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A Graph theory approach for geovisualization of land use change: An application to Lisbon

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Abstract

Urban sprawl and growth has experienced increased concern in geographic and environmental literature. Preceding the existence of robust frameworks found in regional and urban planning, as well as urban geography and economics, the spatial properties of allocation of urban land use are still far from being completely understood. This is largely due to the underlying complexity of the change found at spatial level of urban land use, merging social, economic and natural drivers. The spatial patterns formed, and the connectivity established among the different subsets of land-use types, becomes a complex network of interactions over time, helping to shape the structure of the city. The possibility to merge the configuration of land-use with complex networks may be assessed elegantly through graph theory. Nodes and edges can become abstract representations of typologies of space and are represented into a topological space of different land use types which traditionally share common spatial boundaries. Within a regional framework, the links between adjacent and neighboring urban land use types become better understood, by means of a Kamada-Kawai algorithm. This study uses land use in Lisbon over three years, 1990, 2000 and 2006, to develop a Kamada-Kawai graph interpretation of land-use as a result of neighboring power. The rapid change witnessed in Lisbon since the nineties, as well as the availability of CORINE Land Cover data in these three time stamps, permits a reflection on anthropogenic land-use change in urban and semi-urban areas in Portugal's capital. This paper responds to (1) the structure and connectivity of urban land use over time, demonstrating that most of the agricultural land is stressed to transform to urban, gaining a central role in future. (2) Offer a systemic approach to land-use transitions generating what we call spatial memory, where land use change is often unpredictable over space, but becomes evident in a graph theory framework, and (3) advance in the geovisual understanding of spatial phenomena in land use transitions by means of graph theory. Thus, the structure of this combined method enables urban and landscape to have a better understanding of the spatial interaction of land-use types within the city, promoting an elegant solution to rapid geovisualization for land-use management in general.

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1. Introduction

The fragmentation of landscape and its subsequent effects on land use and ecosystems has become a global concern (Nagendra et al., 2004). Brought by economic growth, the creation of new infrastructures to support demand, have led to profound structural changes in the traditional concept of the city (Davidson, 1998). This has changed the local perceptions of the city to a much larger urban agglomerate in transition of urban and rural interactions (Helbich and Leitner, 2009), understood as the urban region leading often to environmental degradation (Czamanski et al., 2008). While traditional cities have represented positive sources of economic prosperity, the agglomerated city (Rosenthal and Strange, 2001), sets out a new role. This role emphasizes the importance of urban areas, and debates whether or not the methods of sustainable urban growth are most suitable for future generations as they will ultimately face the challenge of promoting a low carbon society and preserving the vitality of the urban-rural fringe (Han et al., 2012). Pollution for instance, has an adverse impact on development as most of the urban regions today show an augmenting number of mortalities caused by a pollutants, as well as, changes in territorial occupations. Urban areas have seen an increase in crime rates as coping with excessive concentrations of people in these areas has shown to be difficult (Cusimano et al., 2010). With their growing technological enhancements, better transportation (Litman and Burwell, 2006), health and education systems, as well as fostering social movements (Nicholls, 2012), cities offer a source of hope for better lives with sustainable solutions. The ecofriendly city has brought greener planning initiatives to a research agenda of environmental science and offered, as a consequence, a holistic vision of urban processes (Roseland, 1997), where the interactions of human with ecosystems can promote a better social conscience, but also lead to a clearer understanding of how urban regions must interact with nature. One of the most important interactions is linked to the carrying capacity of land, in which a function-analysis, function-valuation, and conflict analysis, should be present to understand the landscape dynamics, and foster sustainable development (de Groot, 2006). This is strongly linked to a better understanding of the spatial dimension of land-use change and land-use transitions, fostered by the integration of Geographic Information Systems as tools to assess and manage present and future. In this sense, land use plays a vital and fundamental role in maintaining a balance on the environment in general, and one of the culprits of urban growth has become the loss of certain types of land which have a unique function for the complex interactions of environment (Xiao, et al. 2006). An entire set of literature has been built on this premise, concerning impacts of land-use, which has aided in a more accurate and better planning for sustainable development at a spatial level (Batty, 2005). These models are designated by urban growth models, and draw largely from an integration of geography, economics, mathematics and social sciences. This leads to the paramount importance of land use planning and understanding the changing land use patterns over a given extend of time (Koomen et al., 2007). In this sense, manipulation of spatial data brings a spatial multilevel assessment, leading to a better understanding of the urban structure (Schwanen et al., 2004) helping to optimize urban regions. Geographic Information Systems have proven to be a effective tools to understand underlying patterns of spatial phenomena, offering through spatial analysis a quantifiable and assertive technique to propose a better understanding of the spatial structure. The scattered nature as well as the often fragmented characteristics of urban growth are however still hard to fully understand and represent a burden also on the aesthetics of the landscape (Sullivan and Lovell, 2006). One of the reasons is linked to the fact that land-use change models and urban growth models foment stochastic understanding of possible outcomes of urbanization processes (Han et al., 2009) little attention has been given to the interactions and consistency of land use types. This landscape and land use consistency, is however a a common prerequisite for sustainable development. While in the short term local sustainability plays a major relevance, in the long term, common structural changes must be considered be considered (Capello 2001). In this sense, we have addressed the following research questions in this paper:

