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A New Methodology for Measuring Land Fragmentation

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Abstract

The presence of land fragmentation implies that the existing land tenure structure is defective. It is a major problem in many regions because it restricts agricultural development and reduces the opportunities for sustainable rural development. Whilst policies to counter land fragmentation require reliable measurement indices, current fragmentation indices have significant weaknesses which prevent adequate representation of the land fragmentation problem. In particular, they ignore critical spatial variables such as the shape of parcels as well as non-spatial variables such as ownership type and the existence or absence of road access for each land parcel. Furthermore, there is no flexibility for users to select the variables that they think appropriate for inclusion in the fragmentation index, and no variable weighting mechanism is available. The need for a new methodology for measuring land fragmentation is therefore apparent so the aim of this paper is to introduce a new 'global land fragmentation index' that combines a multi-attribute decision-making method with a geographic information system. When applied to a case study area in Cyprus, the new index outperforms the existing indices in terms of reliability as it is comprehensive, flexible, problem specific and knowledge-based. The methodology can be easily applied to assess the quality of any existing system for which evaluation criteria can be defined with values ranging from the worst to best conditions.

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

1. Introduction

Land fragmentation, also known as pulverization, parcellization and scattering (Bentley, 1987), 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 that are 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 increased agricultural market competition and the industrialization of the agricultural sector.

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 perspectives (King and Burton, 1982; Bentley, 1987; Niroula and Thapa, 2005; Tan *et al.* 2006; Van Hung *et al.* 2007). Other factors noted in more specific situations include: social and administrative decrees (Bentley, 1987); long-established cultivation (Binns, 1950); shortages of land and nucleated settlement (Papageorgiou, 1956); the piecemeal conversion of forests and moorland to arable land (Grigg, 1980); and the privatisation transition process, e.g. in ex-eastern block and central European countries (Van Dijk, 2003). 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.

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. However, 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, 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 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 many factors are involved, there appears to be no standard or comprehensive measure of land fragmentation (Bentley, 1987; Van Hung *et al.* 2007). Most authors have utilised a simple uni-variate fragmentation 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. More complex indices were developed in the 1960s and 1970s that incorporate more than one factor (e.g. Edwards, 1961; Simmons, 1964; Dovring, 1965; Januszewski, 1968; Igbozurike, 1974; and Schmook, 1976). However, existing indices remain partial at best as they do not take all of the relevant factors into account (Monchuk *et al.,* 2010). Current indicators appear to 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 flexibility for the user in the selection of variables used in the fragmentation index, and there is no mechanism to allocate different weights to the factors selected. These limitations clearly indicate the need for a new methodology for measuring land fragmentation (Demetriou *et al.,* 2012a).

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 (LAnd CONsolidation Integrated Support System for planning and decision making) (Demetriou *et al.,* 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 the certain 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 with have values that range from the worst to the best conditions.

2. Land fragmentation

2.1 A global picture of land fragmentation

Whilst land fragmentation has been closely associated with Europe and Mediterranean countries (e.g. Yates, 1960; Thompson, 1963; Karouzis, 1971; Falah, 1992), it is a problem that has been studied in many other countries and regions around the world (e.g. Soltow, 1983; Goland, 1993; Ram *et al.*, 1999; Verry, 2001; Wan and Cheng, 2001; Blaikie and Sadeque, 2000; Nguyen *et al.*, 1996; Kjelland *et al.* 2007). FAO statistics from 1986 to 2004 for six continents (113 countries) reveal that the smallest average holding size is found to be less than 5 hectares (ha) in 20 out of 24 Asian and 16 out of 20 African countries respectively. In almost half of the Central American and Oceania countries, the average holding size is less than 5 ha. In contrast, 10 out of 10 South American and 23 out of 28 European countries have an average holding size greater than 5 ha.

It is also remarkable that some countries have an even smaller average land holding size which indicates serious land fragmentation. Six Asian countries have an average land holding size of less than 1 ha: Bangladesh (0.35 ha), Sri Lanka (0.5 ha), China (0.67 ha), Vietnam (0.71 ha), Nepal (0.79 ha) and Indonesia (0.79 ha). Not only are these land holdings extremely small, but each land holding consists of about 1.8 parcels, a fact that exaggerates the problem. Four African countries also have very low average values: Congo (0.5 ha), Comoros (0.6 ha), Malawi (0.7 ha) and Egypt (0.82 ha). Some of these are among the most densely populated countries in the world, a factor that is strongly related to land fragmentation; Bangladesh is ranked 9th in terms of population density, China 14th, Comoros 27th, Sri Lanka 38th, Vietnam 48th and Nepal 59th among the 238 countries of the world.

At the other end of the spectrum, five countries have much higher average land holding size: Australia (3,243.21 ha); Brazil (582.45 ha); Uruguay (287.40 ha); Canada (273.38 ha); and the USA (178.35 ha). The highest figure for EU countries is for Slovakia (172.1 ha). Average holding size has a strong relationship with the size of each country since Canada (2nd), USA (4th), Brazil (5th) and Australia (6th) are among the six largest countries in the world while Australia (232th), Canada (227th), Brazil (189th) and USA (177th) are among the least densely populated countries in the world. All EU countries (except Finland, 198th, Sweden, 192nd and Estonia, 179th) are more densely populated than the last ranked country (i.e. USA) of the previous group.

2.2 Land fragmentation in the European Union

The problem of land fragmentation in Europe has been identified by many researchers (Shaw, 1963; Van der Meer, 1975; Burton and King, 1982; Bentley, 1987; Van Dijk, 2003). Moreover, several studies focus on particular EU countries such as Cyprus (Karouzis, 1971; Burton and King, 1982); Portugal (Bentley, 1990); Greece (Keeler and Skuras, 1990); Czech Republic (Sklenicka and Salek, 2008); Romania (Rusu, 2002); Bulgaria, Germany, Hungary, Romania and Slovenia (Thomas, 2006).

