COMPARING RESIDENTIAL DEVELOPMENT SCENARIOS REGARDING THE ACCESSIBILITY TO VARIOUS AMENITIES: THE CASE OF LUXEMBOURG

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ABSTRACT

Locations of green spaces are a major concern for population especially regarding their consequences on health, spatial equity, house pricing, and residential choices. In this paper, we aim to explore the interactions between the spatial distribution of various amenities (green and leisure amenities, shops and services) and the possible forms of residential development. The objective is to determine how different forms of residential development improve or reduce the accessibility to various amenities. Our hypothesis is that fractal forms of residential development allow minimizing distances between residential areas and amenities better than do business-as-usual scenarios, compact scenarios, or even TOD scenarios. As an output of the modelling process, we produce ex-post accessibility indicators to various amenities (distance to the closest facility, global coverage…). Our findings highlight the interest of using comprehensive simulation tools for urban and regional planning.

Keywords: spatial simulation, urban growth modelling, green and leisure amenities, accessibility, residential location

1. INTRODUCTION

Since the 1950s, households in Western countries have been relocating from inner cities to the suburbs. Generally, the desire to access private property is reinforced by the desire to access more amenities, including more green space and leisure areas. However, the phenomenon of urban growth is not without consequences. In Luxembourg and its neighbouring countries, urban sprawl is a source of nuisances. Congestion (Cervero, 2002), air pollution (Randall, 2003), noise (Sharp, 2002) and parking problems are the consequences of the increase in vehicular traffic as a result of residential growth that is often poorly mastered. Based on the relationship between urban forms and the functioning of urban systems (Hansen, 1959; Newman, Kenworthy, 1989; Wegener, 2004, 2011), many models have been developed by the scientific community in the quest for the "optimal" city. The compact city was one of the first models to have been studied (Dantzig and Saaty, 1973). The increase in density and urban containment should have been the preferred solution to avoid the longer distances needing to be covered by individuals and the process of urban sprawl in general. However, the compact city model has proved to have its limitations, particularly in the reduction of access to green spaces (Pouyanne, 2004). It seems that the compact city is also a source of greater congestion (Burton, 2000) and an increase in housing prices (Hall, 1997). Therefore, other models have been proposed, such as the polycentric city, the diffuse city, the New Urbanism (Calthorpe, 1993) or the Transit Oriented Development (Bernick and Cervero, 1996). Nevertheless, the debates concerning the quantification of the relationship between the nature of the urban form and the mobility associated with are still relevant (Schwanen et al, 2001; Conway, 2009). It is in this context that the fractal model of urban growth has been developed (Frankhauser, 2004). Early work stressed the importance of applying fractal models to urban issues (Frankhauser and Genre-Grandpierre 1998; Frankhauser, 2000). Simulation scenarios of fractal urban growth confirmed these initial results. At first glance, it seems that the fractal city offers better access to varied natural amenities, especially when one considers the distance required to reach them (Tannier et al, 2006; Tannier et al, 2012). An amenity is defined here as a positive externality, which comes into play in the choice of a place of household residence, shops, services, green and leisure areas ...

Research question and hypotheses

The objective of this paper is to simulate the application of various development standards that determine the forms of residential development in the Grand Duchy of Luxembourg. Through this simulation approach, the suggested links between urban form and function (intra-urban mobility) are translated into development standards. It is not the choice of households that is being modelled here, but rather the link between a normative urban form and the potential residential satisfaction of individuals (Thomas et al, 2008). These standards represent the point of view of the developer[1] who aims to meet the aspirations of individuals as well as the goals of sustainable urban development.

The developer seeks to improve accessibility to shops and services, especially locally, in order to reduce the number and length of trips in private motorised vehicles. For short-distance trips, the goal is to promote walking. We also know that the quality of the residential environment comes into play in household residential satisfaction. The presence of shops, services, and green and leisure areas that can be reached in a short time is thus a positive element, both from the point of view of individuals as well as persons in charge of planning policies. In this context, one needs to succeed in harmonising the link between urban development scenarios and accessibility objectives (McCormack, Giles-Corti, 2004; Boarnet et al, 2011).

In a second step, it is necessary to compare various types of residential development according to the criteria of accessibility to amenities. In 1998 and 2000, Cyrille Genre-Grandpierre and Pierre Frankhauser hypothesised that a fractal urbanisation model would improve accessibility to green and natural spaces located outside the built-up agglomeration, while maintaining good access to secondary urban centres. The simulation tools we have at our disposition today allow us to test this hypothesis. In this context, we use the MUP-City simulation platform (Tannier et al, 2010) to simulate the fractal residential growth in Luxembourg by integrating consideration of accessibility standards for various amenities. These fractal urbanisation scenarios are compared to a residential development scenario that generates more conventional urban forms, both moderately compact and axial.

[1] The term developer is used here in a general sense, i.e. it includes all or part of the system of actors in charge of development (government, local officials, engineers, developers, consultants, citizens ...).

2. Methodology

2.1 Data and study area

As we saw earlier, the objective of the research presented in this paper is twofold. Firstly, it is to simulate different types of residential extensions in Luxembourg. This simulation is based on a logical scenario. We thus compare the fractal and non-fractal model (moderately compact and axial), taking into account the population projections made by the Luxembourg government statistics agency (STATEC, 2010). The model generates urbanisation potentials, expressed in the form of a breakdown of the area into cells of 400m² (20 metres square). This division into small size cells allows accurate calculation of accessibility to amenities from each building. By applying the average ratios for housing density (number of dwellings per hectare) to cells defined as potentially urbanised, it is possible to convert the results into a total number of units produced. The residential growth simulated is thus according to the population projections provided by STATEC.

The existing buildings in Luxembourg are made up of approximately 300,000 cells, i.e. more than 12 000 hectares. With an average density of 15 dwellings per hectare in Luxembourg, this gives 170 000 dwellings (or households) existing in 2001 according to the last census (STATEC, 2001). This initial state is the starting point for the simulation process. The results described below are summarised in Table III. With the breakdown into cells of 400m² (20x20 metres), 2 500km² of Luxembourg are made up of 6 481 560 cells. From this number, one must of course subtract the cells already built up (representing exactly 301 941 cells), but also all the non-urbanisable areas (woodlands, waterways, highways network, electrical infrastructure ...) which represent 2 670 988 cells, or 106 840 hectares. In total, the surface theoretically available in Luxembourg represents 3 779 631 cells, i.e. 150 000 hectares.