- What is the relation of land use classes per type over an urban metropolitan area over time? Is there an underlying pattern that allows for graph theory to visualize urban land use consistency?
- Can we arrive to conclusions on future growth patterns and add on the process of urban land use in a region where economic recession, after a large urbanization process, shows signs of stagnation?

2. Materials

2.1. Study Area

Lisbon, the capital of Portugal constitutes part of the Metropolitan Area of Lisbon (Figure 1) and holds a total population of over 2.6 million people and a total area of 2,957.4 km2 (AML, 2005). The city core itself is located at 38°42′49.72″N 9°8′21.79″W, and has an urban area of 985km2, with a population density of 6,458 km2.

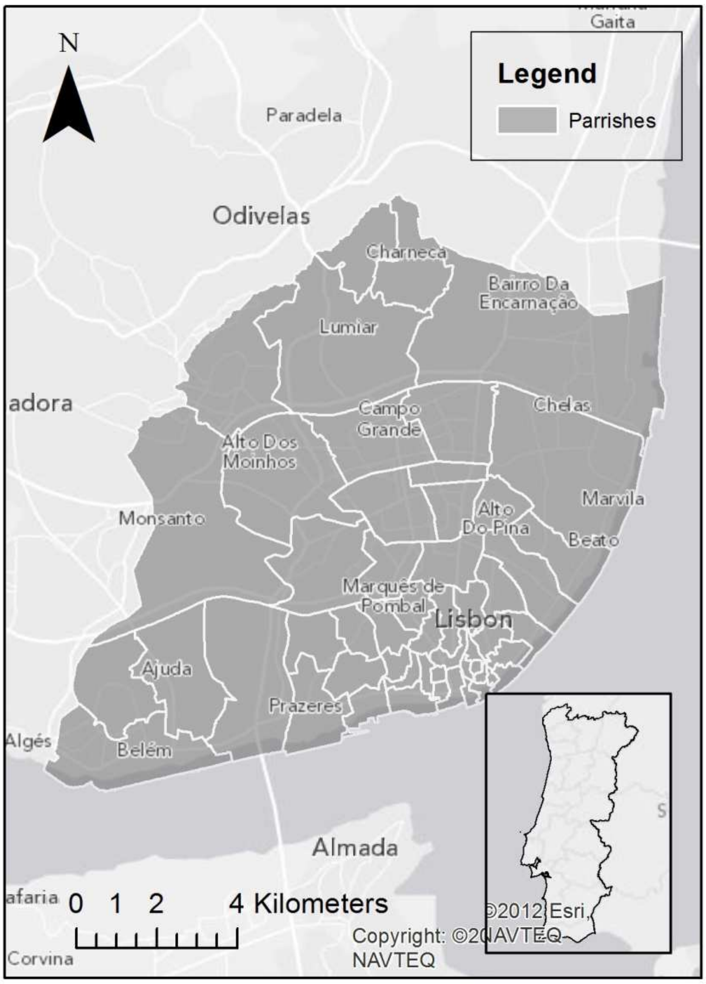


Figure 1 – Location of study are

Urban sprawl has started in the beginning of the eighties, where economic growth witnessed in the nineties, created suburban areas where local intervention have shaped high connectivity areas lead to a polycentric city, stagnating on the urban growth of Lisbon's core. The region underwent several profound social and political phases that can be defined as: (i) urban to rural migration, a unique phase that took place in the fifties and sixties creating a higher concentration on a concentrated and monopolistic urban fringe (Malheiros, 1996), (ii) the return of thousands from the overseas ex-colonies in the seventies, settling mostly in suburban parts of the Lisbon metropolis (Carlos, 2005; Malheiros, 1998), (iii) the integration in the mid-eighties of Portugal in the European Union, changing the economic activities from a Fordist model to a service sector based, where European support allowed to modernize and create new infrastructures on the urban fringe and finally, (iv) the economic recession witnessed in recent years, leading to obsolete infrastructures and abandonment of urban land and investments. As mentioned by Dias and others (2009), the territorial development model for Lisbon sets out three priorities: (1) to strengthen Lisbon's role in the global and national networks, (2) consolidate the city and promote sustainability and (3) promote urban qualification and public participation. These three priorities are strongly linked to the complexity of spatial decision, and tools found in geovisualization and spatial analysis. Of pivotal importance is the role of a changing urban landscape that resulted from the different economic patterns the city has witnessed over the last decades, it is important to foment sustainability by understanding within the polycentric morphology of the urban area, the relations of space and to adjacent land use types. This is a dimension often neglected in urban regions, and that should be catered in countries such as Portugal, where the present recession accrues to the importance of coping with obsolete infrastructures and developing solutions for continued land sustainability without jeopardizing the environment, biodiversity and the landscape.

3. Methodology

3.1. From connectivity to land use connectivity

The difference between land use types and contrasting characteristic of anthropogenic activity are a reflection of the complexity of anthropogenic activity in the case of urban land. This complexity is dealt by integration of different sets of input parameters that allow generating multiple scenarios and supporting best management options using the inherent potential of numerical models in a GIS environment (Dragicevic and Marceau, 2000). This has led in recent years to a growing concern on which techniques can be used to monitor and understand the change of anthropogenic land. The difficulty however, is