# INVESTIGATION OF COGNITIVE NEIGHBORHOODSIZE BY AGENT-BASED SIMULATION

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## ABSTRACT

Different social groups tend to settle in different parts of cities leading over time to social segregation. Neighborhood obviously plays an important role in this process – and what constitutes neighborhood is a cognitive notion. In segregation analysis neighborhood borders are often drawn arbitrarily or simple assumptions are used to weight neighbor influences. Some authors have developed ideas to overcome such approaches by more detailed models. In this work we investigate the size of a cognitive neighborhood on the base of a continuous, geographically unlimited definition of neighborhood, using a distance-dependent function as such neighborhood "size" definition. We use agent-based simulation of the choice of residence as our primary investigation tool. Tobler's first law of geography tells us that close things are more related than far ones. Extrapolating this thought and applying it to the question discussed here one could expect that closer neighbors have – on their own and in sum – more influence than those living further apart. The "sum" in the last sentence would lead to a neighborhood weighting of less than the inverse square of distance. The results of this investigation confirm that this is the case.

## INTRODUCTION

The population of a city is not equally distributed, but tends to segregate according to the different characteristics of the inhabitants and the areas in the city. That means different inhabitants *tend* to live in different areas. Segregation plays an important role in city planning and in many cases it is deemed negative. Urban planners try to maintain a state of social sustainability in urban areas, which in very short words means that the mixture of different inhabitants should not exceed certain threshold values. In particular, planners try to avoid clusters of socially underprivileged people because the real world has shown that such areas evolve in a negative way in many respects, e.g. crime.

Cities are living and ever-changing entities. Most things to be found in cities are the result of some kind of human-driven process or processes. Urban planners try to control these processes to some degree, but from today's point of view, these will probably never be fully predictable. The work presented in this paper aims to contribute towards a better understanding of segregation as one important process in a city.

## RESEARCH QUESTION

We assume that segregation in a city is the result of a long-lasting process of choice of residence by the inhabitants. Every place of residence exists within a neighborhood (a collection of places with relevant characteristics), and the neighborhood plays an important role in the choice of residence. According to Tobler's first law of geography (Tobler 1970) close things are more related than those that are far apart. Accordingly, the far neighborhood should be less important for the choice of residence than the one close by. The question we ask here is how distance-dependent this importance is. In other words we try to find a distance-dependent function that allows us to mathematically weight the distant neighborhood against the one close by for the choice of residence.

## STATE OF THE ART

Methods for the numerical measuring of segregation from the 1950s are still significant today (Duncan & Duncan 1955). The corresponding calculations are now a standard procedure used by official statistics in many countries. A next important step was the introduction of entropy-based segregation indices in the 1970s (Theil 1972), which are used in this work.

A milestone in the explanation of the causes of segregation was the work of Schelling in the 1970s (Schelling, 1978), who used agent-based simulations. He demonstrated that feedback effects can play a significant role in segregation. The detection of these effects is naturally difficult using static statistical methods (non-dynamic, not regarding time lapse). Static statistical methods for correlating segregation with other factors are now standard tools in administrative practice.

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Researchers increasingly use simulations, see e.g. Feitosa et. al. (2007) and Crooks (2010). In this paper we follow the simulation approach of Schelling. Further direct predecessors of this paper, who also follow the basic idea of Schelling, are Benenson (1998), Benenson and Omer (2002) and the Circle City model in Koenig (2010).

Geographic Information Systems (GIS), which allow the provision of high-resolution digital data, are used on a regular basis as a tool in segregation analysis today. Until now, raster-based GIS/raster-based spatial simulation systems are used by researchers, for example in Feitosa et. al. (2007), Laurie and Jaggi (2003), Fosset and Waren (2005). Crooks (2010), however, proposed the application of vector-based systems, which is the method used in the present work.

Various authors have asked questions about the influence of neighborhood size on the outcome of segregation models (Wasserman and Yohe 2001, Laurie and Jaggi 2003, Crooks 2010). They have noted that an increasing neighborhood size (more generally: an increasing weight of far neighbors) results in stronger segregation effects, like the value of a segregation index or the size of segregation cluster areas.