Table 1 shows the average agricultural area per holding in EU countries for the decade 1993-2003. It shows a linear rising trend in the average agricultural area per holding for all the countries. This trend is also revealed in the results for EU-12 and EU-15. It is remarkable that a significant rise in this measure has been observed in some countries such as Portugal (67.9%), Germany (54.1%), Italy (50.9%), Luxemburg (48.1%), Sweden (48.0%) and Denmark (47.4%). Smaller increases are evident in other countries. The reasons for this increase are the general decline in the number of holdings combined with the rather stable level in the total agricultural area, and the agricultural policies adopted by EU countries for improving farm structures for more productive agriculture.

The average agricultural area per holding varies within the EU. Prior to the expansion to EU-25, the UK reported the highest average across the EU-12 and EU-15 (around 70 ha) following its accession in 1975. Slovakia joined the EU on 1 May 2004 and took over in first place with an average of 172.1 ha according to the 2003 agricultural census. The Czech Republic also had an average (143.8 ha) higher than that of the UK (85.2). The high values in Slovakia and the Czech Republic are due to the fact that, following the collapse of communism, large areas of agricultural land passed to private land owners who consolidated their holdings into bigger enterprises (Van Dijk, 2003). Other countries with relatively high averages are Luxembourg (55.4 ha), Denmark (54.7 ha), Sweden (50.9 ha), France (48.9 ha) and Germany (43.3 ha). In contrast, the average area per holding is less than 10 ha in Malta (1.3 ha), Cyprus (5.2 ha), Greece (5.9 ha), Slovenia (7.3 ha) and Italy (8.9 ha).

Table 1: Average agricultural area per holding (in hectares) in EU countries, 1993-2003

	1993	1995	1997	1999/2000	2003
EU-25	:	:	:	:	22.6
NMS-10	:	:	:	:	17.9
EU-15		17.4	18.4	22.2	24
EU-12	16.4	17.2	18.2	18.4	:
Belgium	17.6	19.1	20.6	23.7	26.4
Czech Republic	:	:	:	:	143.8
Denmark	37.1	39.6	42.6	45.8	54.7
Germany	28.1	30.3	32.1	37.6	43.3
Estonia	:	:	:	:	48.3
Greece	4.3	4.5	4.3	5.3	5.9
Spain	17.9	19.7	21.2	21.7	23.2

France	35.1	38.5	41.7	45.8	48.9
Ireland	26.8	28.2	29.4	32.9	33.8
Italy	5.9	5.9	6.4	8.2	8.9
Cyprus	:	:	:	:	5.2
Latvia	:	:	:	20.5	22.8
Lithuania	:	:	:	:	20.4
Luxembourg	37.4	39.9	42.5	48.2	55.4
Hungary	:	:	:	22.7	25.3
Malta	:	:	:	:	1.3
Netherlands	16.8	17.7	18.6	20	23.5
Austria		15.4	16.3	17.1	19.3
Poland	:	:	:	:	12.2
Portugal	8.1	8.7	9.2	11.9	13.6
Slovenia	:	:	:	6.8	7.3
Slovakia	:	:	:	171.4	172.1
Finland	:	21.7	23.7	28.3	30.2
Sweden	:	34.4	34.7	40.5	50.9
United Kingdom	67.3	70.1	69.3	84.6	85.2

(Source: European Commission, 2000; 2003; 2005)

The distribution of holdings by size class indicates that the large majority of European holdings are relatively small in size since 75.7% of all holdings across the EU-27 in 2003 use less than 5 ha. It is noticeable that there has been a continuous increase in the proportion of small parcels with every EU enlargement. The percentage of small parcels for the EU-15 was 60.4 ha and for the EU-25 was 63.1 ha. The percentage increased by 12.6% at the time of the last EU enlargement (1 January 2007) when Bulgaria and Romania became members. This is due to the fact that 95.6% and 98.8% of their respective holdings are less than 5 ha. Other countries with high percentages of holdings less than 5 ha include are Malta and Hungary (97%), Slovakia (96.2%), Bulgaria (95.62%), Cyprus (87.6%), Italy (87.3%) and Portugal (85%). Three of these countries, Malta, Cyprus and Italy, are Mediterranean countries, a region with a long tradition of land fragmentation (Shaw, 1963; Burton and King, 1982).

The other four countries, Romania, Hungary, Slovakia and Bulgaria, are all ex-Communist Central European countries which, after 1989 and the collapse of the iron curtain experienced the transition to privatisation (in terms of land as well). According to Swinnen *et al.* (1997), 78.4% of agricultural land in Bulgaria was in collective farms and 21.1% in state farms. The figures for Hungary were 71.4% and 14.9%, and for Romania were 54.7% and 28.9%, respectively. After the transition to a free market, total land tenure restructuring took place. As a result, the figures on land fragmentation in these countries show quite a varied pattern. In the case of the countries mentioned above, a large number of small farms use a relatively modest share of the total agricultural land (Van Dijk, 2003).

A different situation, i.e. where the proportion of small holdings is limited to around 10% or less, occurs in Denmark (3.7%), Ireland (6.5%), Sweden (9.3%) and Finland (10.5%). Three of these are Scandinavian countries that have a very long tradition of land consolidation projects (i.e. the first land consolidation act was prepared in Denmark in 1781 and completed in 1801). At the other end of the spectrum, holdings with more than 50 ha account for some 4.7% in the EU-27. Among the member states, based on the 2003 census, Luxemburg presents the largest proportion of such holdings with 45.9%, followed by France and Denmark (35.7%), UK (26.3%), Sweden (25.4%) and Germany (21.4%). These countries have a long tradition of land consolidation projects apart from the UK, which applied a form of land consolidation in the 15th century but has not done so since that time.

2.3 Policies to control land fragmentation

The statistics presented above suggest that agricultural land is still fragmented in many parts of the world including EU countries. However, this is not a problem in principle. Every country should be aware of this potential problem and its consequences so as to adopt the proper land policies that relate to three strategies: the promotion of appropriate legislation; the application of specific land management approaches; and the application of specific land protection policies/programmes.

Legal provisions, most of which are restrictions, involve changing legislation regarding inheritance, minimum size of parcel division, absentee landowners, prevention of transfer to non-farmers, leasing, imposition of a maximum limit on the size of a holding, *et cetera*. Although some of these legal restrictions (e.g. preventing the transfer of land to a non-farmer) have been applied in some EU countries in the past, at present they could be considered as non-democratic and unconstitutional according to the current institutional framework of the EU. However, other countries, such as India and Nepal, still apply such rigid restrictions, e.g. any parcel of land less than one unit of the standard area set by the state government is considered a fragment that cannot be transferred to anyone (Niroula and Thapa, 2005).