In view of the rules which will be described later, data were collected in the context of applying a typology of amenities. This typology is based on the potential frequency of use, which reflects the intention to have standardised development and which corresponds to the residential choice of households.

They were obtained from two sources:

- Databases by address, then geotagged. These data refer to shops and services.
- Topographic bases, generated from aerial observations/satellites and GIS processing, which yielded layers of green and leisure amenities.

The typological list of amenities (table 1) was obtained from previous work on the MUP City project and was brought into line with what is available across the whole of Luxembourg. For each of the two groups of amenities (shops and services, green and leisure amenities), three levels of potential use are differentiated (daily, weekly, monthly or less frequently). It may be recalled here that this classification reflects a choice of development from a normative point of view, and does not attempt to duplicate exactly the living conditions of individuals.

Table 1 – Type of shops and services used in the model

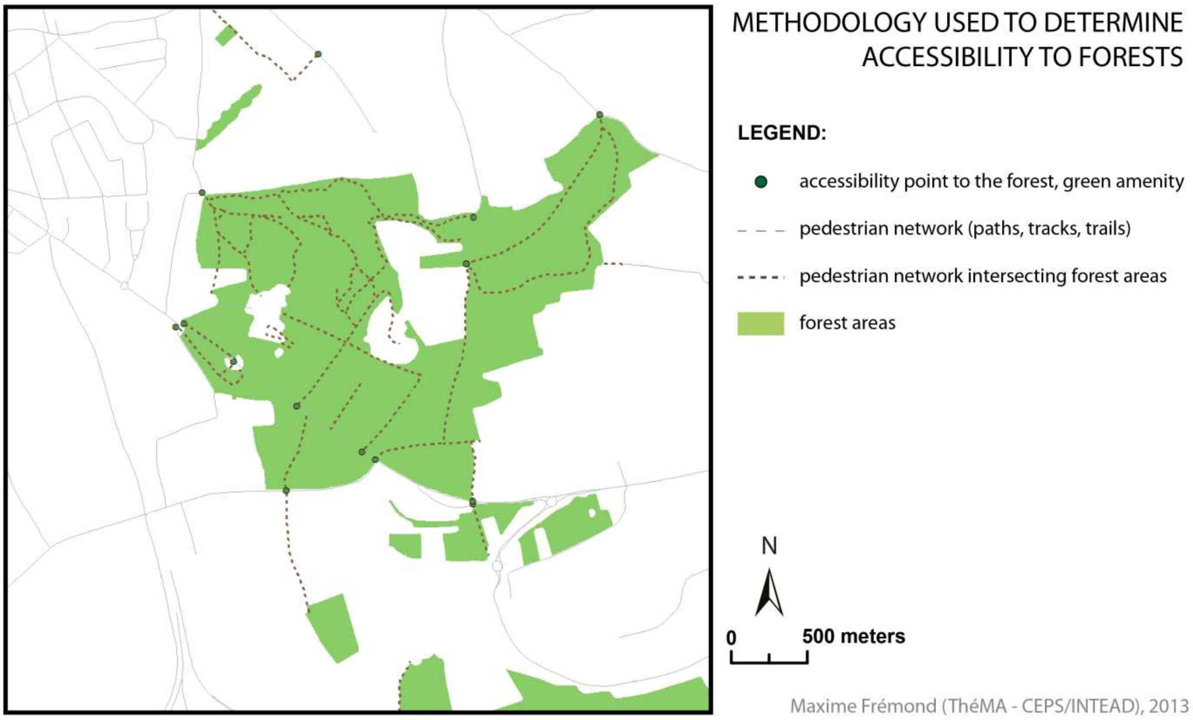
Type of access to retail and service facilities
Level N1 (daily frequentation)
General supplies, biological, sports, grocery, etc.
Bakeries, chocolate makers, confectioners
Butchers, processed meat shops, fish, poultry, cheese
Nurseries
Primary schools, private schools
Supermarkets
Tobacconists, newsagents
Level N2 (weekly frequentation)
Bank branches
Cafes - bars
Hairdressers
Shoe shops
Clothing shops
ATMs
Keep-fit centres
Florists
Car washes
GPs
Chemists
Post office
Laundries - dry cleaning
Restaurants
Service stations
Supermarkets/hypermarkets
Level N3 (monthly or rarer frequentation)
Government departments
Cultural amenities (theatres, cinemas, libraries, concert halls)
Dentists
Hospitals - medical homes
Libraries
Town halls
Medical specialists

Type of access to green spaces and leisure areas
Daily frequentation L1:
Parks and gardens
Woods and forests under 2Ha
Weekly attendance L2:
Football ground
Tennis ground
Golf courses
Gymaniums
Swimming pools
Woods and forests from 2 to 100Ha
Monthly or more frequent attendance *L3*:
Woods and forests of over 100Ha

The daily amenities are made up of shops, services and amenities that may be visited every day or several times a week, and whose proximity to the home limit the length and time of travel. Pedestrian trips or cycling seem more privileged in terms of distances. The weekly amenities are made up of shops, services and amenities that may be visited once or twice (maximum) a week. Less frequent use allows a greater relative distance to residential areas and therefore a little longer travel time. The amenities visited monthly (or less frequently), such as government departments are mostly located in the city of Luxembourg, which may impose relatively long travel as and when needed. Even if each municipality has a municipal administration, the frequency of use is rather limited. It is the same for accessibility to health facilities and cultural services. A more relative proximity to these amenities may be defined, involving longer distances to be covered by car or public transport.