In Benenson & Omer (2002) the authors emphasize that segregation measures are dependent on the settlement unit (city, borough, district, block, etc.) used for their calculation, and can differ significantly according to the selected scale for the same data used. They therefore investigate the question of how large the environment is that people perceive as their neighborhood, which would be best suited for the description of residential segregation. Voronoi polygons are used to define neighborhoods at various levels (level 1: direct neighbors, level 2: direct neighbors of the direct neighbors, etc.). This discrete approach of neighborhood definition is further developed in the present work to a continuous approach.

## RESEARCH APPROACH

Segregation is a time-dependent process and there are many decision makers – the people who choose a residence. Using agent-based simulation as an investigation tool is therefore an obvious choice and in this respect we follow Schelling's approach. The nice thing about agent-based simulation is the simplicity of modeling it allows to explain complex phenomena.

These two levels we use here, too. The phenomenon we try to explain is segregation. In the (agent-based) simulation model we need some kind of social submodel for the inhabitants and an infrastructure submodel for the environment they live in (the city) along with status transition rules to run the simulation. These rules involve the social and the infrastructure submodel and need to incorporate the aforementioned distance-dependent weighting function. Using this simulation model we try to reproduce a given segregation scenario by optimizing the weighting function.

## SOCIAL SUBMODEL

To measure segregation it is necessary to define certain differences between the inhabitants. A common approach is to divide the inhabitants into groups. We use the sinus milieus of Sinus Sociovision GmbH, Heidelberg, Germany. These milieus divide the inhabitants into ten groups, which serve as the base of the social submodel. An overview of the milieus can be found in figure 1.

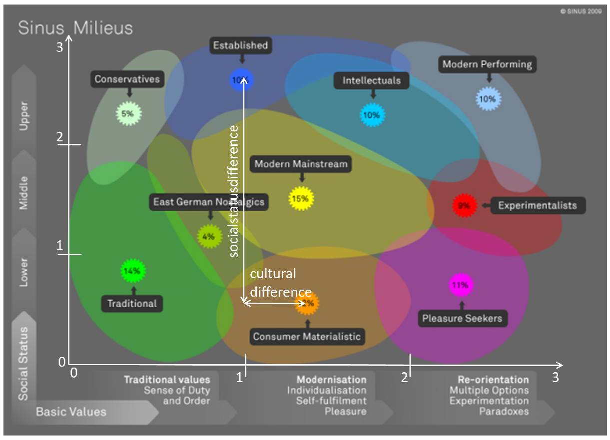


Figure 1: Sinus Milieu Diagram (after a figure by Sinus Sociovision GmbH) / Measuring the Differences of two Milieus

As shown in figure 1 the definition of these groups takes into account the social status (income etc.) and the cultural orientation, visualized by basic values. Each group (=milieu) covers a certain area in the milieu space. The rather small overlapping areas do not play a role in this work as described later.

The basic social entity we care for in the social submodel is the household. Every household belongs to a certain milieu, which never changes in the simulation. For simplicity, a household has no other attributes such as number of members, age etc.

## INFRASTRUCTURE SUBMODEL

The infrastructure model consists of the road graph of the city and buildings with a certain number of dwellings. Each building is connected to the road graph as shown in figure 2.

The road graph does not change during the simulation. Again, for simplicity, we use only one feature of the road graph: the distances between every pair of buildings, which are measured along the road graph. These distances are calculated using a variant of the well-known Dijkstra algorithm before the simulation runs.

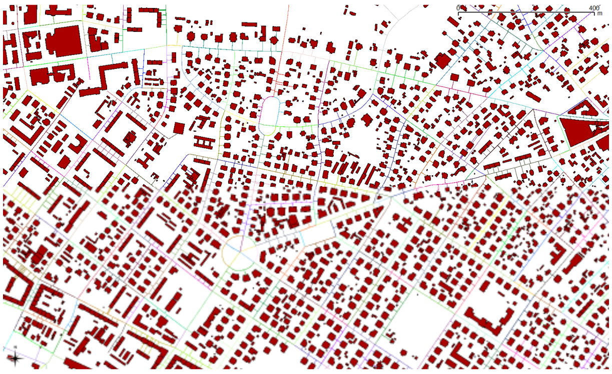

Figure 2: Infrastructure Model: Buildings connected to the Road Graph of the City

**TRANSITION RULES**

The matter of this work is segregation, which is caused by repeated choice of residence. Because the households themselves don't change during the simulation, transition rules only need to determine the choices of residence and nothing else.

