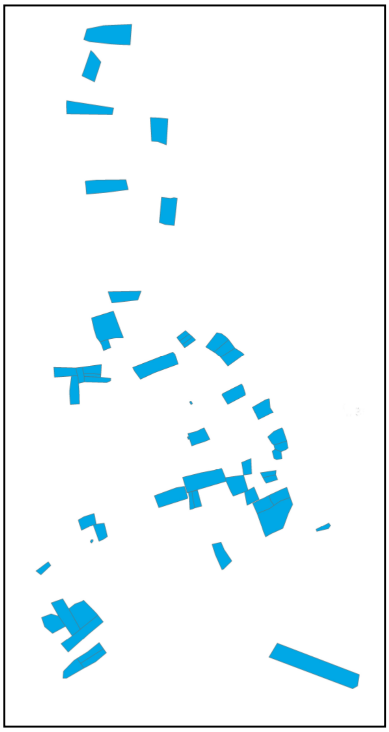
Category 4: PSI ≥ 0.3 - <0.4

Category 5: PSI ≥ 0.4 - <0.5

Category 6: PSI ≥ 0.5 - <0.6

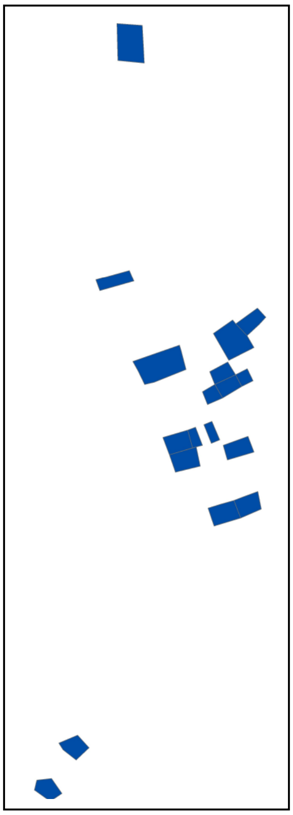
Figure 36: Parcel shapes with PSI ≥ 0 to <0.6

Category 7: PS I≥ 0.6 - <0.7



Category 8: PSI ≥ 0.7- <0.8

Category 9: PSI ≥ 0.8 - <0.9



Category 10: PSI ≥ 0.9 - <=1.0

Figure 37: Parcel shapes with PSI ≥ 0.6 to ≤ 1.0

In contrast to the first five categories, the other categories involve better shapes with more accuracy and consistency among them. As the PSI increases, the shapes begin to look more acceptable. In particular, categories 6 and 7 contain parcels with irregular shapes but these are definitely better than the shapes found in the previous groups. Both categories have shapes with common characteristics and most of them could be in either group. Category 8 includes shapes that are quite close to being regular. The similarities in the shapes illustrate the accuracy and consistency of the index. Similarly, category 9 involves almost regular shapes. Some of them are absolutely regular although they do not meet all the requirements of the optimum shape; for instance, the length: breadth ratio is different from the optimum. Finally, in category 10, almost all the parcels are optimum or close to optimum. The category also illustrates that the index is able to discern optimum shapes.

Based on the above analysis, the 10 categories were collapsed into the following four groups as shown in Figure 38: highly irregular shapes (categories 1, to 5); irregular shapes (categories 6 and 7); regular or near regular shapes (categories 8 and 9) and; optimum or near optimum shapes (category 10). It is logical that the majority of parcels (65.9%) have either highly irregular shapes or irregular shapes which is in accordance with the previous finding that the factor F3 (parcel shape) had the biggest negative impact on land fragmentation for the four weighting scenarios discussed earlier. Moreover, a small minority of parcel shapes (5.3%) have optimum or near optimum shapes whilst a significant number (28.8%) have regular or near regular shapes.

