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Title

ASSURE: a model for the simulation of urban expansion an intra-urban social segregation

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Abstract

Numerous cities in developing regions worldwide are expanding at a tremendous rate. This requires adequate strategies to address the needs of these growing cities with diverse populations. Nonetheless, the development of urban policies is often hampered by the lack of reliable data or insight in the socio-spatial dynamics of this urban expansion. This paper therefore presents ASSURE, a spatially and temporally explicit model that can simulate urban growth and intra-urban social segregation, taking into account alternative policy strategies and expected social dynamics. The model has a flexible structure that allows incorporating specific city-conditions that influence residential decision making and adapting the simulation to the data available. This, in combination with the transparent model structure, makes ASSURE a potentially valuable decision support tool for urban planning. The potential is demonstrated with an example where the urban growth of and social segregation in Kampala (Uganda) is simulated based on (semi-)quantitative and qualitative data for ca. 800 households collected through interviews. The results of the simulations show that depending on the scenario, the spatial segregation and accessibility problems will evolve highly differently.

Keywords

Urban expansion, Social segregation, Agent-based model, Africa, Kampala

1. Introduction

At present more than 50% of the world population is living in urban environments and it is expected that this percentage will increase to 66% by the year 2050, driven by natural growth and rural-urban migration (United Nations, 2014). Although urbanization is higher in the developed world, cities in developing countries currently experience the highest urban growth rates (UN-Habitat, 2010). Despite the fact that much of the GDP growth of most of these countries is concentrated in urban areas, these cities are often characterized by large internal socio-economic inequalities (UN-Habitat, 2012; Werna, 2014). This inequality is often spatially translated as social segregation whereby the most vulnerable groups end up in the least suitable places with limited access to utilities, services and job opportunities (Potter and Lloyd-Evans, 1998; Rakodi and Lloyd-Jones, 2002).

The growing social inequality in the new urban areas is considered as one of the main challenges for society in the 21st century (Hall and Pfeiffer, 2013). Various strategies, like decentralisation, neighbourhood upgrading and adjusted housing policies, have been implemented during the last decades to counter such urban inequalities (e.g. Smet and Salman, 2008). Despite significant improvements in the quality of life (Duran and Adrian, 2008; Chung, 2010), these kinds of transformations often induce gentrification that can lead to the dislocation of urban poor to even less suitable environments and further increase the inequality (Newman and Wyly, 2006). These complex interactions between different social groups make it difficult to foresee the impacts of urban growth and the effects of adopted urban policies. Therefore there is a strong need for tools that allow simulating expected urban and social dynamics, given the specific context of a city.

This paper presents ASSURE, a model developed to simulate urban expansion and social segregation which aims to serve as a tool for decision support in the development of rapidly expanding cities. Based on the currently existing bottlenecks in urban growth modelling research we aimed ASSURE (1) to be transparent and straightforward in its use; (2) to allow for the incorporation of conditions that are specific for the considered city; (3) to have sufficiently low data requirements.

The following section discusses the literature on urban growth modelling, followed by a third section which describes the overall model structure and data requirements. Section 4 describes the model set-up for a case study where we simulate the urban growth and social segregation of Kampala (Uganda) and discuss the results of four alternative scenarios for future urban growth and social segregation. The last section lists some concluding remarks and provides a scope for future research.

2. Modelling urban growth: a current research gap

Since the advent of GIS, many computational models have been developed to describe urban dynamics. The power of such models is two-fold: (1) to synthesize scientific knowledge by translating processes into mathematical equations and test hypotheses regarding these dynamics; and (2) to serve as a tool in applied urban planning. On the basis of computational models the spatial impact of expected demographic developments and/or policy measure can be simulated. By comparing alternative future scenarios, decision makers can develop informed strategies for urban development.

Although hybrid and mixed models exist, computational urban models can generally be categorized into 3 types: (1) models based on logistic regression equations, (2) models based on cellular

automata, and (3) agent-based models. Table 1 provides a (non-exhaustive) list of representative examples of each category. For more extensive reviews, we refer to Matthews et al. (2007) and Triantakonstantis and Mountrakis (2012).

Table 1: *Examples of models used to simulate urban development, including the ASSURE model proposed in this paper.*

Type	Model	Spatial extent	Spatial Resolution
Logistic Regression	Hu and Lo (1997)	Major cities	50m x 50m
Logistic Regression	Vermeiren et al. (2012)	Major cities	30m x 30m
Cellular automata	SLEUTH (Clarke et al., 1997)	Major cities or clusters of cities	210m x 210m
Cellular automata	DUEM (Batty et al. 1999)	Hypothetical landscape	Hypothetical
Cellular automata	Environment Explorer (White and Engelen, 2000)	National scale	100m x 100m
Agent-Based Models	Parker and Meretsky (2004)	Hypothetical Landscape	Hypothetical
Agent-Based Models	Benenson (2004)	Small city	Individual dwellings
Agent-Based Models	Augustijn-Beckers et al. (2011)	Slum areas of major cities	Conceptual
Agent-Based Models	ASSURE (this paper)	Metropolitan area of major African city	100m x 100m

Urban models based on (logistic) regression equations are commonly used. These models assess the suitability of a location for residential area by using predictors such as accessibility, topography and existing population density (Hu and Lo, 2007). The use of logistic regression models is quite popular because of their simplicity and the relative ease to combine them with remotely sensed time series of urban extent (Poelmans and Van Rompaey, 2009).