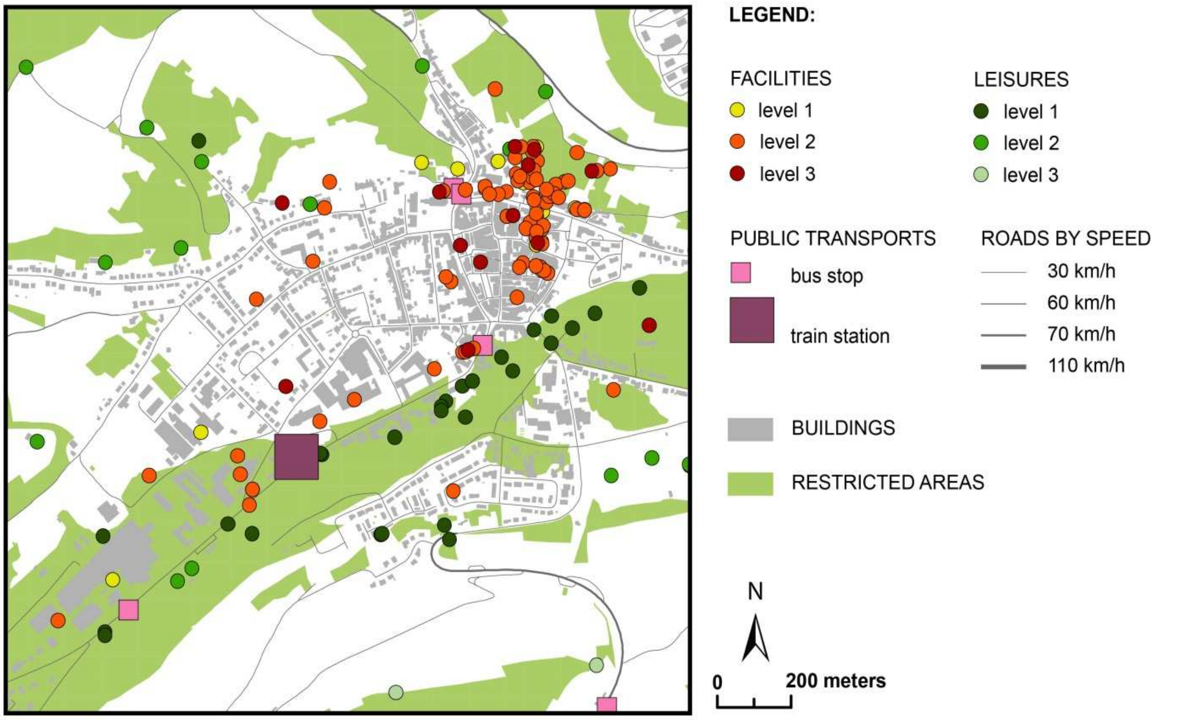
Forest areas, usually represented as polygons (surface area), are considered as point features in the model. To perform this transformation, the network of footpaths in the forest was intersected with the boundaries of the forested polygons. The result is a layer composed of dots, symbolizing the access points to the forest in the network.

Figure 1 – Illustration of the methodology used to determine accessibility points to forests



The map (Figure 2) below summarises the data input to the model. It includes shops and services (3 levels of accessibility), the green and leisure amenities (3 levels of accessibility), public transport (bus-stops and railway stations), roads (declined based on theoretical traffic speeds), existing buildings, and non-buildable areas.

Figure 2 – Examples of inputs used in the simulation



2.2 Accessibility standards

The development objectives mentioned earlier are translated into nine assessment rules applied to all the cells in the area studied.

1. One rule concerns the proximity to open spaces; it aims to prevent new residential extensions restricting access to green spaces from existing buildings (*morphologic*)
2. One rule assesses accessibility to shops and services subject to daily attendance (N1), (*facility level 1*)
3. One rule assesses accessibility to shops and services subject to weekly attendance (*facility level 2*)
4. One rule assesses accessibility to the existing road network to limit the construction of new infrastructure (*road proximity*)
5. One rule assesses accessibility to shops and services subject to monthly (or rare) attendance (N3), (*facility level 3*)
6. One rule assesses accessibility to the transport infrastructure (train and bus), (*public transport proximity*)
7. One rule assesses accessibility to green and leisure amenities subject to daily attendance (L1), (*leisure level 1*)
8. One rule assesses accessibility to green and leisure amenities subject to weekly attendance (L2), (*leisure level 2*)

9. One rule assesses accessibility to green and leisure amenities subject to monthly (or more rare) attendance, (L3), (*leisure level 3*)

Each rule is described by means of either one or two variables, formalised as fuzzy membership functions (Oh and Jeong, 2002; Zadeh, 1965). The combining of variables in a rule involves aggregation operators that are also derived from fuzzy set theory (Zimmermann, 1987; Zimmermann and Zysno, 1983). Fuzzy set theory offers a range of mathematical tools for manipulating imprecise knowledge. In this paper, it is especially interesting to formalise compensation phenomena between variables with varying compensation degrees according to both the absolute and relative values of the variables considered. The result of each rule is an assessment value between 0 (poor assessment) and 1 (good assessment). These different assessment values are then aggregated to form an overall determinant assessment of each cell to be urbanised.

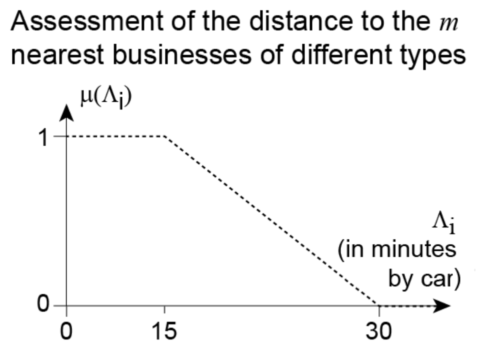
The formalisation of the first four rules of accessibility is described in (Tannier et al, 2012). The five last rules are formalised as follows.

Accessibility to shops and services subject to monthly or more frequent attendance, N3, (facility level 3)

Unlike shops and services subject to daily and weekly attendance, where it is advantageous to have an extensive supply offering very close by, one can consider that having a business or service in each category at a "reasonable" distance from the cell is sufficient. For example, it is not necessary to have two hospitals, two dentists and two libraries close to a home. However, it is of interest to have a complex of these businesses and services a few tens of minutes away. This arrangement is also justifiable with respect to access to government departments. It is not necessary to be equidistant from two municipal administrations, since, by definition, a home is located in a single municipality. In this case, proximity to the town hall (or at least the responsible town hall) is desirable. The purpose of this rule is to measure the distance to the closest amenities *m* of different types. Again, the criterion of distance must be less than or equal to a standard. As businesses and services potentially subject to monthly (or more frequent) attendance correspond to central functions, we must take into account their accessibility both by car and public transport. This suggests working in terms of distance-time (in minutes of travel).

