LandFragmentS: A New Model for Measuring Land Fragmentation

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Keywords: Land fragmentation; global land fragmentation index; multi-attribute decision making method; value functions, GIS.

SUMMARY

Land fragmentation, which implies a defective land tenure structure, is a major problem at various spatial scales, and may hinder effective agricultural production and sustainable rural development. Policy decisions to reduce land fragmentation require reliable measurement indices. However, current indices present significant weaknesses since they do not take all of the relevant factors into account. In particular, they ignore critical spatial parameters such as the shape of parcels and non-spatial parameters such as the ownership type and the existence or absence of road access for each parcel. 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.

This paper reports our response to the need for a new methodology for measuring land fragmentation. A new model called *LandFragmentS* (Land Fragmentation System) integrates geographical information systems (GIS) with a multi-attribute decision making method (MADM) to produce a 'global land fragmentation index'. When applied to a case study area in Cyprus, the new index outperforms the existing indices in terms of reliability because it is comprehensive, since it integrates six core land fragmentation factors; it is flexible and problem specific, because the user may select which factors should be taken into account and may assign a different weight to each factor depending on a certain project; and it is knowledge based, that is, it incorporates expert knowledge through value functions. The methodology can be easily applied to assess the quality of any existing system for which the worst and best conditions can be determined through explicit definition of the evaluation criteria.

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1. INTRODUCTION

Land fragmentation is defined in the literature as the situation in which a single farm consists of numerous spatially separated parcels (King and Burton, 1982; McPherson, 1982; Van Dijk, 2003). King and Burton (1982) characterise land fragmentation as a fundamental rural spatial problem concerned with farms whose land is poorly organised at locations across space. Similarly, many authors (e.g. Yates, 1960; Thompson, 1963; Karouzis, 1971; DeLisle, 1982; Jabarin and Epplin, 1994; Blaikie and Sadeque, 2000) consider land fragmentation as a serious obstacle to optimal agricultural development because it hinders mechanisation, causes inefficient production and involves large costs to alleviate the adverse effects, resulting in a reduction in farmers' net incomes. This situation is even more severe today because of the increasingly competitive agricultural market and the industrialization of the agricultural sector.

Although land fragmentation has negative connotations, it is not necessarily a problem in all cases (Bentley, 1987; Van Dijk, 2003) and there are benefits from risk management, crop scheduling and ecological variety. Farmers have to minimise the potential risk of climatic and natural disasters and having dispersed parcels is one solution (Shaw, 1963; King and Burton, 1982; Bentley, 1987; Tan *et al.*, 2006; Van Hung *et al.*, 2007). Risk is also reduced through a greater variety of soils, crops and growing conditions when several locations are being used (Van Hung *et al.*, 2007). Crop scheduling occurs when parcels are scattered between various locations at different altitudes so that crops mature at different times. Ecological variety is realised through the formulation of a natural mosaic of parcel shapes, crops and colours.

When land fragmentation is a problem, the main shortcomings associated with it include the small size and irregular shape of the land parcels, the dispersion of parcels and, in particular, the large potential distance between the parcels and the owner's farmstead. In Cyprus (Demetriou *et al.*, 2012a; 2012c) there are additional complexities due to the lack of road access to land parcels in certain areas and issues relating to ownership rights. For instance, a parcel may be owned in undivided shares, i.e. it may belong to more than one landowner, or there may be 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 for water.

Land fragmentation is evident in many areas throughout the world. Despite causes of land fragmentation varying from country to country and from region to region, there is general agreement that the four main factors that trigger fragmentation are: inheritance; population growth; land markets; and historical/cultural issues (King and Burton, 1982; Bentley, 1987; Niroula and Thapa, 2005; Tan *et al.*, 2006; Van Hung *et al.*, 2007). Depending on the causes, various policies have been adopted to control land fragmentation that can be divided into three categories: legislation; land management approaches and land protection policies/programmes. Although taking policy decisions requires a comprehensive study of the impacts of land fragmentation, decision makers and planners very often need a reliable indicator for quantifying the land fragmentation problem. However, current indices present significant weaknesses since they do not take all of the relevant factors into account and hence they do not adequately represent the land fragmentation problem. This finding suggests the need for a new methodology for measuring land fragmentation.