As stated above (see RESEARCH QUESTION), in the approach used here every choice of residence taken by a household is based on the neighborhoods of the potential new residence locations (free dwellings, not occupied by a household). The neighborhood of a dwelling is defined by all the neighbors of that dwelling, and these are all households in the city. The rating of each neighborhood is accordingly based on the ratings of all neighbors.

To be of use for the choice of residence by a household the neighbors need to be rated differently. The phenomenon of segregation as observed in real cities shows that this is the case and that people tend to live with similar people more than they do with different people.

The authors have developed a neighbor rating based on the Sinus milieu diagram in a pragmatic way. This rating is arbitrary and based on nothing else than general rules which in the opinion of the authors feel right and are plausible and, again, the criterion of simplicity.

The general neighbor rating rules are as follows:
(R1) Regarding just the "Basic Values" (cultural axis) of the milieu diagram (see figure 1 above), every household wants to live with neighbors who are as close as possible in the diagram.
(R2) Regarding just the social status axis every household wants to live with neighbors slightly above its own position in the milieu diagram.

To operationalize these rules, the neighbor rating is again broken down into a cultural (neighbor) rating and a social status (neighbor) rating. The milieu diagram was overlaid with a coordinate system with coordinate value ranges of [0..3] for each axis. The cultural and social status differences between the milieus have been measured using this coordinate system. To be able to measure these differences every household needs to have a position in the milieu diagram. In the given segregation scenario, the milieu (group) of a household is known, but not its position in the milieu diagram. Therefore the position of the centroid of each milieu area was used as the position of all the households belonging to this milieu. Figure 1 illustrates the statements of this paragraph.

The differences measured have to be turned into cultural and social status rating values for a neighboring household.

For the cultural rating the following function is used: the rating value is 1 (the maximum) when the cultural difference is 0, and the rating value is 0 (the minimum), when the cultural difference is +3 or -3. For all other cultural differences the values are interpolated piecewise linear as shown in figure 3.

To apply the "slightly above" statement in neighbor rating rule (R2), a different piecewise linear function is used as social status rating. See figure 3. Notably the maximum rating value of 1 is not reached at a social status difference of 0, but for a small positive difference (0.25).

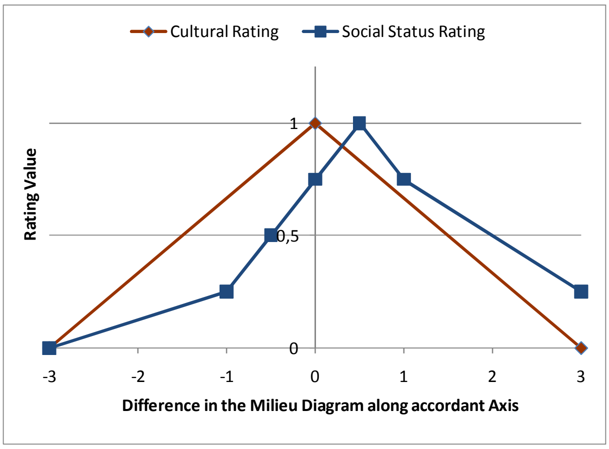


Figure 3: Rating Functions for Cultural and Social Status Differences

The rating value for a neighbor of a certain milieu is calculated by adding the cultural and social status rating values vectorially in a Cartesian coordinate system. The value range of the neighbor rating is therefore [0..1]. Because there are 10 milieus and every milieu is rated by every milieu, a 10 x 10 matrix of possible neighbor rating values results.

To calculate a neighborhood rating, all the neighbor ratings are incorporated into a weighted mean value.

The weight w is the inverse of distance $d$ exponentiated by a fixed exponent $E$:

$$w = 1/d^E \text{ (F1).}$$

The final neighborhood rating function is

$$r_{nbh} = \frac{\sum r_{nb}/d^E}{\sum 1/d^E} \text{ (F2)}$$

over all neighbors with $r_{nb}$ as the rating for a single neighbor.

The simulation is run in discrete time steps. The neighborhood ratings for all dwellings are calculated first and then stay fixed for that time step. The agents in the simulation can act in the following ways:
(A1) A household leaves the city. This happens spontaneous by a fixed leave probability.
(A2) A household tries to move to a free dwelling with a better neighborhood rating. If one is available the household moves. All free dwellings in the city are considered.
(A3) New households try to move into the city. A new household occupies the best dwelling it can get, if one is available. If not, the household is withdrawn from the simulation. The number of new households is determined by a truncated Gaussian distributed probability with fixed parameters (derived from an input mean).