Evaluation of the PSI

The evaluation of the PSI is based on the ability to satisfy the five requirements noted in section 9. In particular, requirements (iv) and (v) are satisfied by the PSI because it ranges from 0 to 1 and it takes into account six geometric parameters that comprehensively describe a shape. In addition, requirement (i) that each shape should be represented by a unique number, is also satisfied, especially if comparison is made with a precision of three of four decimal places. However, some shapes may have very close indices either because they are similar (as noted in requirement (iii)) or because they differ by the same distance in terms of quality compared to the optimum shape. This may seem as if requirement (ii) is not satisfied. However, this is possible when a method compares each shape with the optimum one as used here.

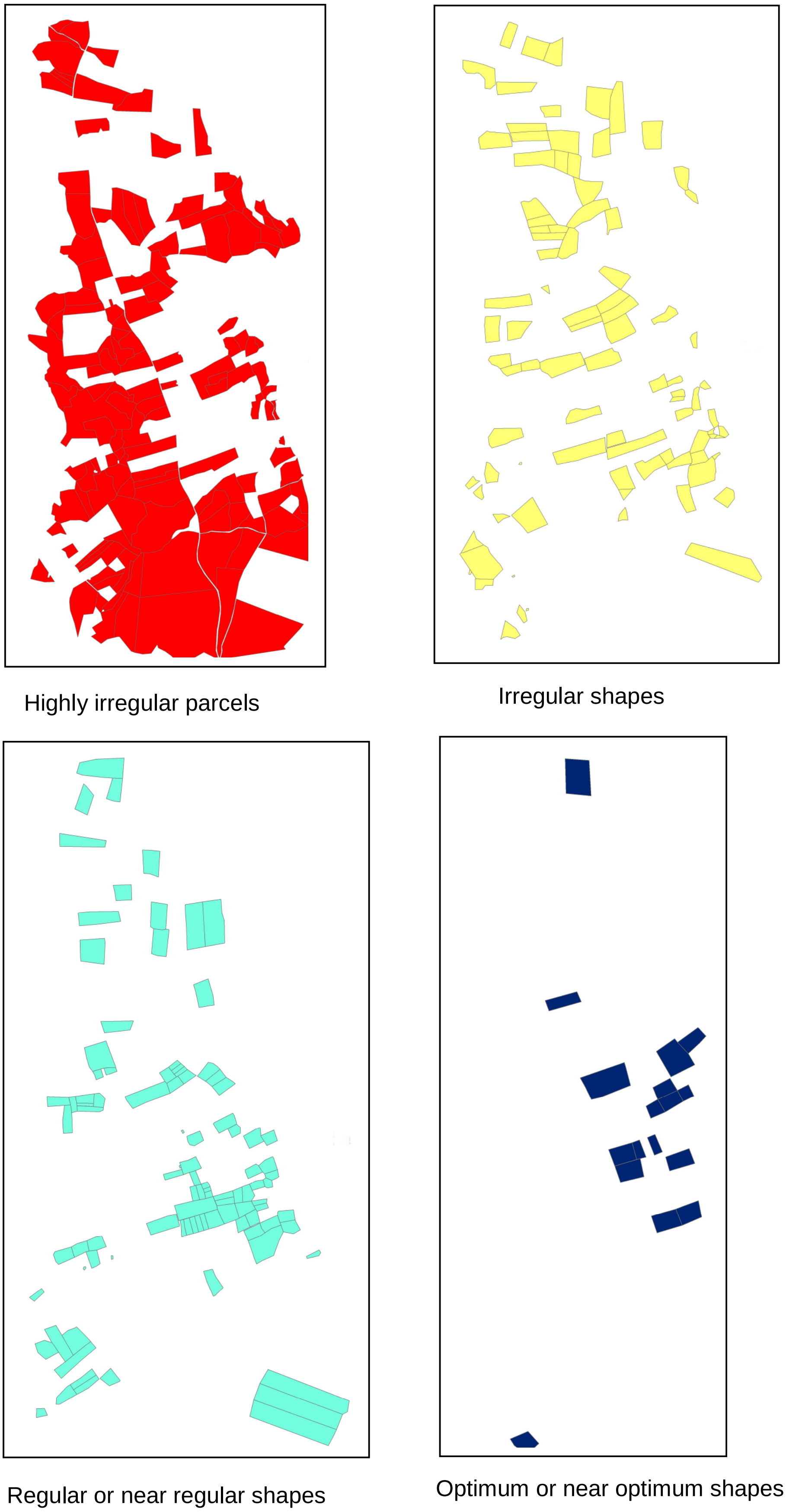


Figure 38: Classification of parcel shapes based on four groups

As a result, two dissimilar shapes may have a similar index because they differ by almost the same distance in terms of quality from the optimum shape but for different undesirable geometric parameters.

Two weaknesses of the index are that: symmetrical shapes are favoured and hence they may have a higher index than expected, e.g. shapes with a triangular form as shown in Figure 39 have a relatively high PSI; and shapes with a general regular form, i.e. those having some straight sides and some not straight, as shown in Figure 40, are perhaps penalised more compared to shapes that have a completely irregular shape along their entire periphery. These weaknesses could be improved by either investigating a different form of the relevant value functions or by adding new value functions, e.g. for obtuse angles or by penalising symmetrical shapes with angles different than the limits suggested.

Comparisons of the PSI with the SI, FD and AAF based on the same parcel shapes as shown in Figures 12-14 are provided in Figures 41-43. The PSI values are underlined within parentheses while the values of the index with which it is being compared are not. In all these cases, the PSI overcomes the deficiencies of the existing indicators (as noted in section 9).This is evident through a visual inspection from the gradual way in which the index increases as the shapes improve towards the optimum. Hence, the PSI clearly outperforms existing indices. Based on all of the above considerations, a qualitative comparison of the existing indices with the PSI, based on whether they satisfy the five requirements, is presented in Table 5.

In addition to the above methods, it could be said with confidence that the indices developed by Amiama *et al*. (2008) and Libecap and Lueck (2009), which were noted in section 9, present the weaknesses of the three existing methods shown in the above table because: for the former it has been noted by the same authors that they produced only slightly better results than AAF and for the latter, the index is a kind of area: perimeter ratio like AAF, SI and FD.