The main land management approaches used to address land fragmentation in agriculture include: land consolidation; land funds and land banking; voluntary parcel exchange; and cooperative farming. Amongst these, land consolidation (Thomas, 2006; Demetriou *et al.,* 2012a) is a powerful tool which aims at increasing productivity and hence agricultural income through the reorganisation of space by reconfiguring the land tenure structure (land reallocation or readjustment) in terms of parcels and landowners and the provision of appropriate infrastructure (e.g. roads, irrigation networks, drainage). Land consolidation is considered to be the most effective land management approach for solving land fragmentation.

Land funds and land banking are terms that can be used interchangeably. They involve the process when a landowner is not interested in exploiting their property and thus sells or rents all the holding or part of it for a long period of time to an established land bank/land fund. The available land is then distributed to other landowners possessing adjacent holdings or migrating from another area. Voluntary parcel exchange involves the exchange of parcels among three or more landowners resulting in a more efficient spatial layout since the aim is to merge the adjacent parcels of each landowner. This process does not involve any change to the size or shape of the parcels (Van Dijk, 2003). Both methods are applied in Germany and in the Netherlands.

Cooperative farming involves the joint cultivation of land by a group of households. It was considered by some Asian countries such as India and Nepal until 1970 as an effective solution to land fragmentation, through the creation of economically operational farm units. However, according to Niroula and Thapa (2005) the practical experience has shown negative results, mainly because of the reluctance of landowners to participate in these programmes. Reluctance is due to conflicting interests and perceptions among landowners and the fear of losing their rights. As a result, this approach is no longer practiced in these countries.

Land protection policies are of three main types: a purchase of development rights (PDR) programme; a clustering programme; and a transfer of development rights (TDR) programme (Brabec and Smith, 2005). The PDR programme involves the use of public funds for purchasing and funding to eliminate the development rights of agricultural land. It is a farmland conservation tool which is considered very effective, is fair to landowners and provides a permanent solution. The most common disadvantage is the high cost of implementation. The programme involves the transfer of the development rights of a parcel located in the sending area, which is a specific area protected from development, to another parcel in the receiving area, which is an area where development is allowed to occur. This programme, which is mandatory for all landowners of an area once this has been initiated by a local government, is considered to be the most aggressive form of preserving farmland. In contrast to PDR and TDR policies, which refer to the regional scale, cluster development programmes focus on development on a site by site basis and work with the zoning density, reducing minimum parcel sizes and ensuring that a part of the site remains as open space. Although this strategy is popular among various communities, it is not regarded as a very effective tool to protect agricultural land. These kinds of measures are used in United States (Brabec and Smith, 2005).

Before examining which policy measures might be adopted to deal with land fragmentation, a critical question is whether land fragmentation constitutes a real problem or not for the area under consideration. Although the answer to this question should result from a comprehensive study of the economic, social and environmental impacts of land fragmentation, on most occasions planners and decision makers need a reliable indication of the extent of the land fragmentation. As a result various measures have been utilised for this purpose as discussed in the subsequent section.

3. Measuring land fragmentation

3.1 Problems associated with land fragmentation

The main problems associated with land fragmentation can be outlined as the dispersion, the small size and the irregular shape of land parcels. In addition, as noted earlier, in Cyprus there are problems due to lack of road access to parcels, shared ownership and dual ownership. Figure 1 shows a cadastral plan of a highly fragmented area in Cyprus. It is apparent that the parcels are small with irregular shapes and many have no access to roads. Moreover, the figure shows an example of 19 dispersed parcels that belong to a single landowner who owns a further eight shares in other parcels dispersed throughout the area.

According to Bentley (1987), the discussion about the dispersion between parcels of a given holding and in particular the distance from the farmstead began in 1826 with the publication of Johan Von Thunen's 'The Isolated State', whose argument was based on the premise that the costs of farming increase with distance. In particular, when parcels are spatially dispersed, then the travel time and hence the costs in moving labour, machines *et cetera* from one parcel to another are increased (Karouzis, 1977; Bentley 1987, Burton, 1988; (Niroula and Thapa, 2005) and therefore parcels at a greater distance are cultivated less intensively (Van Dijk, 2003). Many case studies have proved the consequences of this problem in practice, such as Thompson (1963) in Greece, Karouzis (1971) in Cyprus, DeLisle (1982) in Manitoba, Canada and Blaikie (1971a; 1971b) in India.