linked to the uncertainty and complexity of predictive modeling approaches, and the shifts in policy and decision making processes by stakeholders. Deciphering these patterns however, is of utmost importance as it may allow to better plan the relations that exist over space in land use types, leading to better management and decision processes for a sustainable future. From an ecological perspective, the existence of heterogeneous landscapes has been long understood (Levin, 1976, DeAngelis et al., 1985), and a framework of landscape ecology built under the pertinence that Geographic Information Systems can be used as exemplary tools for monitoring impacts on sustainability of the landscape (Burrough, 1986). One of the main characteristics imported from the relation of Geographic Information Systems and ecology, has been the possibility to understand through connectivity of the landscape to measure the structure of the landscape (Taylor et al., 1993). This has allowed understanding the interdependency between different patches that represent functional characteristics over space, and allow for interpretation of landscape processes over larger areas (Bergerot, et al., 2013). From an ecological perspective, and given the link to biodiversity this has been a very important development for sustainable development. Many of the techniques however, can be used to examine anthropogenic patterns over land use, by transforming the concept of patches formed in a functional connectivity perspective brought from ecology, to an understanding of neighboring adjacency of land use types.

3.2. Graph theory: An abstract approach to urban areas

A Graph represents an abstract mathematical concept of a network. By any means, it is always a portrait of many types of relations. Combined by 'nodes' and 'edges', the nodes (represented usually as points or vectors) are the end that permits the linkage through an 'edge' to another 'node'. In Mathematics, this concept has been used very early, and is the best structural relation we may have of a two-dimensional space and the relations of interactions over space. Graphs represent a defined topological structure, where the connection between one 'node' to another, or the relation formed between the connection, is much more than spatial, and permits a quantifiable understanding of connections, far different from traditional geometric Euclidean spaces. The length as such of a graph, can be discarded from a purely mathematical background, and may represent different types of phenomena, and serve to find patterns of discrete relations over space. The interest in describing the complexity of the structure of the landscape enables to assess but also to quantify the interactions over space in representing and understanding the connectivity of the landscape in its complexity (Cantwell and Forman, 1993). The relations of land-use over the total landscape are however quite complex, and thus, one of the main elements that should be considered in framing the complexity of spatial interactions is land-use.

3.3. Aggregation of land use types by adjacency

This paper considers that land use and land cover, independent of its area, format or size, is adjacent to another type of land use. This not only makes land-use connected, but also harbors characteristics of similarity between land-use types given the first law of Geography, where things closer to each other are inherently more related (Tobler, 1970). This concept of neighboring land and spatial proximity is translated by a graph of a finite number of connections, varying sizes of spatial areas, type of land, and geomorphological characteristics of the terrain and the landscape through adjacency (Figure 1).