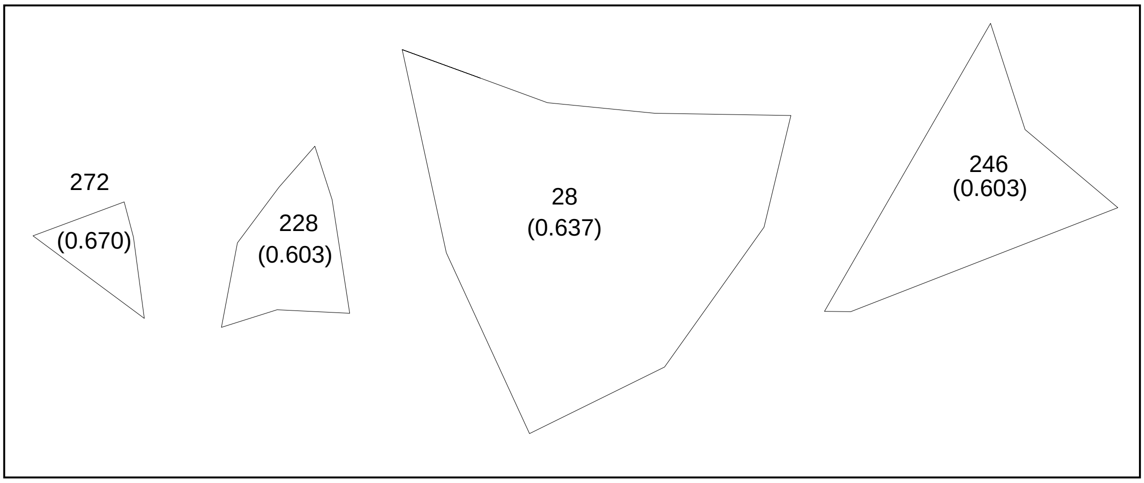


Figure 39: Shapes which are favoured in terms of the PSI

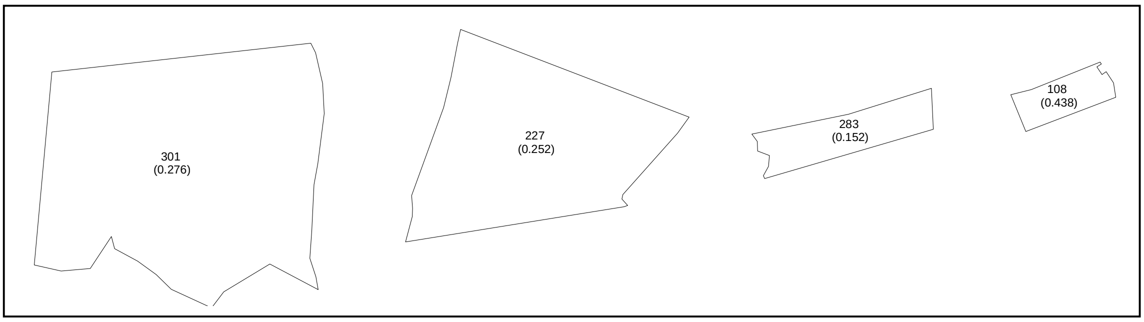


Figure 40: Shapes which are undesirable based on the PSI compared to fully irregular shapes

Table 5: Comparison of existing indices with the PSI

Indices	AAF	SI	FD	PSI
Criterion				
i	×	×	×	✓
ii	×	×	×	×✓
iii	✓	✓	×	✓
iv	×	×	×	✓
vi	×	×	×	✓

✓: criterion satisfied; ×: criterion not satisfied; ×✓: criterion satisfied with preconditions