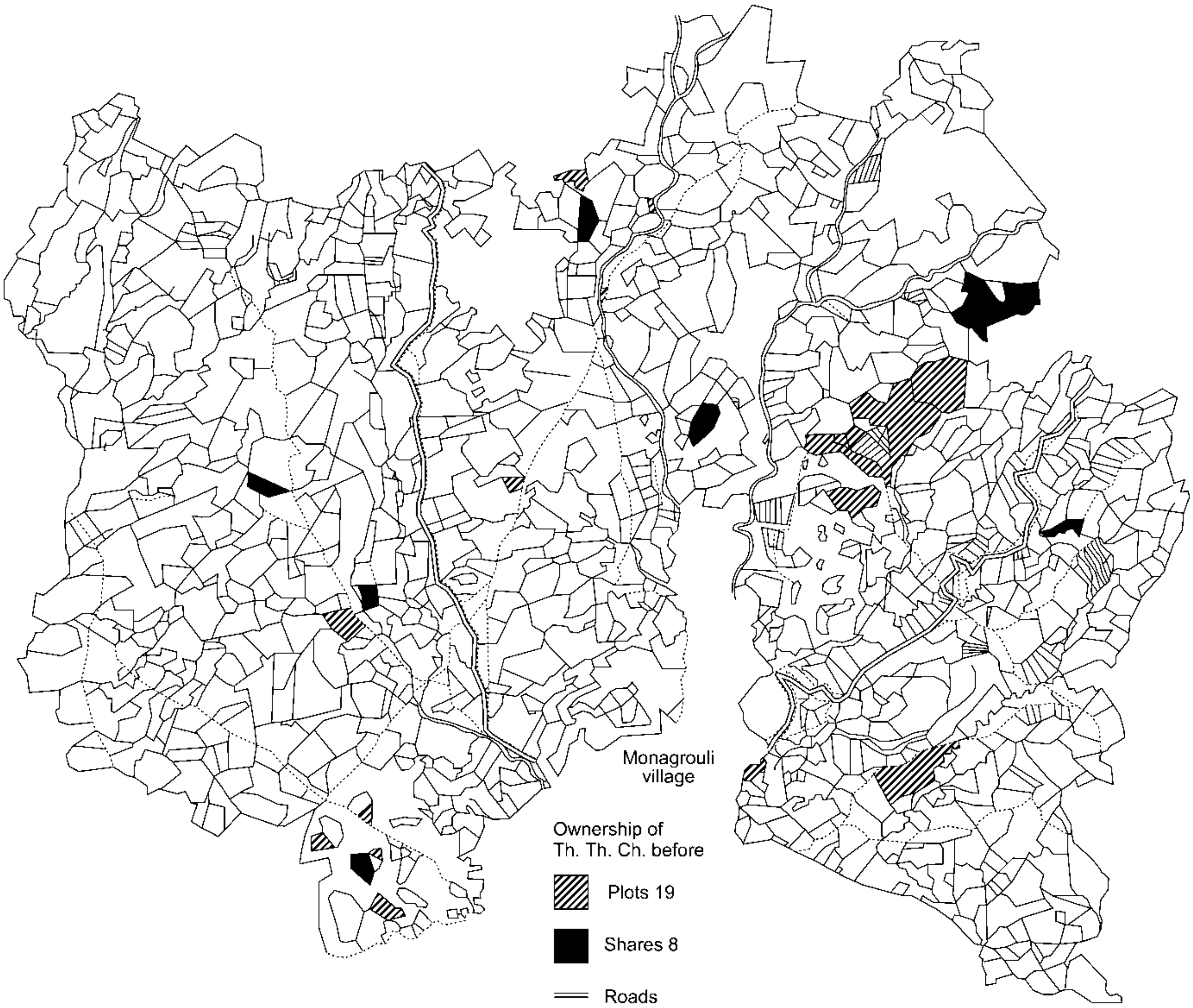

Figure 1: A highly fragmented area in Cyprus

Small parcel size and irregular shape are the dominant problems of land fragmentation (Yates, 1960). The use of modern machinery becomes more difficult or could be impossible on tiny parcels and may require an excessive amount of manual work in the corners and along the boundaries (Karouzis, 1977 and 1980; Bentley 1987, Burton, 1988). Furthermore, irregular parcel shape prevents the proper cultivation of the land, especially for some crops (e.g. vines, olives) which need to be cultivated in rows or series. Moreover, the implementation of soil conservation measures is difficult, the construction costs are higher, more fencing is needed, and roads, which are usually adjusted to the shape of the parcels, have low geometrical (horizontal and vertical) standards, meaning that they have bends and high gradients. In addition, irregular shapes involve a complicated boundary network among parcels (e.g. of hedges, stone walls, ditches), which results in wastage of land (Karouzis, 1977; Bentley 1987; Burton, 1988), and hence parts of a holding (especially the small parcels) will remain uncultivated at the margins of the parcels. In addition, neighbouring conflicts between landowners increase due to this problem. As a result, this problem decreases productivity and hence the income of the farmers. However, although the above issues are straightforward and many authors have found a positive relationship between farm size, productivity and net income (Wattanutchariya and Jitsanguan, 1992; Jian-Ming, 1997), other authors (Schultz, 1964; Berry and Cline, 1979) support an inverse relationship between farm size and productivity. Niroula and Thapa (2005) argue that this situation was a reality in the past but is no longer true in the present.

Lack of road access is commonplace, especially in highly fragmented areas. Access to a parcel is the primary factor that enhances its value. Small fields often have no road access (Yates, 1960; Thompson, 1963; Blaikie, 1971a; 1971b; Morgan, 1978). Many parcels without access are abandoned and remain uncultivated (Karouzis, 1977). Furthermore, the lack of an agricultural road network prevents the introduction of other agricultural infrastructure such as irrigation and drainage systems. Moreover, this problem causes conflicts between neighbouring landowners, which may clog up the local courts, e.g. part of a 'front' parcel may be used as road access or path access to a 'back' parcel.

Parcels with shared ownership very often involve landowner disagreements regarding the exploitation of a parcel, i.e. the kind of cultivation; execution of development works such as soil conservation, drainage, irrigation, *et cetera.* Moreover, this form of ownership is not preferred by land purchasers or developers and landowners consider it to be of secondary importance. Nevertheless, the landowners very often find ways and means to operate the land and minimise potential conflicts with their co-landowners. Similarly, parcels with dual or multiple ownership represent an anachronistic and undesirable situation because the involvement of several landowners can cause conflicts between them, which sometimes prevent the appropriate exploitation of the land.

3.2 Existing indices

Ideally, all the above factors which relate to land fragmentation should be taken into account in a comprehensive and reliable index so that the problem is properly defined. Three of the aforementioned factors are further broken down by King and Burton (1982) into the following six variables: the holding size; the number of parcels belonging to the holding; the size of each parcel; the shape of each parcel; the spatial distribution of the parcels; and the size distribution of the parcels. None of the existing indices combine all of these variables into a single equation, and there is no standard measure of land fragmentation (Van Hung *et al.*, 2007; Bentley, 1987). Most authors who have tried to measure fragmentation have used a simple average of the number of parcels per holding (either regional or national), an average of the holding size and an average of the parcel size. Edwards (1961) calculated a fragmentation index as the percentage of a holding's land which is not adjacent to the farmstead, and Dovring (1965) computed fragmentation by measuring the distance which a farmer would have to travel to reach each of his parcels, returning back to his farmstead after each visit. Although these isolated indices are useful, each represents only one aspect of land fragmentation.