Thus, in this paper we present a new methodology for measuring land fragmentation that links multi-attribute decision making (MADM) with a geographic information system (GIS) to build a model called *LandFragmentS* (Land Fragmentation System) (Demetriou *et al.*, 2011d), which is a sub-system of LACONISS: a Land CONsolidation Integrated Support System for planning and decision making (Demetriou *et al.*, 2011a; 2011b). The new method results in a 'global land fragmentation index' (GLFI) which is shown to outperform existing indices. It is comprehensive since it takes all six land fragmentation parameters into account; it is flexible and problem specific in that the user may select which factors need to be taken into account for a specific area under investigation and may assign a different weight to each factor representing its importance for a given problem; and it is knowledge-based by incorporating expert judgment through the definition of value functions (Beinat, 1997) for the criteria involved. A broader contribution of this research is that the methodology employed can be easily applied to assess the quality of any existing system for which evaluation criteria will have values that range from the worst to the best conditions.

2. LIMITATIONS OF EXISTING 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). As noted earlier, in Cyprus, land fragmentation has additional complexities including the lack of road access to land parcels and problematic ownership rights (undivided shares and dual or multiple ownership). 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. Edwards, 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 which is outlined below.

3. THE OUTLINE OF A NEW METHODOLOGY

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. In most cases, experts determine the range of values for each factor used in measuring land fragmentation and then standardise them so as to be additive. The proposed process is based on the multi-attribute decision making (MADM) method (Sharifi *et al.*, 2004) and has four main steps as set out in Figure 1.

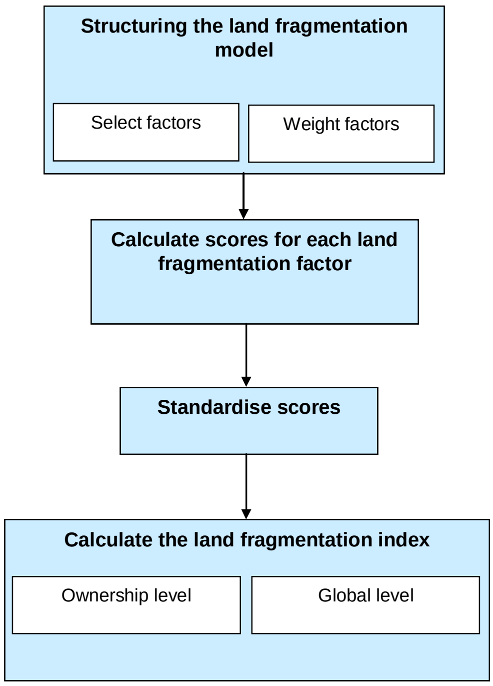

Figure 1: Outline of the *LandFragmentS* model (Demetriou *et al.*, 2011b)

Although MADM is conventionally utilised for the assessment of alternative solutions of a problem (Demetriou *et al.*, 2011c; 2011e), 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' (Table 1).

Table 1: A land fragmentation table of land fragmentation factors for each holding

	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

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:

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

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.

The above methodology has been transferred to a GIS-based module called *LandFragmentS* that is operationalised as a toolbar with seven icons as shown in Figure 2. 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 appear in the order in which they must be executed.

Figure 2: The *LandFragmentS* toolbar

4. CALCULATION OF LAND FRAGMENTATION FACTORS

The factors/criteria involved in any MADM need to satisfy a number of requirements (Malczewski, 1999; Sharifi *et al.*, 2004), the most critical of which is the independence between the factors, i.e. to avoid duplication of associated factors. Thus, after a refinement process (Demetriou *et al.*, 2011d; 2012c), 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/holding. In particular, the dispersion of parcels (F1) can be calculated for the original cadastral situation (DoPb), i.e. before applying land consolidation as follows:

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

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.

The size of parcels (F2) 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 3 and 4 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; 2011e). Figure 3 presents a fifth-order polynomial function:

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

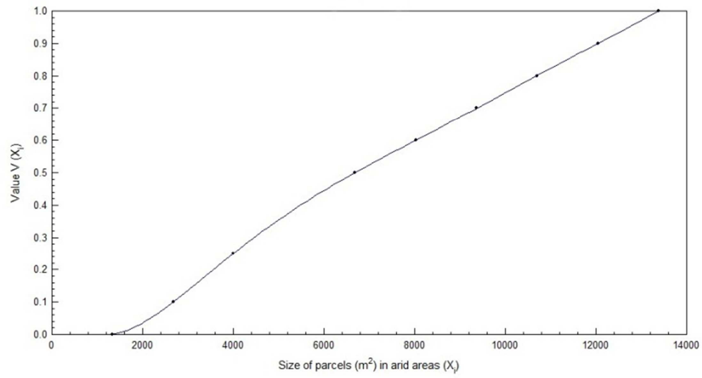

Figure 3: The value function for the size of parcels in arid areas

Figure 4 shows a concave benefit fourth-order polynomial function:

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

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.