Figure 3 – Description of the fuzzy variable relative to retail and service facilities used monthly (or more rarely)

Fuzzy variable used to assess the accessibility to retail and service facilities used monthly (or more rarely)



For each facility of type δ:
Where d_{ij} is the minimum distance-time between the assessed cell i and the establishment (business or service, using the faster mode of transport) j
Where n is the number of establishments j
And where $D_j = \{d_{i1},\ldots, d_{ij}, \ldots, d_{in}\}$

One calculates:

$$\lambda_{ij} = MIN[D_j]$$

Where *m* is the number of different types of establishments: $\delta = \{1, 2, \ldots, m\}$
Where l_i is the distance to the closest amenities *m* of different types for cell *i*

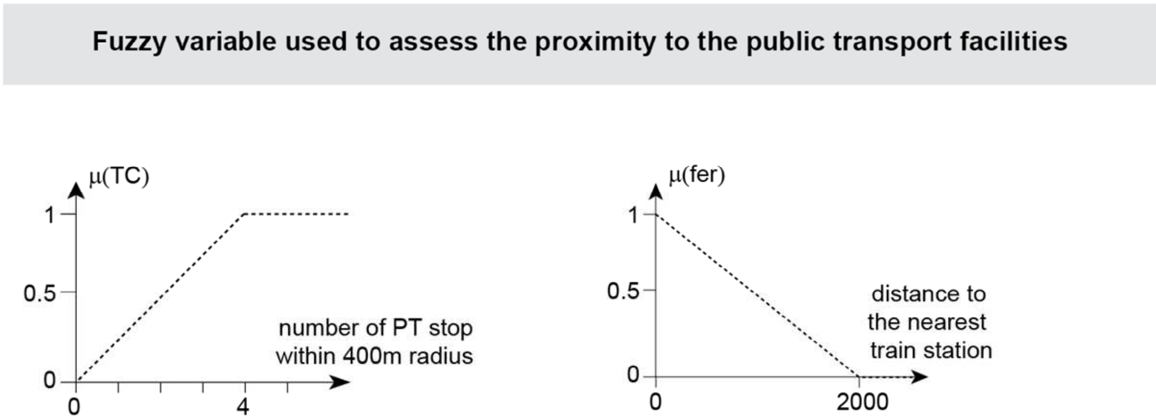
$$\Lambda_i = \frac{1}{m} \sum_{\delta=1}^{m} \lambda_{ij}$$

The result of this rule is the assessment of the distance Λ_i using a fuzzy variable $\mu(\Lambda)$ for which the standard fixed distance (defined as the median of the distribution of distance-times to amenities m closest to each type of cell to be assessed) corresponds to the value $\mu(\Lambda)= 1$. In this distribution, the value of $\mu(\Lambda)= 0$ corresponds to the maximum time to reach the nearest amenity of each type by means of the faster transport, 30 minutes by car.

Accessibility to public transport (public transport proximity)

The bus stops and railway stations have a threshold of about 2000m around the bus stop to define the fuzzy variable μ*(fer).* The number of bus stops within 400 metres of the cell is used to define the fuzzy variable μ*(bus)*. We count the number of stops per line. The stops on the lines going in one direction are differentiated from those going in the other direction. In fact, there are over 2000 bus stops in Luxembourg but some offer only limited opportunities due to relatively limited frequencies. This is why the proximity of the bus network is based on the so-called structuring of the network, i.e. where the network is likely to overcome the lack of rail transport nearby because it has bus stops with a substantial offering in services and frequency.

Figure 4 – Description of the fuzzy variable relative to public transport facilities



The assessment of access to the transport network is calculated as follows:

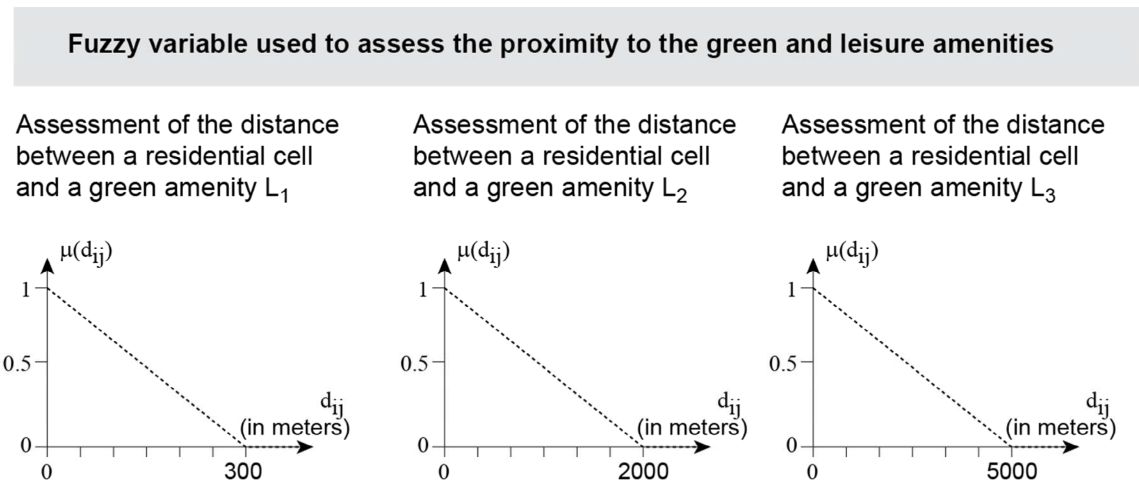
$$MAX[\mu(TC); \mu(fer)]$$

Accessibility to green and leisure amenities L1, L2 and L3 (leisure level 1, 2 and 3)

During the assessment of a cell that can be potentially urbanised, good access to a limited number of these amenities is sufficient to obtain a high value. For example, having access to a single football field is as interesting as access to two fields. However, having access to both a football field and a tennis court is strongly valued.

The first step in the calculation of accessibility is the assessment of each amenity as a function of the distance to the cell in question. We consider only the nearest amenity of each type.

Figure 5 – Description of the fuzzy variable relative to proximity to green and leisure amenities



Notations for the level L_1 (assessment equal to 0, as of a distance of 300m or more) :

- $\mu[L_{1(forest)}]$
- $\mu[L_{1(parc)}]$

Notations for L_2 (assessment equal to 0, as of a distance of 2000m):

- $\mu[L_{2(forest)}]$
- $\mu[L_{2(football)}]$
- $\mu[L_{2(tennis)}]$
- $\mu[L_{2(golf)}]$
- $\mu[L_{2(swim)}]$
- $\mu[L_{2(gym)}]$

Notation for L_3 (assessment equal to 0 as of a distance of 5000m):

- $\mu[L_{3(forest)}]$

The second step in the calculation of accessibility is the aggregation of these partial assessments in an overall assessment. The principles of this aggregation are: the better the partial assessments, the better should be the overall assessment; at the same distance, it is better to have two different amenities than one; a single amenity close by is less attractive than a single amenity close by and another further away[2]. This is a cumulative approach and there is no compensation: a poor partial assessment should not lower a good partial assessment. It is therefore necessary that the aggregation operator gives results that are superior or equal to the maximum, and all the more higher as the number of partial assessments to be aggregated is high. In other words, the number of criteria aggregated must increase the optimism of the operator.