In contrast, indices that incorporate multiple factors have been developed by Simmons (1964), Januszewski (1968) and Igbozurike (1974). Simmons (1964) proposed a land fragmentation index which takes into account the number of parcels belonging to a holding, the relative size of each parcel and the size of the holding. The formula for the Simmons land fragmentation index (*FI*) is:

$$\mathrm{FI} = \frac{\sum_{i=1}^{n} \alpha^2}{A^2} \qquad (1)$$

where *n* is the number of parcels belonging to a holding, α is the size of a parcel and *A* is the total holding size. An *FI* value of 1 means that a holding consists of only one parcel and values closer to zero mean higher fragmentation. The Simmons index becomes the Simpson index if it is subtracted from 1 (Shuhao, 2005).

Januszewski (1968) also developed an index, *K*, by combining the number of parcels per holding and their size distribution as follows:

$$K = \frac{\sqrt{\sum_{i=1}^{n} \alpha}}{\sum_{i=1}^{n} \sqrt{\alpha}} \qquad (2)$$

The values of *K* range from 0 to 1 where values tending towards 0 indicate a high degree of fragmentation. This index has three main properties: the degree of fragmentation increases proportionally with the number of parcels; the fragmentation increases when the range of parcel sizes is small; and the fragmentation decreases as the area of large parcels increases and that of the small parcels decreases. Blarel *et al.* (1992) note that the Januszewski and Simmons indices are the most popular indices employed for measuring land fragmentation.

Igbozurike (1974) suggested a ‘relative index of land parcellization’. In contrast to the above indexes, this measure is based on the average size of the parcels and the distance travelled by a farmer to visit all his parcels sequentially (i.e. in one round trip). This parcellization index, P_i, for holding *i* is given by:

$$P_i = \frac{1}{\frac{\bar{S}}{100}} Dt \qquad (3)$$

where *S* is the size of each parcel and *Dt* is the total round-trip distance covering all parcels. King and Burton (1982) criticized this index because distance was not clearly defined by the researcher and is overemphasised, and no account is taken of the number of parcels. An example is quoted based on a holding with two parcels with size *a* and a distance of 10km apart, which would give a P_i twice as high as a holding with 10 parcels of size *a*, each 1km from its neighbours.

Another fragmentation index was defined by Schmook (1976) known as *Po*, which is the ratio between the area of a polygon which circumscribes all the parcels of a holding and the area of that holding. The values of this index are always above 1, and a high value of *Po* indicates intense fragmentation. This method has the advantage of taking into account both the holding size and the distance.

All of the above methods have certain limitations because only a few variables are taken into account and hence other critical land fragmentation factors are ignored. In particular, all of the current indicators ignore core spatial factors such as the shape and the dispersion of the parcels (except for the Igbozurike index) and non-spatial factors such as the ownership type of each parcel (i.e. dual/multiple, undivided shares) and the existence or absence of road access to a parcel. Another shortcoming is the fact that the variables that are taken into account in each equation have the same weight in terms of importance. For example, in the case of Cyprus, the importance of distance between the parcels of a holding may be less than the shape or the number of parcels. Also, planners, policy makers and farmers may have different perceptions about the importance of particular factors and hence may want to utilise different weights for different variables. As a result, current indices are not comprehensive and therefore incapable of representing the problem of land fragmentation because they focus only on some dimensions of the problem. Clearly, a new index that will overcome these aforementioned shortcomings is required.

4. A new land fragmentation index

4.1 The process

To overcome the deficiencies associated with 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 and problem specific because the user may select which factors need to be taken into account and may decide the weighting given to each component factor for a specific project. The new method is also knowledge-based since expert judgement is incorporated through value functions, and it is explicit because the index involves a rigid range of values between 0 and 1. Value functions (Beinat, 1997) are mathematical equations defined by experts reflecting the desired values of a variable in a range of best to worst conditions. In particular, the method measures how far the existing land fragmentation condition is from the status of being ‘perfect’ (index equals 1), 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 (index equals 0). The proposed process is based on the multi-attribute decision making method (MADM) and has five main steps as set out in Figure 2.

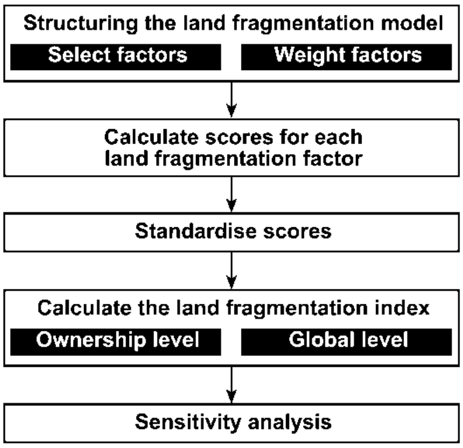

Figure 2: Outline of the LandFragmentS model

Although MADM is conventionally utilised for the assessment of alternative solutions to 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, representing the importance of the factor in a given project. The selection of factors is discussed in the next section. Thereafter, the scores associated with each of these factors are automatically calculated by the system to create a ‘land fragmentation table’ (Figure 3). 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:

$$LFI_i = \sum_{i=1}^{m} f_{ij} w_j \qquad (4)$$

	Land fragmentation factors (Weights)							Index
Ownership ID of ownership	F_1 (w_1)	F_2 (w_2)	F_3 (w_3)	..	F_j (w_j)	..	F_m (w_m)	
1								
2	f_{11}	f_{12}	f_{13}	..	f_{1j}	..	f_{1m}	LFI_1
3	f_{21}	f_{22}	f_{23}	..	f_{2j}	..	f_{2m}	LFI_2
.	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 3: A land fragmentation table of land fragmentation factors for each holding

*LFI*s take values between 0 and 1. A global land fragmentation index (*GLFI*) for the whole study area is then calculated as the mean of the *LFI*s:

$$GLFI = \sum_{i=1}^{n} LFI_i / n \tag{5}$$

or the mean weighted by the size of the holdings. The *GLFI* also takes values between 0 and 1. A median value could be considered if the distribution of *LFI*s is skewed. In addition to *LFI* and *GLFI*, the contribution of each factor to the ownership level of land fragmentation is calculated as the percentage of the value relative to the whole value and the global contribution of each factor is estimated as the mean value of these percentages for all ownerships.