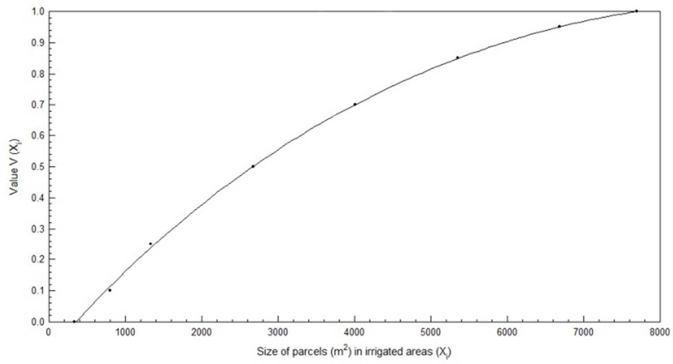

Figure 4: The value function for the size of parcels in irrigated areas

The shape of parcels (F3) is represented by a new parcel shape index (PSI) which takes into account the following six factors: length of sides, acute angles, reflex angles, boundary points, compactness and regularity. Extensive presentation and discussion about the PSI is found in Demetriou *et al.* (2011d; 2012b).

Regarding the 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. The ownership accessibility index is calculated as the average value of assigned 1s and/or 0s for the parcels that belong to a holding. Similar to the accessibility of parcels, dual ownership (F5) 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. Similar to the two previous factors, shared ownership (F6) 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.

5. A CASE STUDY

LandFragmentS has been applied in a case study area in Cyprus aimed at comparison of the GLFI with existing indices. In particular, the Simmons and Januszewski indices present very similar patterns as shown by their distributions in Figures 5 and 6, 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. 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).