Here is an example of formalisation for the first level of green amenities; the principle behind the calculation is the same for the following two levels.

Where $y_i(L_1)$ is the number of different amenities of level L_1, whose assessment is greater than 0, in the vicinity of the cell i in question,
Where $y_{max}(L_1)$ is the maximum number of different amenities of level L_1 in the vicinity of the cell to be assessed in the space in question,
Where $o_i(L_1)$ is the degree of optimism of the operator as a function of the number of partial assessments to be aggregated. (Only calculated in the case where $y_{max}(L_1) > 0$),
Where $s_i(L_1)$ is the overall assessment of a cell i with respect to green and leisure amenities of level L_1,

Thus:

$$o_i(L_1) = 1 - \left[(y(L_1) - 1) \times \left(\frac{1}{(y_{max}(L_1) - 1)} \right) \right]$$

$$s_i(L_1) = \left[MAX \left(\mu_i[L_{1(forest)}; \mu_i[L_{1(parc)}) \right] \right]^{o_i(L_1)}$$

[3]

[2] NB: For each level (from 1 to 3), one works on the closest amenities; the amenities whose partial assessment is equal to 0 are not considered.

[3] NB: in the case where $y_{max}(L_1) = 2$, when a cell has two different amenities of level L_1 within 300m, its overall assessment $s_i(L_1)$ is always equal to 1, whatever the values of the partial assessment $\mu[L_{1(forest)}]$ et$\mu[L_{1(parc)}]$.

Aggregation of the various assessment values in a synthetic value of interest for urbanization

The idea is to vary the weight of each rule in the synthetic evaluation S_i of interest for a cell to be urbanised, in order to simulate various development possibilities

Formalisation
Where S_i is the synthetic interest that cell *i* be urbanised,
Where $s_i(r)$ is the assessment of cell *i* resulting from the rule *r*,
Where w_r is the weight of the rule *r*,

$$S_i = MIN[s_i(1)^{w_1}; s_i(2)^{w_2}; ...; s_i(r)^{w_r}]$$

To determine the weight (values of importance) of the various rules, a method of *pairwise comparison* borrowed from decision analysis tools was adopted (Saaty, 1977, Yager 1978). This method allows the comparison of the rules in pairs in order to identify which is the most important rule in each pair, and to quantify this importance. To this end, the following table was used with the *X* and *Y* criteria of the rules being compared for each pair.

Table II – Importance of criteria defined as a function of *X* and *Y* (according to Saaty, 1970)

IMPORTANCE w_{XY}	Definition
1	Equal importance of the criterion *X* with respect to criterion *Y*
3	Weak importance of the criterion *X* with respect to criterion *Y*
5	Strong importance of the criterion *X* with respect to criterion *Y*
7	Absolute importance of the criterion *X* with respect to criterion *Y*

For example, to determine the two by two importance for three criteria, we use the following method. If the criterion *X* is greater than the criterion *Y*, we assign a value of importance w_{XY} in the table below and assign the value $[1/(w_{XY})]$ to *Y*.

Table III – Example of values of importance defined as a function of the three criteria *X, Y* and *Z* (according to Saaty, 1970)

Importance of a criterion with respect to another	Value of importance for a criterion	Corresponding value for the other criterion
Y is a little more important than *X*	$w_{XY} = 1/3$	$w_{XY} = 3$
Z is between equal and a little more important than *X*	$w_{XY} = 1/2$	$w_{XY} = 2$
Y is slightly more important than *Z*	$w_{XY} = 3$	$w_{XY} = 1/3$

From the table above, a comparison matrix of the importances (X, Y and Z) is generated.

$$\begin{bmatrix} 1 & 1/3 & 1/2 \\ 3 & 1 & 3 \\ 2 & 1/3 & 1 \end{bmatrix}$$

The eigenvector of this matrix is then calculated. The weights *w* correspond to the values of the eigenvector multiplied by the number of attributes considered (3 in the example above).

$$w = \begin{pmatrix} 0,48 \\ 1,77 \\ 0,75 \end{pmatrix}$$

Thus, the fuzzy value of each of the 9 rules is aggregated with weights equal to its value of *w*. This method avoids a simple arithmetic average that would result in giving equal weight to each assessment criterion. A modification of this weighting would be a step backwards to development standards.

2.3 Construction of development scenarios

In this analysis, we retained two main scenarios, with the two variants for the first.

Fractal scenarios of residential development
For creating them, the software application MUP-City uses a multi-scale modelling, whose principles have been described elsewhere (Tannier et al, 2012). The application of the fractal model is performed in two stages. First, the fractal decomposition of the built-up areas enables the establishment of a morphological rule of urbanisation based on the dimension of self-similarity, similar to the definition of the Mandelbrot fractal dimension. This dimension, denoted, D_s, is calculated according to N, the number of elements built in each iteration step, and r, the factor of reduction of the decomposition grid.

$$D_s = \frac{\ln N}{\ln(1/r)} .$$

Scenario 1:
This is a fractal scenario where the fractal dimension of the simulated built pattern D_s equals 1.46; all the nine accessibility rules are activated. This is the baseline scenario that serves as the basis for the remainder of the comparisons. In this scenario, the chosen fractal dimension (hence the local built density) is quite low.

Scenario 1.1:
This is a fractal scenario where the fractal dimension of the simulated built pattern D_s equals 1.63; all the nine accessibility rules are activated.
In this variant of the first scenario the fractal dimension is higher.

Scenario 1.2:

This is a fractal scenario where the fractal dimension of the simulated built pattern D_s equals 1.46; only the first four accessibility rules are applied.
This scenario aims to assess the contribution of new rules integrated into the model compared to the previous version described in (Tannier et al, 2012).

Scenario 2:
This is a non-fractal scenario with the same number of cells as in the fractal scenario number 1; all the accessibility rules are activated. For simulating this scenario only the accessibility rules are applied but not the multi-scale modelling. As such, the non-fractal model may be considered as a compact model of urbanisation generating both compact and axial residential developments.