A number of parameters such as minimum neighborhood rating of the current dwelling before moving, minimum improvement of the neighborhood rating of the potential new dwelling compared with the current dwelling and others could be removed during the development of the simulation in order to simplify it without damaging the reproduction quality.

## SEGREGATION SCENARIO REPRODUCTION

The segregation scenario reproduction quality is measured using a segregation index. The Information Theory Index $H$ first published by Theil (1972) has been chosen for this purpose. Other indices could have been employed, but most of them are highly correlated (Massay and Denton 1988), and this one has nice properties. It is widely accepted, well investigated, has a fixed value range of [0..1] and allows for the calculation of a single segregation value for the whole city for any number of groups.

Segregation index values are calculated for the given segregation scenario (target value) and after every step (including the final step) of a simulation run. The reproduction is considered better the smaller the difference to the target value is.

Because segregation indices are fairly dependent on the base unit used for their calculation (Benenson and Omer 2002) we have chosen two quite different ones, the road segment as a quasi one-dimensional base unit and the building block (a couple of buildings surrounded but not divided by a road) as a two-dimensional base unit.

## USED DATA

To run the simulation the following data is necessary:

- a dataset containing the building entities including the number of dwellings in each building
- a road graph of the city including geometrical connections to the buildings
- a given segregation scenario containing the milieu of the household for all occupied dwellings

For the simulation runs carried out for this paper we used data from the city of Dresden Town Planning Authority, and from the company Microm GmbH. The building connections have been derived from the road graph and geometrical building data provided by the city of Dresden. The Microm data is the base for the list of buildings, the number of dwellings and the given segregation scenario.

The used dataset contains about 250,000 households living in about 50,000 buildings.

## TECHNICAL NOTES

The simulation program was developed using C# in a Windows environment. For the most time-consuming parts of the simulation program native libraries and system functions are used. The main simulation computers were 4- and 8-core Intel XEON machines with 64GB RAM, of which about 40GB are used at program start. Simulation run times were between 1 hour and 10 days for a single run.

## THEORETICAL EXPECTATIONS

Extrapolating Tobler's first law of geography and applying it to the question discussed here one could expect that for the choice of residence:
(S1) A close neighbor has more influence than a far one.
(S2) Close neighbors in sum have more influence than the far ones in sum.

The authors of this paper would expect the "sum" statement (S2) to be true from personal and professional experience, considering that everyone in the world has more far than close neighbors.

To express the "more influence" statements (S1) and (S2) in a mathematical way we develop now a continuous city model. This model is derived from the city model used for the simulation by further simplification.

In a first step we assume equally distributed inhabitants living in buildings connected by a uniform grid road graph. Consequently, the city looks the same everywhere. In a second step we abstract further to obtain a continuous inhabitant distribution with no roads at all. One could imagine such a city as a large plate with the inhabitants like a thin film of water on it, and the inhabitants like water molecules can move in it without any roads. The distance between two dwellings or points is then just the Euclidean distance.

The research aim is to find a distance-dependent weighting function. The approach used is to optimize parameter *E* in formula (F2). The question in this chapter is what values of *E* are to be expected. To investigate this we look at the influence of different neighbors on a neighborhood rating calculated by (F2). We use the continuous city model described above.

Looking at (F2) one sees that the denominator $\sum 1/d^E$ is a constant for a given neighborhood and a given distance exponent *E*. For the influence investigation this is of no interest. In the remaining nominator $\sum r_{nb}/d^E$ we abstract from different $r_{nb}$ (e.g. setting them all to 1). The remaining formula for the influence of a group of neighbors is $\sum 1/d^E$ .

The influence of a single neighbor is just the weighting function $w = 1/d^E$ . To fulfill influence statement (S1) that a close neighbor should have greater influence than a far one, *w* must decline as d grows, and therefore *E* must be chosen to be greater than 0, even if only slightly (e.g. 0.01).