A sensitivity analysis should then follow to assess how robust the outcome is regarding uncertainties and potential errors. In particular, 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). LandFragmentS provides a SA operation for the former source of uncertainty but not for the latter. The reason is that it is impossible to investigate systematically the potential sensitivity of performance scores since they may result in considerably different values with an irregular pattern if value functions change. Therefore, standardisation methods need to be applied with awareness. Value functions in particular need to be carefully considered by experts when analysing their behaviour, i.e. the sensitivity of each function during the process of its definition. The system recalculates the land fragmentation indices based on selected increases or decreases (for various percentages from 10 to 100%, at increments of 10%) 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.

4.2 Land fragmentation factors

4.2.1 Selection of factors

The following eight factors were initially considered for inclusion in the new index: dispersion of parcels; size of parcels; size of 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. However, 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 based on independence testing (Demetriou *et al.,* 2011d), the following six variables were chosen:

- dispersion of parcels (F1);
- size of parcels (F2);
- shape of parcels (F3);
- accessibility of parcels (F4);
- dual ownership (F5); and
- shared ownership (F6).

After the refinement process, 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. It is clear that these six factors exactly correspond to the six main associated sub-problems that constitute the land fragmentation problem noted earlier.

4.2.2 Calculation of factors

Dispersion of parcels (F1)

A basic measure of spatial dispersion is standard distance (Ebdon, 1985; Wong and Lee, 2005), the spatial equivalent of the standard deviation, showing how locations or points are scattered around the spatial mean (Wong and Lee, 2005). The spatial mean or mean centre of gravity is also an important spatial statistical measure of central tendency which indicates the average location of a set of points defined in a Cartesian coordinate system. Thus, standard distance measures the degree to which parcels (or more precisely the centroids of parcels) are concentrated or dispersed around their geometric mean. Although, in practice, the dispersion of holdings is dependent on the location of the farmstead or the village where the farmer resides, the extra information needed is usually not available, so the mean centre of parcels of a holding is a proxy criterion that gives an adequate representation of the dispersion of parcels. Thus the dispersion of parcels (*DoP*) can be calculated as:

$$DoP = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{hmc})^2 + \sum_{i=1}^{n}(y_i - y_{hmc})^2}{n}} \qquad (6)$$

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 since it may take any positive value whilst 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 and corresponding equations shown in equations 7 (Figure 4) and 8 (Figure 5) for arid and irrigated areas respectively. They are different for arid and irrigated areas because legislation provides a different minimum size of parcels. Value functions for this factor and the shape of parcels have been created by a group of five experts based on the methodology described in Demetriou *et al.* (2011c). Figure 4 presents a fifth-order polynomial function:

$$V(x_i) = -1.71(10^{-20}x_i^5) + 6.83(10^{-16}x_i^4) - 9.97(10^{-12}x_i^3) + 6.36(10^{-8}x^2{}_i) - 7.37(10^{-5}x_i) + 5.58(10^{-3}) \qquad (7)$$

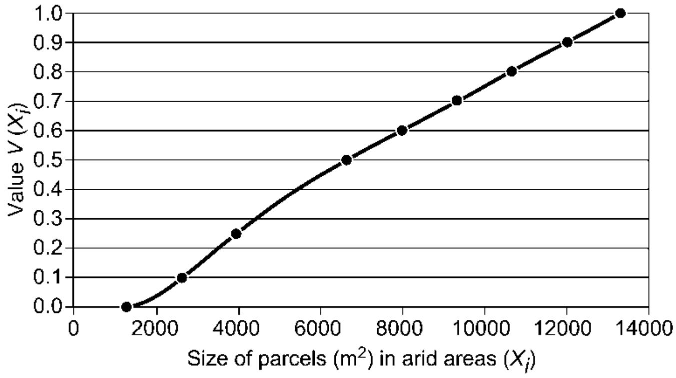

Figure 4: The value function for the size of parcels in arid areas

Figure 5 shows a concave benefit fourth-order polynomial function:

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

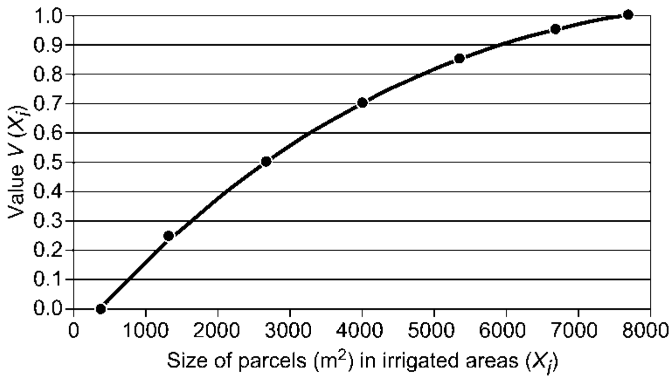

Figure 5: The value function for the size of parcels in irrigated areas

In both functions, scores lower than x_{min} are standardised to 0, while scores higher than x_{max} are standardised to 1. A description of each function is provided in Demetriou *et al.* (2011c).

Shape of parcels (F3)

The shape of parcels is represented by a new parcel shape index (*PSI*) which takes into account the following six geometric parameters: length of sides, acute angles, reflex angles, boundary points, compactness and regularity. A detailed analysis of this index is provided in Demetriou *et al.* (2012b).

Accessibility of parcels (F4)

The system automatically detects if a land parcel has access to 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 owned 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 outlined above.

4.3 Standardisation

As noted earlier, the only land fragmentation factor that needs standardisation (further to the six shape parameters) is the dispersion of parcels (*DoP*) since it may take any positive value (in metres). There are no factual data available on this index so it is hard for experts to define a value function based on their judgment. In addition, the *DoP* is measured on a ratio scale, i.e. values are real and may vary considerably from project to project; hence 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.* (2004) 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 parcel priority index (*PPI*) (Demetriou *et al.*, 2011a), which balances the potential extreme minimum and maximum values by taking into account the mean of the sample. Therefore the modified formulae are:

$$E_i = 1 - \left(\frac{(S_i - \min S) * 0.5}{meanS - \min S} \right) \qquad (\text{if } S_i \leq meanS\ ) \tag{9}$$

and

$$E_i = 1 - \left(\left(\frac{(S_i - meanS) * 0.5}{\max S - meanS} \right) + 0.5 \right) \qquad (\text{if } S_i > meanS\ ) \tag{10}$$

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 the standardisation of the values obtained using both methods. This example includes ‘extreme’ values, i.e. three 0s and one value of 10,000 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 and vice *versa* 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 overcomes this limitation by using the mean value and therefore produces better results.