Weight of accessibility rules

Table IV below shows the *pairwise comparison* matrix used in the creation of the development scenarios.

Table IV – *Pairwise comparison* matrix used in the scenarios

	M	R	F1	F2	F3	PT	L1	L2	L3
Morphologic	-	1	1	1	1	1	1	1	1
Road proximity	1	-	1	1	1	1/5	1	1	1
Facility level 1	1	1	-	7	5	1	7	5	3
Facility level 2	1	1	1/7	-	3	1	3	5	7
Facility level 3	1	1	1/5	1/3	-	1	1/5	1/3	1
Public Transport proximity	1	5	1	1	1	-	1	1	1
Leisure level 1	1	1	1/7	1/3	5	1	-	5	3
Leisure level 2	1	1	1/5	1/5	3	1	1/5	-	3
Leisure level 3	1	1	1/3	1/7	1	1	1/5	1/3	-

In order to avoid supplanting the assessment of the morphological rule by the other rules and thus to limit urban sprawl, it was decided not to overemphasise this rule in relation to others. On the contrary, no rule is in "competition" with the rule that optimises the interaction between built-up and non-built-up areas. The same applies equally for the assessment rule of proximity to the road, with the exception of its importance with respect to the assessment rule of proximity to public transport, which has been quite strongly reduced to give greater priority to public transport.

The assessment rules of proximity to shops and services were weighted in a decreasing manner with respect to the frequency of use. In fact, according to the initial assumptions, it seems more appropriate to favour accessibility subject to the most frequent use, so that the distances to be covered are smaller. The same principle was applied to green and leisure amenities, where the weighting of the accessibility assessment rules increases with increasing frequency of use.

3. RESULTS

3.1 Assessment of the initial situation

This first part of the results reports the overall assessment values obtained following application of the rules to the initial state. These data are used to assess how the study area corresponds to the development criteria set by the standards. They therefore include all the cells already urbanised within the national boundaries.

The rule regarding proximity to the road is one of the least discriminating. In fact, the road density in Luxembourg allows a large number of cells to be properly assessed (97% of the cells already urbanised). At the local level, one can thus find a large number of well-assessed spaces in close proximity to the road. This result confirms that the lack of construction of new road infrastructure is not a barrier to residential growth.

Proximity to public transport is highly rated. With over 80% positive assessments, Luxembourg seems well served. However, this value needs to be considered against the number of bus stops that are scattered around the country (over 2000), while the frequencies are not very high and this means that travelling by public transport is very uncompetitive compared to the use of private transport (Klein and Schmitz, 2011).

The first level of shops and services is poorly rated by the model. Less than 45% of the territory of Luxembourg appears to be close to one or more level 1 amenity. It must be remembered that the assessment is carried out according to distance with relatively short thresholds based on the assumption of accessibility on foot. Thus, the initial situation in the Grand Duchy is not conducive to the implementation of such stringent standards. This result needs to be considered in relation to the high rate of car ownership in the country, which is 666 cars per 1 000 inhabitants, and the second largest in the world after Monaco (771 cars per 1 000 inhabitants) (STATEC, 2012). These data form a fundamental marker of the dependence of the Luxembourg system on the private car and thus to motorised travel (Dupuy, 1995, for the Luxembourg see Petit, 2005). This results in a certain defect in the functional diversity in the development of the land.

On the other hand, the assessment rule for accessibility to level 2 shops and services is not very discriminating from a quantitative point of view. A large number of built cells is positively evaluated, which does not exclude them from the subsequent processing.

The rule for accessibility to level 3 shops and services is numerically the least constraining in the analysis (along with level 3 of green amenities). The entire territory of Luxembourg is well rated in terms of accessibility to central amenities that can be reached in 15 minutes by car or 30 minutes by public transport. The relative dispersion of health professionals (dentists, specialists) is certainly an element that contributes significantly to this result. Perhaps more tests should be performed while removing the typology properties and leaving, for example, the cultural amenities and public administrations. Strengthening private car accessibility criteria might also be considered because of the size of Luxembourg and the good coverage by public transport.

The first level of green and leisure amenities is the most constraining of the analysis. Only 8% of existing constructions in Luxembourg have access to a park, a garden or a small forest at less than 10 minutes on foot. This result is somewhat qualified by the two upper levels. In fact, while only a small percentage of the surface of the Grand Duchy has good access to level 1 amenities, over 80% has quite good access to slightly larger woodlands (2 to 100 ha), but located further away from potentially urbanisable areas (2km or a half-hour walk). Finally, almost all the national territory has good access to large areas of forest in the country, with 97% of the built within 5km. These last two results can be explained quite well by the high rate of forestation in Luxembourg, with over 35% of the area covered.

Table V – Summary of results obtained after calculation of the accessibility rules at the initial state

Initial situation	mean of assessment value for cells	Number of cells assessed positively	rate of cells assessed positively among total number of built cells	cells assessed positively in hectares
road proximity	0,82	294339	0,97	11774
facility level 1	0,47	134239	0,44	5370
facility level 2	0,78	267895	0,89	10716
facility level 3	0,93	294789	0,98	11792
public transport proximity	0,54	250494	0,83	10020
leisure level 1	0,40	24213	0,08	969
leisure level 2	0,59	265583	0,88	10623
leisure level 3	1,00	294257	0,97	11770
total amount of built cells	-	301941	1	12078

In the light of this assessment of the initial situation, it is necessary to look at how the application of different forms of urban growth can increase or decrease the accessibility assessment.

3.2 Results from the scenarios

The four scenarios were used to compare the application of different assumptions to the initial situation described above. In the case of the fractal scenarios, the systematic consideration of the fractal dimension leads to the random generation of many cells. To better analyse the impact of the different models, only positively-assessed cells were selected (see table VI).