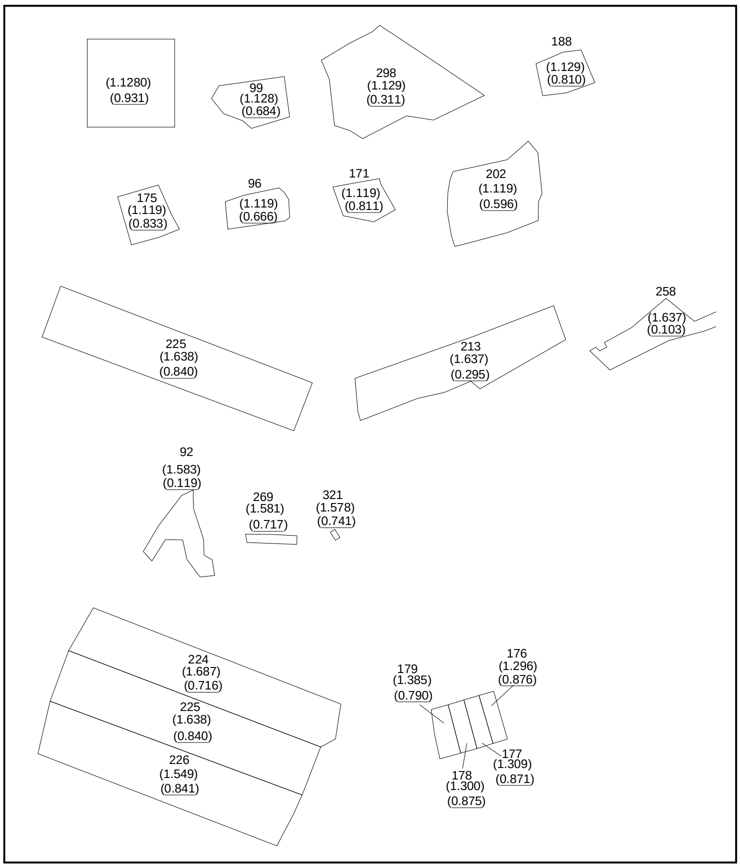


Figure 41: Comparison of the PSI with the SI

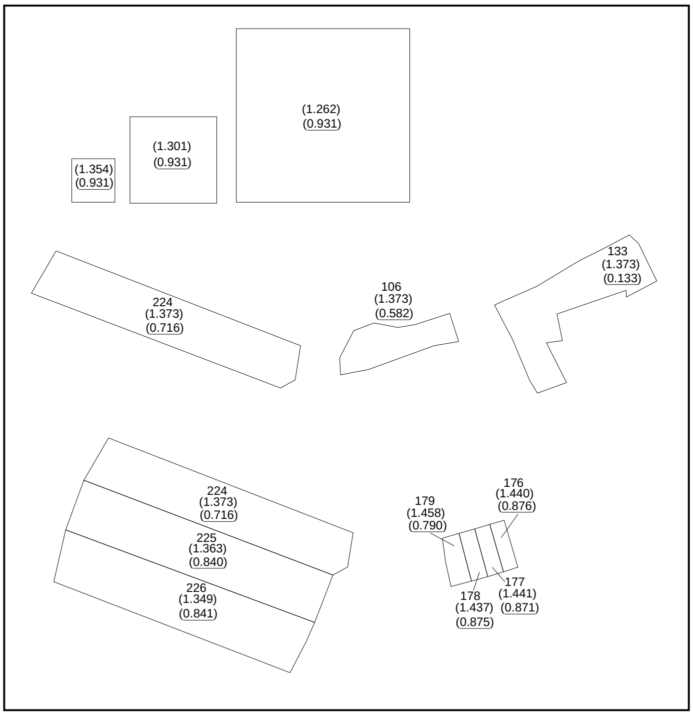


Figure 42: Comparison of the PSI with the FD

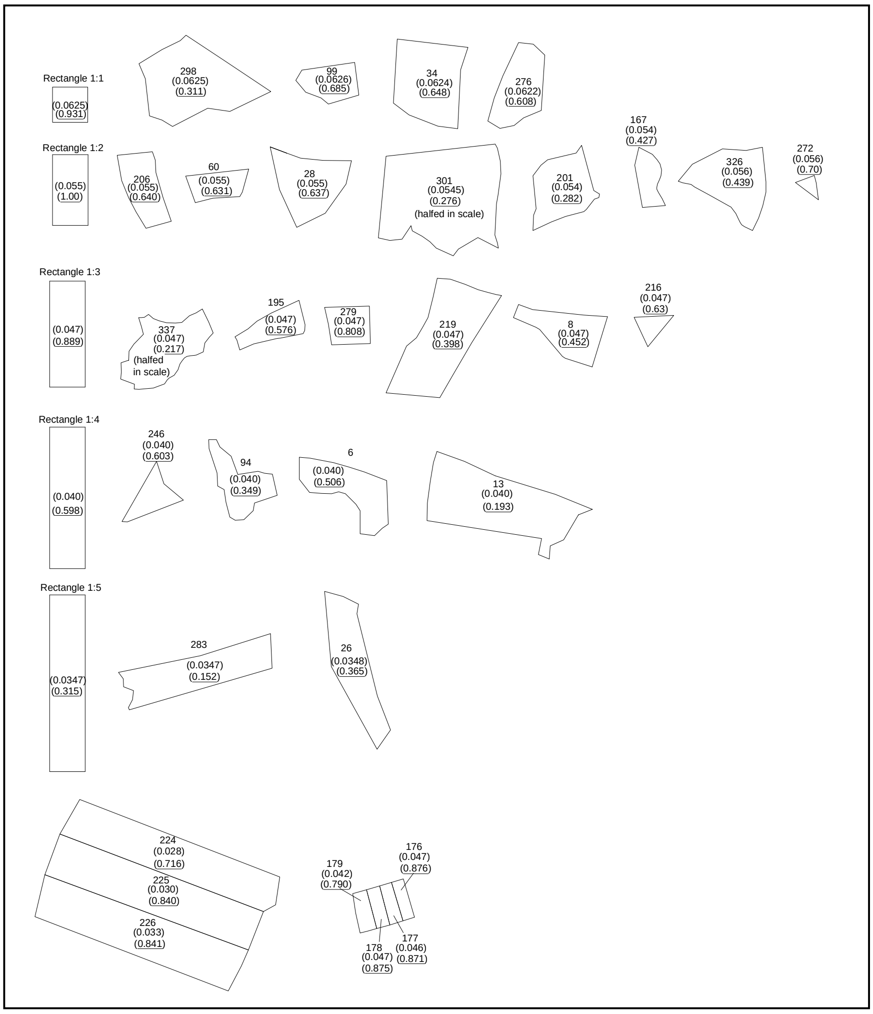


Figure 43: Comparison of the PSI with the AAF

12 Conclusions

A literature review has shown that existing land fragmentation indices are poor since they only take a small number of relevant factors into account. In addition, the factors are generally given equal importance, which is not a reasonable assumption in most cases, and there is little flexibility for the planner regarding which factors should be taken into account for a specific project. This paper has presented a new land fragmentation index which overcomes the weaknesses of existing indices.

The global land fragmentation index (GLFI) has the following features: it is comprehensive since it integrates six core land fragmentation factors; it is flexible because the user may select which factors should be taken into account for a particular project; and it is problem-specific since the planner may decide the weighting given to each factor for a specific project. The application of this new model using a case study and the comparison with the results produced by two popular existing indices showed that the latter indices underestimate the problem of land fragmentation, simply because they ignore several important variables, and hence they may be misleading in terms of the consequent decision making that might ensue. In comparison, the GLFI has been shown to be a more reliable and robust measure of land fragmentation and significantly outperforms the existing indices

Furthermore, some other innovations should be highlighted. In particular, similar to the land fragmentation indices, existing shape analysis methods and especially parcel shape indices also suffer from some basic deficiencies. First, they are not comprehensive since they take only a couple of parameters (area and perimeter of a shape) into account and ignore all others (angles, length of sides, number of