5. Case study

LandFragmentS has been applied to the case study area in Cyprus (Demetriou *et al.*, 2011d). The extent of the study area is around 200 hectares with 480 parcels/shares and 253 landowners. The cadastral plan was stored in a GIS as a shapefile with three related database tables containing data regarding parcels, landowners and ownership. Three issues are investigated: four weighting scenarios; a comparison of the GLFI with existing indices; and a sensitivity analysis focused on changes in the weights.

5.1 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 first author as: very high, high, extremely high, extremely high, intermediate and high.

Table 3 reveals that there is no combination of weights that results in a considerably different picture regarding existing land fragmentation in the case study area. The maximum difference, i.e. between the minimum and maximum *GLFI* (scenarios 2 and 3 respectively) is not significant, i.e. 13.0%. Thus, it is clear that a land fragmentation problem exists in this area since the *GLFI* is around 0.5 in all scenarios, i.e. the current situation is around 50% from the optimum and this suggests a significant deficiency in the tenure system. Empirically, it could be said that a *GLFI* of greater than 0.7 implies a satisfactory situation where 1 means no land fragmentation problem and 0 suggests very serious land fragmentation. This assumption could be investigated in more detail by considering other economic indices regarding agricultural production or farmer income but is not undertaken here.

Table 3: The *GLFI* and the impact of each factor (%) for four weighting scenarios

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
GLFI	0.51		0.56		0.49		0.52	
	Weight	Contribution	Weight	Contribution	Weight	Contribution	Weight	Contribution
F1	0.17	26.3	0.30	42.18	0.06	10.98	0.182	28.32
F2	0.17	15.7	0.24	21.25	0.09	9.1	0.14	13.06
F3	0.17	18.92	0.18	18.95	0.12	15.23	0.23	25.33

F4	0.17	6.9	0.12	5.03	0.18	7.66	0.23	9.14
F5	0.17	8. 5	0.09	4.38	0.24	13.03	0.09	4.58
F6	0.17	23.7	0.06	8.21	0.30	44.00	0.14	19.57
Sum	1.00	100.00	1.00	100.00	1.00	100.00	1.00	100.00

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

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 are responsible for the land fragmentation problem in the case study area compared to factors F2, F4 and F5, which have less influence in this particular context.

5.2 LandFragmentS versus existing indices

The indices computed in LandFragmentS, i.e. the LFI and GLFI, were compared with the two most popular existing indices, namely the Simmons and Januszewski indices, all of which provide values on a scale of 0 to 1. The distributions of these indices across all of the landholdings in rank order are presented in Figures 6. Figures 6 suggests that both of the existing indices present very similar patterns and the correlation coefficient between the two indices is very high (r = 0.98). One difference between these two indices is that the Januszewski index gives higher values with a minimum of 0.36, an average of 0.84 (maximum value is 1 for both indices) and a narrow spectrum of values (standard deviation of 0.19). In contrast, the Simmons index gives lower values with a minimum of 0.16, an average of 0.79 and a wider range of values (standard deviation equals 0.26), as shown in Figures 7.

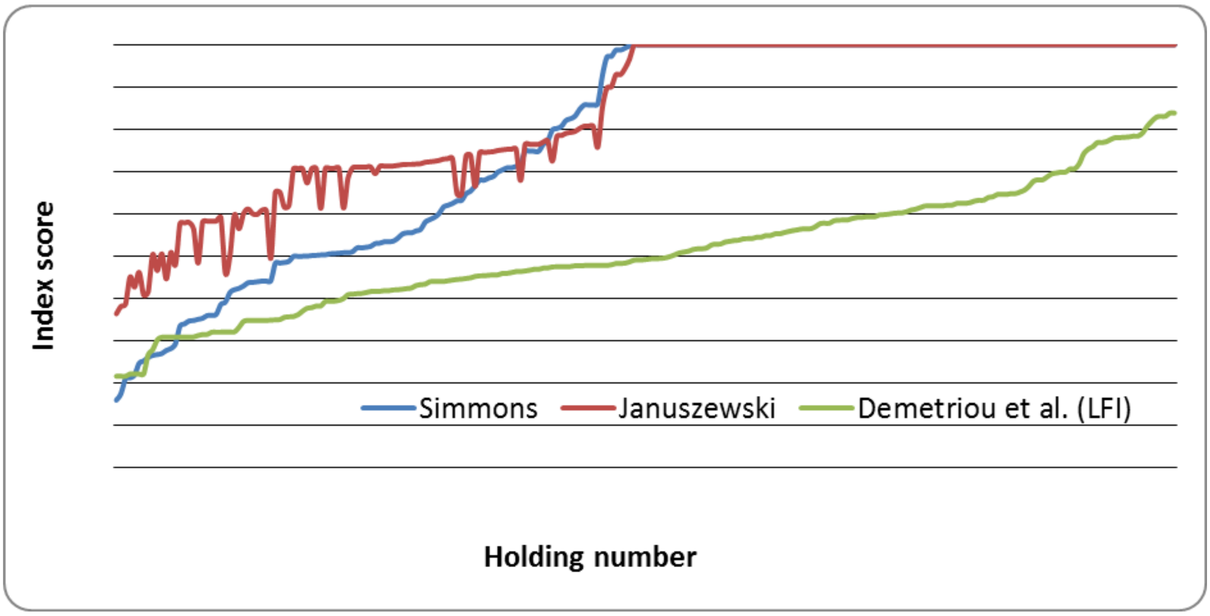

Figure 6: The comparison of Simmons, Januszewski and LFI's distributions

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 6 and revealed by the values of the basic statistics: minimum 0.22; maximum 0.84; and average (*GLFI*) 0.514. It is also noteworthy that no holding achieves the maximum *LFI* value of 1 whilst in contrast, around 50% of holdings were assigned this highest value by both existing indices. 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 7.