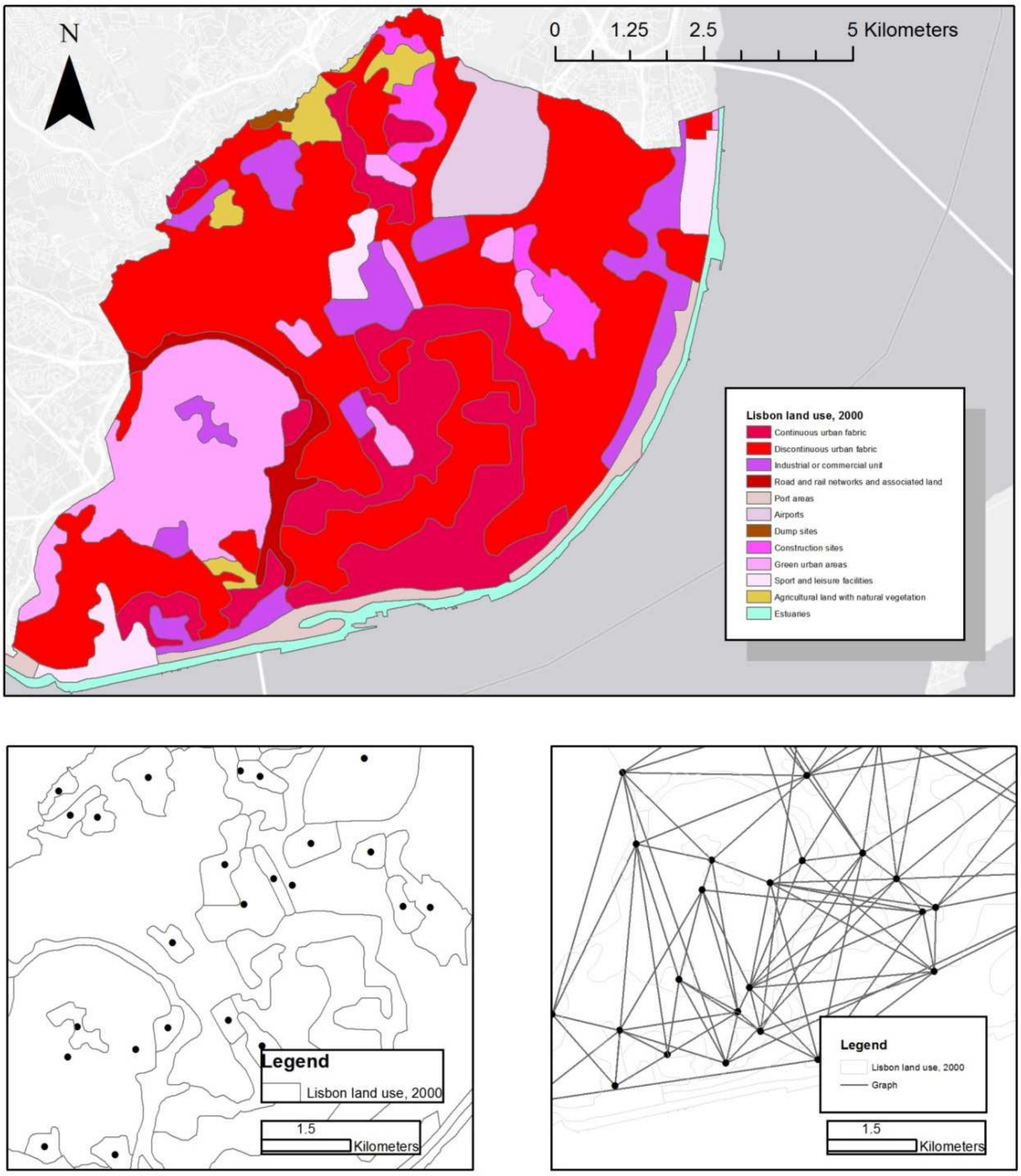


Figure 1 – Geographic abstraction of land-use into graph

I also take for granted that each land use may be represented geometrically as a geometric polygon, of which I can derive a centroid. By definition my centroid is the result of a finite set of k points $x_1 + x_2 + \cdots + x_3$ in $\mathbb{R}^n$ is:

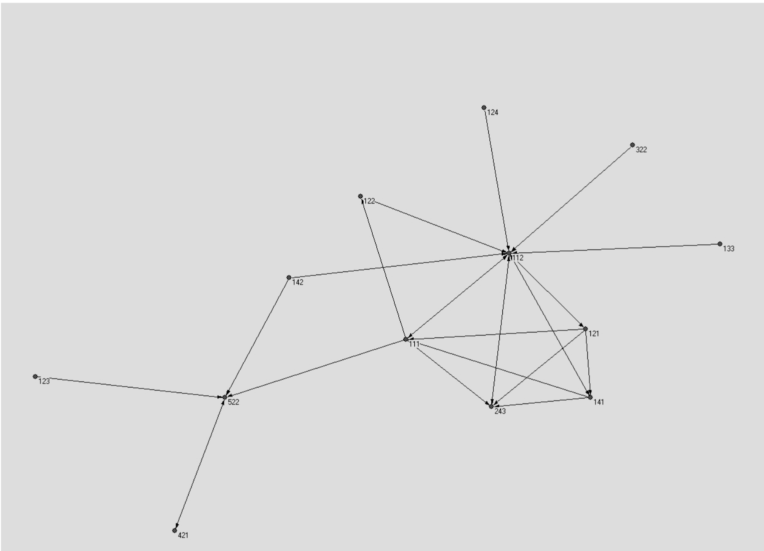
$$C = \frac{x_1 + x_2 + \cdots + x_3}{k}$$ Equation 1.

This centroid may thus represent the central point of equidistance within a given land use type. The geometric point that this centroid represents is characterized by centroids derived from the neighboring land use classes, thus the cumulative land use classes could be represented as $\varepsilon = c_1 + c_2 + \cdots + c_3$ equally in $\mathbb{R}^n$, defined as the centroid geometrical space. This space ε will now be considered $\varepsilon = G$, where G is a pair $G = (V, E)$ in which V is a finite set called the vectors of G and E is a subset of V designated as edges. In our geometrical space of centroids ε, it is thus considered that we can define E as long as $V = c_n$. In doing this, the data is transformed a geometrical space into a representation of a simple graph. Within this representation, it is stated that the spatial relations found between the geometric spaces of land use, may be represented as a simple graph, where interactions of land use can be processed by their adjacency to different land use types. These relations are explored visually by the definition that a graph may be force directed based on the number of connections existing within different land-use types within the geographic area. This pertains to the different connections allowed between land-use for the adjacency of existing land-use types in a city or urban regions.

The position of nodes and the location of the abstract interpretation of land-use per node is of great importance for geovisual analysis. This visually enhances the size of the edges in order to allow for few crossing edges among the different nodes. In the case of land-use, this is of particular importance as this enables a better understanding of the relations of different land-use among the area. The Kamada-Kawai algorithm allows conceptualizing an ideal set of distances between vertices that are not neighbors (Kamada and Kawai, 1988). The ideal distance therefore, becomes proportional to the length of the shortest path between them. In the case of land-use, knowing that the connection of land-use through adjacency does not register the farther away land-use types, but acknowledges through the first law of geography that still this adjacency relation exists, this solution proves to be elegant in considering the number of adjacent features for a total plane of land use registered over space.

4. Discussion

Lisbon, the capital of Portugal, is one of the most vibrant and diverse urban regions of Portugal. Since the early eighties the socio-economic changes in the city have led to a fragmentation of some urban areas, and an increase in urban land in the cities nexus. Portugal, as a country, has changed dramatically since the end of its dictatorship in 1974; several important moments in the Portuguese political and economic scene have contributed to what Portugal is today at a land-use level. With the integration of Portugal in the European Union in 1984, land-use has predominantly become urban land, and rural exodus has led to abandonment of agricultural and rural areas. In the mid-eighties, new urban regions were formed and the tourist industry shaped most of the Portuguese coastal areas into what it is today. The strategy of the service sector allowed cities to become hubs of economic growth, while agricultural land was reformed through funding of the European Union. After the successful growth of Portugal in the nineties, the new millennium gave rise to protected agricultural areas and ecosystems, followed by a stronger legislation on the protection of these land -use types. The recent economic recession has resulted in a stagnating development of urban sprawl, and the analysis of urban land-use change since the nineties for Portugal clearly shows that this is a tendency generally found in most of the mainland, which is deemed to follow over the next years. The land use of Lisbon is an interesting empirical application, given its diversity of urban land-use, its concentrated city nuclei, and the availability of datasets from CORINE Land Cover. A closer analysis on the resulting graph transformed by the Kamada-Kawai algorithm, visually responds to the adjacency relations found over all of the urban metropolis of Lisbon in 1990 (Figure 2).