boundary points). As a result, they actually measure only the compactness of parcel shape. Second, although a diversity of combinations of both parameters has been proposed, they all fail in terms of accuracy and reliability. In particular, two or more irrelevant shapes may have the same index, such as a rectangle with a very complex irregular shape. Third, the index values do not fall within an explicit range from the best to the worst situations. Fourth, existing indices are too generic and not problem specific because they measure compactness of a shape and not the appropriateness of a shape for a particular task. A new measure called the parcel shape index (PSI) has been developed based on six variables: length of sides; acute angles; reflex angles; number of boundary points; compactness and regularity. The case study showed that the PSI overcomes the problems of the existing indices and considerably outperforms the other indices. In particular, it is fairly accurate and reliable so as to classify shapes in four groups: highly irregular shapes; irregular shapes; regular or near regular shapes and optimum or near optimum shapes. Some minor weaknesses of the PSI have been identified and could be investigated in further research.

In addition to the above, a new transformation process called the 'mean standardisation method' (mSM) has been introduced. The mSM is better than similar existing methods such as maximum standardisation because the former produces more balanced values compared to the latter since it takes into account not only the minimum and maximum scores but also the mean score of a sample. Thus, it is appropriate in cases where a sample includes extreme values.

This paper has also shown that MADM can be used not only for assessing a discrete number of alternative solutions as applied more conventionally, but also for exploring and measuring the performance of an existing system compared to an ideal system or evaluating the shape of an object compared to an optimum standard.

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