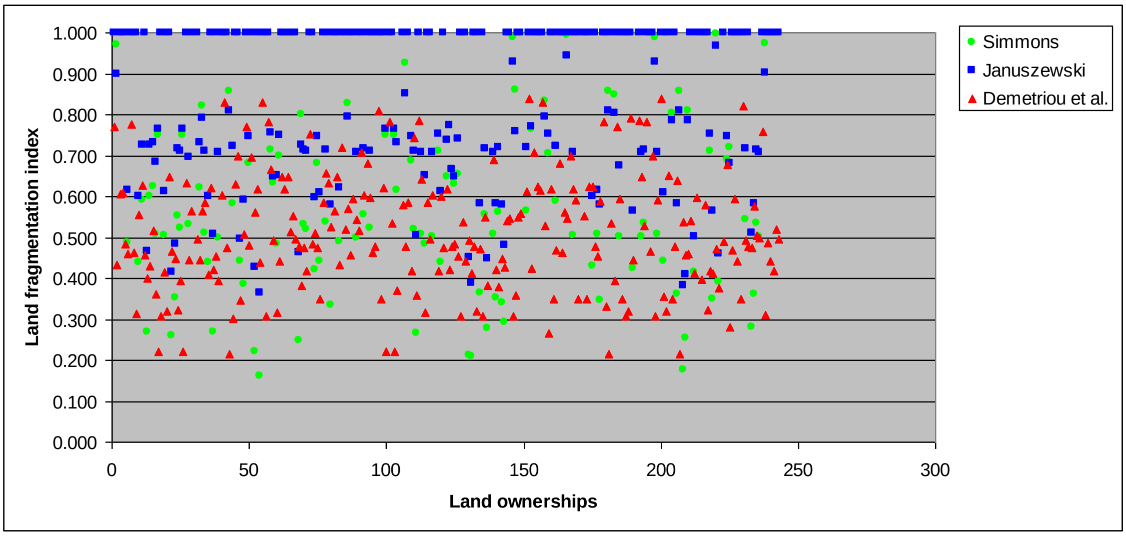

Figure 7: Comparison of the values of the three land fragmentation indices

Based on the above results, it could be argued that both of the existing indices underestimate the problem of land fragmentation with higher average values, i.e. around 0.8 in both cases in contrast to the *GLFI* of around 0.5. The reason is that both existing indices take into account only a few land fragmentation parameters hence reflecting only some aspects of the problem and ignoring critical issues. On the other hand, the *GLFI* combines six land fragmentation parameters and hence represents a more reliable picture of the problem. As a result, existing indices may lead to incorrect decisions. It is interesting to note that in the study area, a land consolidation project was carried out with successful results in practice meaning that land fragmentation was a real problem in this area.

5.3 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	W1				W2				W3			
change (%)	Increase		Decrease		Increase		Decrease		Increase		Decrease	
10	0.52	-0.77	0.51	-0.99	0.51	0.00	0.51	0.00	0.51	0.19	0.51	0.00
20	0.52	0.38	0.50	-1.99	0.51	0.00	0.51	0.00	0.51	0.19	0.51	-0.20
30	0.53	1.33	0.50	-3.02	0.51	0.00	0.51	0.00	0.51	0.19	0.51	-0.20
40	0.53	2.25	0.49	-4.07	0.51	0.00	0.51	0.00	0.51	0.39	0.51	-0.39
50	0.54	3.16	0.49	-5.13	0.51	0.00	0.51	0.00	0.51	0.39	0.51	-0.39
60	0.54	4.05	0.48	-6.22	0.51	0.00	0.51	0.00	0.51	0.58	0.51	-0.39
70	0.55	5.10	0.48	-7.34	0.51	0.00	0.51	0.00	0.51	0.58	0.51	-0.59
80	0.54	4.05	0.47	-8.47	0.51	0.00	0.51	0.00	0.51	0.78	0.51	-0.59
90	0.54	2.98	0.47	-9.64	0.51	0.00	0.51	0.00	0.51	0.78	0.51	-0.79
100	0.53	1.88	0.46	-10.82	0.51	0.00	0.51	0.00	0.51	0.78	0.51	-0.79
Max change (%)	2.71		-8.88		0.00		0.00		0.58		-0.78	

W4				W5				W6			
Increase		Decrease		Increase		Decrease		Increase		Decrease	
0.51	-0.99	0.52	0.97	0.51	-0.99	0.52	0.97	0.52	0.97	0.51	-0.79
0.50	-1.99	0.52	1.92	0.50	-1.99	0.52	1.92	0.52	1.73	0.50	-1.79
0.50	-3.02	0.53	2.85	0.50	-3.02	0.53	3.03	0.53	2.66	0.50	-2.61
0.49	-4.07	0.53	3.76	0.49	-4.07	0.53	3.94	0.53	3.40	0.49	-3.64
0.49	-5.13	0.54	4.66	0.49	-5.13	0.54	4.83	0.54	4.30	0.49	-4.49
0.48	-6.22	0.54	5.54	0.48	-6.22	0.54	5.71	0.54	5.01	0.485	-5.57
0.48	-7.34	0.55	6.40	0.48	-7.34	0.59	6.57	0.54	5.88	0.48	-6.67
0.47	-8.47	0.55	7.25	0.47	-8.47	0.55	7.41	0.55	6.57	0.48	-7.56
0.47	-9.64	0.56	8.08	0.47	-9.64	0.56	8.24	0.55	7.41	0.47	-8.70
0.46	-10.82	0.56	8.90	0.46	-10.82	0.56	9.06	0.56	8.24	0.47	-9.64
-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 0.46 and 0.56 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 occurs in two opposite directions, i.e. factors F4 and F5 have a positive impact on the problem; hence, by increasing their importance, the *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 that noted earlier, i.e., 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.

6. Conclusions

Land fragmentation has been and remains a major problem in many countries of the world. A review of the literature 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 model which overcomes the weaknesses of existing indices.

The LandFragmentS model produces a global land fragmentation index (*GLFI*) with the following features: 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 which weights should be applied 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 existing indices showed that the latter indices underestimate the problem of land fragmentation, simply because they ignore several important variables. 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. 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 for which evaluation criteria can be defined with an explicit range of values representing the worst and best conditions.

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