To look at groups of close and far neighbors we can draw virtual distance circles with increasing radii around a dwelling in the continuous city model. The (differentially small) number of neighbors living on the same circle at distance *d* is $2 \bullet \pi \bullet d$ , while their summated influence is $2 \bullet \pi \bullet d / d^E$

Influence statement (S2) applied to these circles means the influence of a close circle has to be greater than that of a far one. For *E* = 1 the influence of all circles is equal, so *E* must be chosen to be greater than 1, even if only slightly (e.g. 1.01). The same holds true for laminar rings of constant width instead of the circles. E.g. all neighbors within a distance of 300-600 meters have the same (*E*=1) / a greater (*E* > 1) influence than those living at a distance of 600-900 meters.

From influence statement (S2) an even higher requirement can be derived. If one looks at a laminar (filled) circle of reasonable size, the influence of the neighbors inside that circle should be greater than that of all neighbors outside it. To avoid very high and even infinitive influence values of neighbors living close by an inner circle is left neighbor-free. Therefore the inner circle becomes an inner ring from $d_{min}$ to $d_{border}$. Mathematically the resulting statement can be formulated as:

$$\int_{d_{\min}}^{d_{border}} \frac{2 \bullet \pi \bullet d}{d^E} \partial d > \int_{d_{border}}^{\infty} \frac{2 \bullet \pi \bullet d}{d^E} \partial d \quad \text{(F3)}$$

The smallest neighbor distances along the road graph used have turned out to be about 10 meters, which seems a plausible value to use as the general minimum distance of any two neighbors. Solving the inequation (F3) – strictly spoken the equality border case – for $d_{border}$ one obtains the function $d_{border}(E)$, which is shown as a plot in figure 4. It can be read as “the border distance for *E*=2.15 is 1,000 meters”.

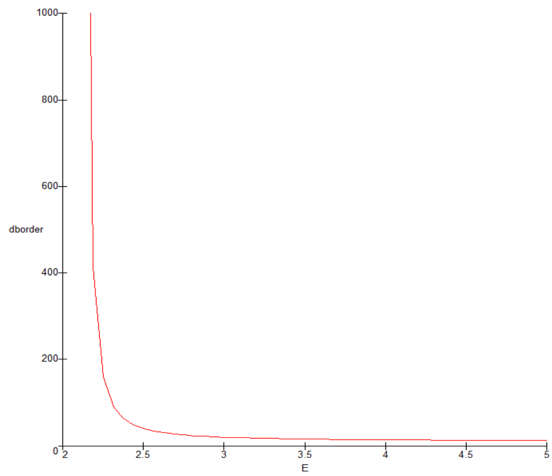


Figure 4: Function $d_{border}(E)$

Other reasonable values for the border distance could be 500 meters (*E*=2.18) or 50 meters (*E*=2.39), but not 1 or 10,000 meters. 50 meters is a nearby value that one can derive from Benenson and Omer (2002). These authors use the concept of a home area and determine a mean value of 10,500 square meters for it. A circle of that size has a radius of about 50 meters.

For *E*=3 the border distance would be 20 meters. Altogether from a theoretical point of view we expect *E* to be greater than 2, but significantly smaller than 3. This expectation is tested by the experiments that are described in the next section.

## SIMULATION EXPERIMENTS

The simulation experiments start with a given data set of buildings, dwellings, the road graph and a segregation scenario (the households). Dwellings are filled randomly with households keeping the percentage of the ten milieus as in the segregation scenario. A percentage of dwellings left free at the beginning can be chosen as a parameter. Two further parameters which impact the simulation at run time are the percentages of households leaving the city spontaneous and the mean of new households moving into the city at one time step. These last two percentages are related to the number of households currently in the city and are used as parameters of accordant random number generators.

They are always kept equal because the city otherwise fills up or is abandoned.

For the main parameter distance exponent *E* a value of 2.0 was chosen as a starting point for the simulation experiments according to chapter THEORETICAL EXPECTATIONS. The other parameters mentioned were set to initial values derived from observed statistical values for the city of Dresden: 11% free dwellings and a percentage of 0.4% for households both moving in and out of the city (thought as monthly movement rates).

Beginning with *E* the parameter values are varied to search the parameter space for an optimal reproduction. The variation was partly done by hand, partly by some parameter production functions in connection with a few reproduction measurement criteria. More automatic parameter optimization approaches have been considered but found not to be necessary in this case. One reason is the long simulation run times.