Table VI – Summary of the results obtained according to the simulation

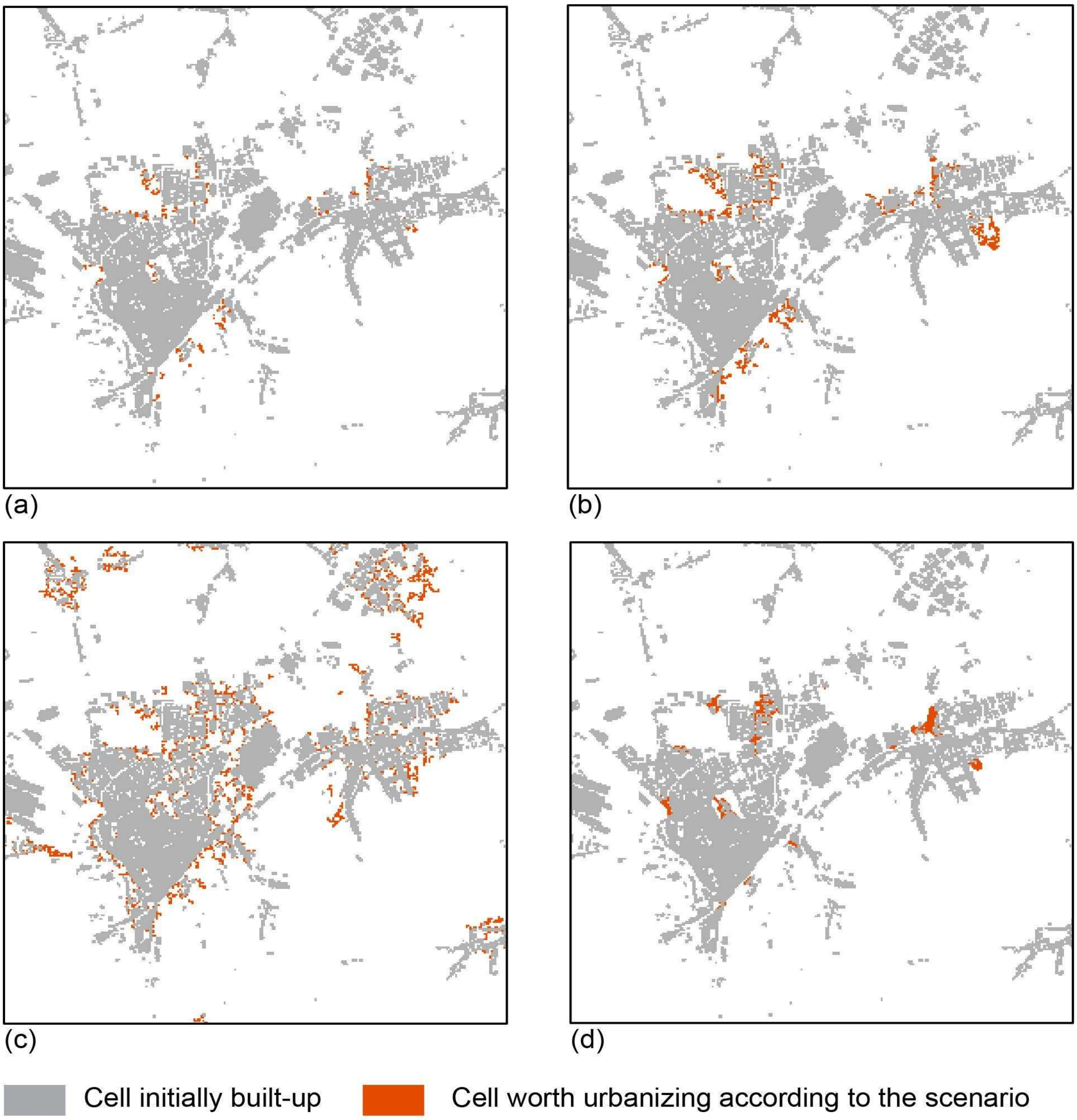
SCENARIO	number of positively-assessed cells	maximum assessment value	mean of assessment values of cells
scenario 1 *fractal - D = 1.46 + 9 accessibility rules*	2745	0.598	0.099
scenario 1.1 *fractal - D = 1.63 + 9 accessibility rules*	6411	0.598	0.093
scenario 1.2 *fractal - D = 1.46 + only 4 accessibility rules*	42882	0.820	0.137
scenario 2 *non-fractal + 9 accessibility rules + same number of newly urbanized cells than in scenario 1*	2745	0.570	0.257

The result obtained is fairly typical of the doubts raised by the initial assessment. In fact, at the end of the simulation approach, which involves the aggregation of accessibility values by *pairwise comparison* and the selection of cells via GIS, few of the spaces defined below are judged to be potentially urbanisable. With scenario 1, only 2745 cells are retained. Converting this potential, we get little over a hundred hectares or less than 2000 dwelling units (18 units/ha). At the current pace of construction, the application of the model would not allow even one year of housing needs to be covered, which is currently at least 3500 units per year. The fractal model of urbanisation, with its amenities' accessibility standards, is not directly transferable and applicable in Luxembourg. However, alternatives are being tested. Simply increasing the fractal dimension of the simulated built pattern leads to the selection of double the number of cells in the analysis. This approach should not be neglected in this modelling method of urban growth.

In the definition of the non-fractal scenario, and for the sake of comparison, the value of 2745 cells was used, although it represented the minimum number of cell generated. This choice was made in order to maintain scenario 1 as the reference in our analysis.

Another fact: the new accessibility rules (last five rules) seem to have a real impact in the assessment of cells, since the test of their deactivation makes the simulation much less restrictive and therefore frees up potentially urbanisable areas.

Figure 6 – Spatial outputs of the various scenarios (zoom)



(a) fractal, scenario 1

(b) fractal, scenario 1.1

(c) fractal, scenario 1.2

(d) non-fractal, scenario 2

3.3 Focus on the accessibility of green and leisure amenities

To assess each scenario, the accessibility to green and leisure amenities closest to each cell is calculated.

Evaluation by the Euclidean distance to the closest green or leisure amenity

The assessment of accessibility to green or leisure amenities relies on the typology of the amenities presented above. Thus we calculate the average distance of each cell to the closest amenity at each level and for each type for level 2[4]. The results obtained for each of the three scenarios are presented in table VII below.