111 – Continuous urban fabric
112 – Discontinuous urban fabric
121 – Industrial or commercial units
122 – Road and rail networks
123 – Port areas
124 – Airports
133 – Construction sites
141 – Green urban areas
142 – Sport and leisure facilities
243 – Agriculture and natural vegetation
322 – Moors and heathland
421 – Salt marshes
522 – Estuaries

Figure 2 – Land use in Lisbon in 1990

We can see that a construct of inter-related land use types is formed between anthropogenic land-use, corresponding to continuous urban fabric, industrial commercial units, and the attempt to add green spaces within the urban area. Agricultural land and natural vegetation are also considered in the context of existing urban areas. This integrated vision in the nineties, is strongly linked to the plans of the national inventory of agricultural land as explored in Vaz and others (2012). Sport and leisure facilities are fundamentally centered along the proximity of the coastal areas, and of natural environment, while forming quite an independent link. Discontinuous urban fabric seems to have been of central importance in 1990 as well as in 2000 (Figure 2). This relation of discontinuous urban fabric fosters the concept that land use is in a permanent transition process, depending on the current economic, social and environmental constraints within the urban nexus. The differences in the morphology of adjacency found in 2000 are clearly evident. A much more centered role seems to exist, where land-use is interchanged among different land -use types and expressed by a land-use mix, where all land-use types are interlinked with the exception of leisure facilities as well as the appearance of a new class, relating to natural grass land. From 1990 to 2000, Lisbon land-use types have become much more functional, expressing by the number of connections within the graph, leading to a more heterogeneous city combining availability of infrastructure, urban fabric, and the natural environment.

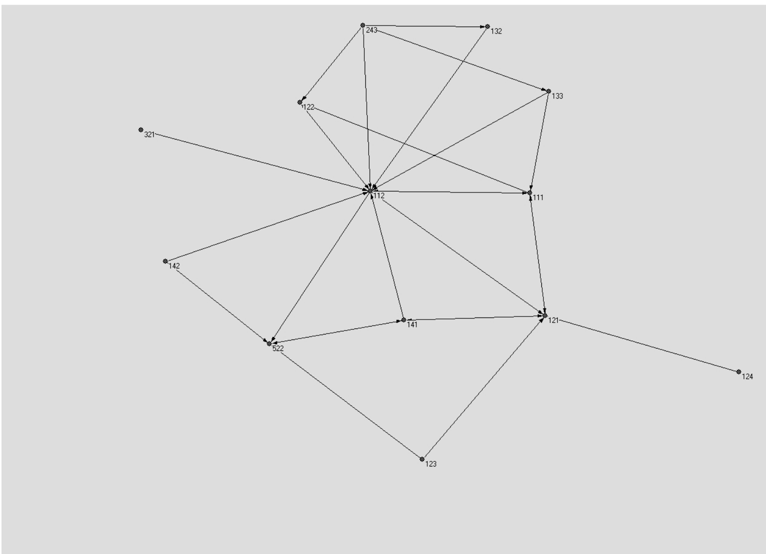


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Figure 3 – Land use in Lisbon in 2000

5. Conclusions

The current methods to assess spatiotemporal change have increased the possibility of understanding and delineating land use transitions. However, a limited set of work has focused from a land use perspective in understanding the relation between land use types and their changes in future. Lisbon, as many urban regions throughout the world, hold vast spatial data resources that allow comparing, assessing and visualizing land use change. This allows consolidating urban dynamics and trends, while entertaining urban dynamics from a land use perspective, and their connectivity. The importance of monitoring this in countries where rapid land use changes have been witnessed is fundamental for planning purposes. While population dynamics are strongly linked to population shifts in the urban area, a relevant increase in urbanization is proportional to the generation of new infrastructures to support population dynamics and causing additional fragmentation (Young and Jarvis, 2008), and tools such as graph theory applied to land use, allow visualizing the connectivity and fragmentation of land use types. An evaluative spatial approach of the interaction of land use categories concludes the relation of spatially sustainable land use choices and the integrative role in urban processes for megacities, and urban regions of highly occupied and developing cities throughout the world.

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