A simulation run was stopped after several thousand steps when the system either reached a stable status or when there was obviously no chance of reaching the target (segregation index) value. The status is considered stable when the average change per step of the segregation index value is (near) zero or when it oscillates within a value range reached before. Because of the permanent stream of households moving in and out of the city a simulation run never stops by itself.

## RESULTS

The simulation experiments have approved that the distance exponent *E* is of major influence on the segregation index, which confirms the findings of other authors (e.g. Laurie and Jaggi 2003). The percentages of free dwellings and moving in/out proved to be much less important.

The free dwellings percentage showed barely any influence. For the moving in/out percentages a positive, but weak correlation with higher segregation index values was observed. Nevertheless, if we set these three parameters to zero nothing ever happens in a simulation run. If we set just the move in/out parameters to zero we change a basic characteristic of our simulation model: being an open system with contact to an environment, and this is an important property of cities (Portugali 2000, p. 75). In our case simulation runs with such a closed system show only little residential move activity after a relatively small number of time steps and leave the city far from what can be observed with the open system model. The in/out flows keep the residential move process running.

The best reproduction is achieved at a distance exponent *E* of about 2.7. This value takes into account the calculated segregation index values based on road segments and on building blocks as shown in figure 5. The road-segment-based Information Theory Index *HRoadSegment* is displayed as the upper curve with a dashed line. The lower curve shows the appropriate building-block-based Index *HBlock*. The grey horizontal lines display the target values for each index. Both indices show a nearly strict dependency on *E*. The target values are reached around *E* = 2.7, for *HBlock* between 2.6 and 2.7 and for *HRoadSegment* between 2.7 and 2.8.

If we use 2.7 as input for the $d_{border}(E)$-function (figure 4), a border distance of about just 27 meters results. In our model a circle of this distance divides the close neighbors that have 50% influence on the neighborhood rating from those neighbors living further away that make up the other 50% influence. Using the same approach one can find a 90%-influence distance of about 270 meters and a 99%-influence distance of about 7200 meters. Because relatively small changes of *E* can lead to significant changes of the aforementioned distance values, one could speak of 30, 300 and 7000 meters, respectively, as approximations.

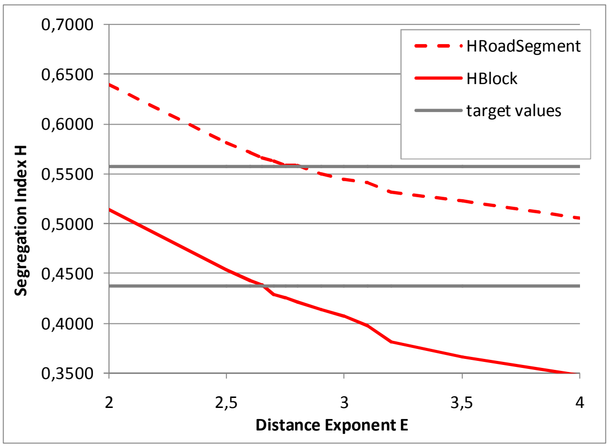


Figure 5: Segregation Index H (the Information Theory Index) Outcomes for Variation of Distance Exponent E

A major input of the simulation is the neighbor rating function as described earlier in chapter TRANSITION RULES, especially figure 3. To assess the influence, tests have been run with an alternative neighbor rating function. The social status rating function was set to be identical to the one used for cultural rating, so that the milieus strongly like living with neighbors from their own milieu (rating value 1). Simulation experiments with this setting result in a distance exponent *E* of about 1.8 for the best reproduction. This result contradicts our theoretical expectations, because for *E* = 1.8 far neighbors have in sum more influence than close ones.

## CONCLUSION

Using the agent based simulation model developed here, important segregation characteristics of a given data set for the city of Dresden were successfully reproduced. It has been shown that the milieu approach of social grouping, a small set of neighbor rating rules and a simple distance-dependent weighting function lead to reasonable results. The results indicate that relatively small neighborhood sizes of about 300 meters are sufficient to cover most cognitive neighborhood effects.

## OUTLOOK

The approach presented here can be developed further in many ways. The results from this case study should be proved by using data from other cities. Characteristics of the environment of a dwelling other than social ones should be added. Possible starting points for a more sophisticated cognitive space model include a more detailed and a group-specific weighting function.

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