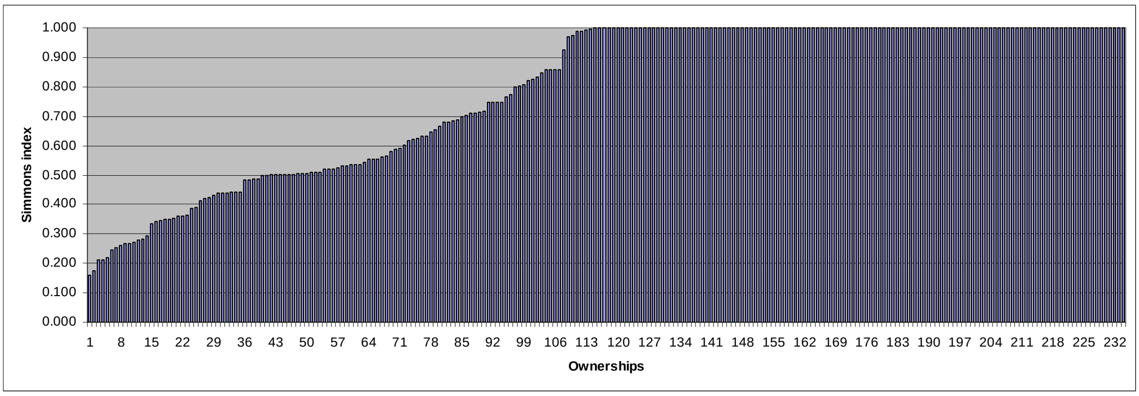

Figure 5: Distribution of Simmons index across holdings

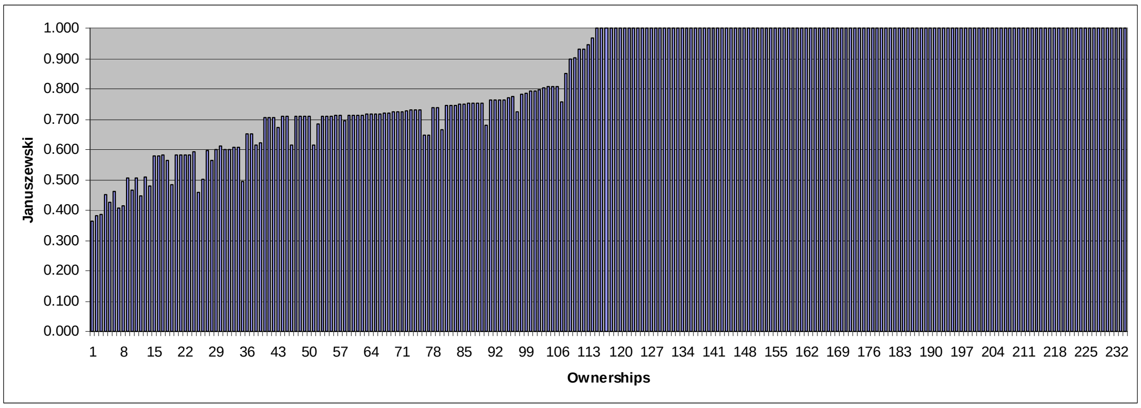

Figure 6: Distribution of Januszewski index across holdings

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 7 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 evident.

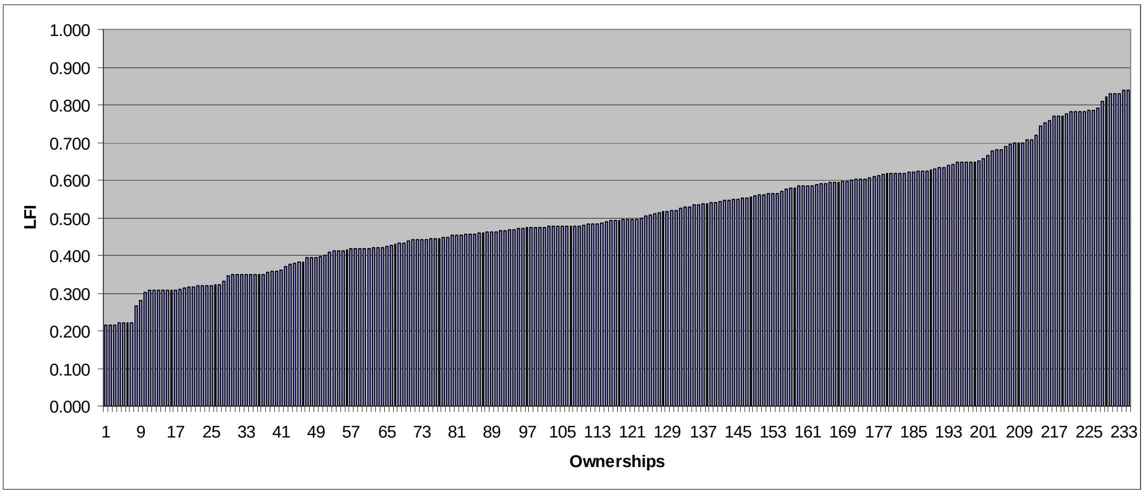

Figure 7: Distribution of the new LFI index across holdings

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.

6. CONLCUSIONS

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.

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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BIOGRAPHICAL NOTES

Demetris Demetriou is the District Land Consolidation Officer for Larnaca and Famagusta in Cyprus. He holds a Diploma (Eng.) in Rural and Surveying Engineering from the Aristotle University of Thessaloniki (Greece). He also holds an MSc(Eng.) in Transport Planning and Engineering and an MSc in Geographical Information Systems; both from the University of Leeds (UK). His MSc dissertation entitled 'The development of a knowledge-based GIS to support land consolidation plans' has been awarded by the Regional Science Association International (British and Irish section) as the best taught postgraduate work in 2008. He is currently a PhD candidate in the School of Geography, University of Leeds (UK) working on 'The development of an Integrated Planning and Decision Support System for land consolidation'. His main research interests are in land management, land consolidation, GIS, Planning Support Systems (PSS), Spatial Decision Support Systems (SDSS), Expert Systems (ES), Genetic Algorithms (GAs) and Multi-criteria decision methods (MCDM).

John Stillwell is Professor of Migration and Regional Development in the School of Geography at the University of Leeds (UK). Among his research interests are urban and regional planning, GIS and PSS. He is co-editor of the journal Applied Spatial Analysis and Policy and of several books about the use of GIS and modelling in planning, including, most recently, 'Planning Support Systems Best Practice and New Methods' (Springer, 2009).

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