Table VII – Summary of Euclidean distance assessment results

SCENARIO	Mean of Euclidian distance to the closest green or leisure amenity (in metres)							
	LEVEL 1	LEVEL 2						LEVEL 3
		FOREST	FOOTBALL	TENNIS	GOLF	SWIMMING POOLS	GYMNASIUMS	
scenario 1	181	657	919	1264	13628	1798	1470	956
scenario 1.1	132	672	908	1299	13601	1734	1468	938
scenario 1.2	1251	872	1372	1746	**12226**	3257	2177	**920**
scenario 2	**92**	**640**	**899**	**1091**	12645	**1570**	**1285**	1040

(in bold and red: the best results for each amenity)

The lowest average distances for access to the closest green and leisure amenities are obtained with the non-fractal scenario. Accessibility to golf courses and forests over 100ha is better with the fractal scenario but without activation of the rules of accessibility to green and leisure amenities. This result may seem paradoxical but can be explained by the fact that deactivating the new rules strengthens the rating of cells further away from existing built-up areas, and therefore favours proximity to amenities located further away from urban areas, such as golf courses or large forest areas. Thus, we find that activation of the new rules implemented in MUP City produces better results than with the previous version. This is particularly the case for access to level 1 green amenities, where the average distance is reduced by 85%, or access to gyms, which is reduced by 45%. Also, the results obtained by higher values of fractal dimension, as it is the case with the scenario 1.1, are better than these from scenario 1, and are quite close to these from scenario 2. As the euclidean distance is a limited indicator, especially for short distances, average distance calculations applied to the network could confirm these claims.

[4] For the evaluation of the distance to level 1 green amenities, the types "parks and gardens", "household gardens" and forests under 2Ha were not differentiated.

Evaluation of accessibility to the closest green and leisure amenities

The average distance to the closest amenity for all cells is assessed, with the distance calculations being applied to the network. The module also calculates the average number of amenities that are accessible from the cell at a distance of 600 metres for level 1 to 2000 metres for levels 2 and 3. According to Tannier et al in 2012, 'the average distance to a given set of amenities indicates the proximity of the residents to those amenities. The average number of amenities at a given distance indicates the supply of amenities in the neighbourhood (Apparicio and Séguin, 2006)'. Theses distances have been calculated by using the distance along the road network.

Once again, for the sake of comparison, calculations were made for the four scenarios, and level 2 was not broken down. It should also be noted that the accessibility calculations are made on all of the cells making up the scenario, including the built-up area existing in the initial situation. Changes in values are thus to be analysed according to the number of cells generated pro rata to the cells already built up (301,941). To complement this information, the second part of the results shows the number of cells in each scenario for which the assessment is better than the assessment of the initial situation. The results are summarised in table VIII and table IX, shown below.

Table VIII – Summary of results of assessments of the closest distance

SCENARIOS	Mean of the minimal distance to the closest facility (in meters)		
	LEISURES L1	LEISURES L2	LEISURES L3
INITIAL SITUATION	2300.1	1056.3	1394.0
scenario 1	2280.9	1052.7	1395.9
scenario 1.1	2257.0	1048.4	1397.9
scenario 1.2	2296.4	1055.3	1394.8
scenario 2	2280.1	1052.4	1396.1

Table IX – Summary of results of the number of cells which are better evaluated than initial situation

	Number of cell, which are better evaluated for each scenario				
SCENARIOS	FACILITIES N1	FACILITIES N2	LEISURES L1	LEISURES L2	LEISURES L3
scenario 1	2719	2536	2724	2265	1255
scenario 1.1	6292	5775	6309	5101	2971
scenario 1.2	2745	2524	1836	1784	1440
scenario 2	2745	2695	2745	2311	1207

At first glance, the three scenarios analysed here improves the accessibility potential of all cells that are urbanised or are to be urbanised in Luxembourg. In addition, the fractal scenario with all the rules activated significantly improves the results obtained compared with the previous version of the model and its 4 rules. Moreover, a much larger number of cells derived from scenario 1 have better access to level 1 and 2 green and leisure amenities (more than 25% of cells in addition). There is an exception with respect to proximity to forests over 100ha, where logically, the explanation coincides with the results obtained in the euclidean distance calculations.

However, the results obtained with the non-fractal scenario are slightly higher than those obtained with the fractal model. For each level of amenity, the average distance to reach the closest cell is less than in the compact model. Similarly, more cells have a higher rating compared to the initial situation in the Grand Duchy.

Evaluation of accessibility to the mean number of facility reachable

For this evaluation, we will focus on evaluation to the number of amenities frequented daily that are reachable in 600 meters and the number of amenities frequented weekly that are reachable in 2000 meters. Both calculations are made using network distance and from the each evaluated cell. The results are shown in the table X below. Once again, the changes in values are thus to be analysed according to the number of cells generated pro rata to the cells already built up (301,941).

Table X – Summary of results of assessments of the mean number of facility reachable within a distance

SCENARIOS	Mean number of facilities reachable	
	FACILITIES N1	FACILITIES N2
initial situation	1.66	54.1
scenario 1	1.68	54.8
scenario 1.1	1.70	55.7
scenario 1.2	1.68	54.3
scenario 2	1.71	55.6

We can observe that the accessibility to the facilities, from both levels, do not differ that much from the different scenarios. According to the weight of generated cells in the analysis, they are very thin deviations. However, we can easily distinguish an improvement of the results compared to the initial situation with the four scenarios. Over again, the scenario 1.1 with a higher fractal dimension and the scenario 2 with compact and axial development provide better access to the levels of facilities.

4. DISCUSSION

This is the first time such a residential growth modelling application has been implemented in Luxembourg. In view of the assessment values of the cells in the initial situation and as a function of the various scenarios described, we can say that the application of such a model in Luxembourg would not follow actual residential growth. The number of cells potentially developable, obtained as a result of our analysis, is not in line with the current pace of construction in Luxembourg. At first glance, it appears that a return to the accessibility rules, and thus to the develpment standards represented, is required. It is possible that by relaxing the criteria of accessibility to various amenities (shops, services, green and leisure areas), the results might give room for more opportunities to emerge for the application of the fractal model in Luxembourg. However, the approach adopted does not provide for such a change in the thresholds governing the rules. It should be remembered that the main objective of the study being conducted is in fact to transpose and implement a model in its entirety and to measure the consequences.

To complement the results obtained, a comparison of the findings in the MOEBIUS project (Gerber et al, 2009) is considered. The development scenarios in that research, inspired by more classical urban theories (compact city, TOD, etc.) were confronted with the Luxembourg policies on urban development. The same methods of assessment based on the accessibility distance to amenities could be applied to provide food for thought.

Finally, it should be emphasised that the assessments have focused on access to green and leisure amenities. These externalities, although highly valued by households in residential location strategy does not form the entirety of their choice. The analysis of the proximity to other types of amenities (shops, services, transport), would form some additional validation of our initial assumption. The application of the fractal residential growth model remains a alternative to be considered in the broad debate on the city.

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