A more advanced approach is 'cellular automata' type models, where the suitability of a residential area mainly depends on the characteristics of neighbouring land units (Clarke et al., 1997). CA-models allow description ofcomplex growth patterns that are a reflection of the self-organizing behaviour of a city on the basis of relatively simple decision rules. CA-based models have led to important insights and their development and applications are still ongoing (Santé et al., 2010). However, a fundamental limitation is the fact that they are based on 'cells' representing a fixed areal

extent of the city and therefore do not allow the movement of city dwellers throughout the city. CA-based models are therefore less suitable for the simulation of social segregation processes that are high on the agenda of policy makers and real estate professionals, such as gentrification or degradation of neighbourhoods within an expanding city (Davis, 2006; Lees, 2012; Cassiers and Kesteloot, 2012).

Not surprisingly, agent-based models (ABMs) that simulate individual behaviour of agents in interaction with their environment and the decisions of other agents are becoming more popular. These agents (individual city dwellers or households) are often grouped into socio-economic classes with a specific utility function describing their behaviour (Filatova et al. 2013). Beside agent-environment interactions, ABMs also allow simulating specific agent-agent interactions that result in social segregation. Examples of this are agent seeking (i.e. agents want to live near members of their own class) or agent pushing (e.g. rich agents avoid living near poor agents (Fossett, 2011; Bailey, 2012)). Hence, ABMs have not only the potential to simulate urban expansion, but also to identify the social state of the urban space. Furthermore, ABMs allow simulation of the effects of macro-level policy interventions, such as modifying the urban environment and constraints or specific regulations on land use and social segregation (Parker et al., 2003). These advantages and opportunities could make ABMs a very valuable tool for policy makers, allowing the anticipation of future or hypothetical scenarios of urban expansion and social segregation and, hence, a better management of the urban space (Li and Liu, 2008).

Since the pioneering work of Schelling (1971) on residential segregation, many applications of ABMs followed, for example focussing on residential segregation of racial classes (Epstein, 1999). However, since the individual behaviour of humans is understood to be a highly complex process, ABM structures have become sophisticated and therefore often remain conceptual (Batty, 2005; Augustijn-Beckers et al., 2011) or limited to small areas for which very detailed data are available (e.g. Benenson, 2004). This high complexity in combination with a lack of data hampers a widespread application of ABMs. This is especially the case for rapidly growing cities in developing countries, where modelling is often limited to simple extrapolations (e.g. based on logistic regression models) or qualitative descriptions of the expected behaviour(Agustijn-Beckers et al., 2011; Young and Flacke, 2010). It probably also strongly contributes to the fact that ABMs are, despite their potential, rarely used in practice by urban planners (Batty, 2005).

This paper aims to help bridgethis important gap in urban modelling and presents ASSURE, a new ABM-tool that allows the simulation ofthe effect of alternative policy measures on urban development in African cities in a quantitative and spatially and temporally explicit framework. ASSURE was specifically developed to explore scenarios of urban evolution in developing (African) cities, while keeping data requirements to a minimum. It can therefore serve as a scientific tool for testing theories on urban growth and social segregation. The straightforward and flexible structure also makes the model of practical use to urban planners who are often constrained by the time and information available.

3. Description of the ASSURE model framework

ASSURE (Agent based simulation of Social Segregation and URban Expansion) is a grid-based model whereby urban expansion is simulated through residential activity decisions taken by different social groups, thereby taking into account physical and social environmental factors as well as preferences, possibilities and limitations. The framework of the model is illustrated in **Fout! Verwijzingsbron niet gevonden.**1.

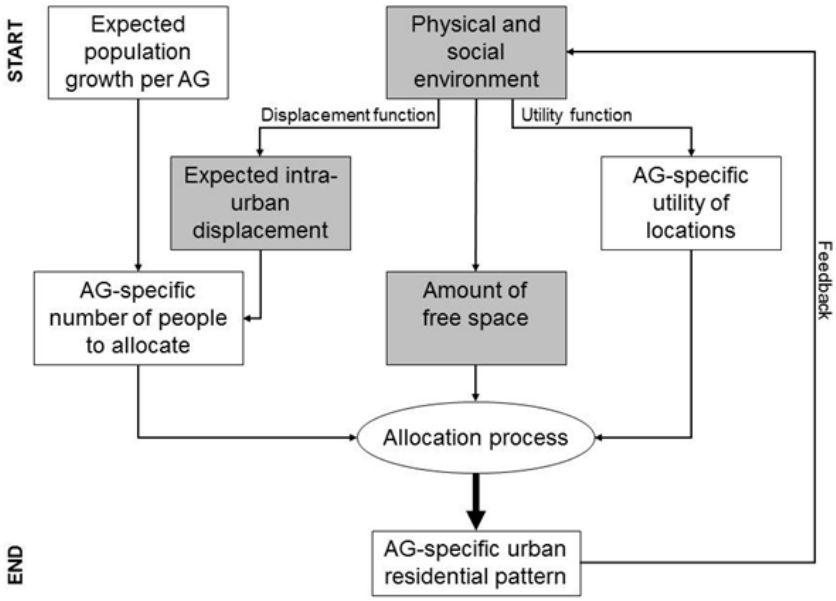

Figure 1: Overall framework of the ASSURE model. 'AG' stands for Agent Group. Grey boxes indicate aspects of the urban environment and dynamics that can be influenced by urban policy.

For each time step (e.g. one year), a number of agents (i.e. households) select their residential location based on a number of criteria and characteristics. Each of these agents belongs to a predefined 'Agent Group' (AG) which represents a socio-economic class of citizens with specific residential habits or preferences and is characterized by an average number of persons per agent (i.e. the household size), an average space usage (i.e. the amount of urban space typically occupied by one agent), a ranking, a utility function and a displacement function. The number of AGs and their characteristics will depend on the intended application and data availability. During each time step, the number of agents per AG is determined by summing up the expected agent increase and the number of displaced agents. The former can be based on any assumption of urban population expansion or socio-economic transitions and depends on the scenario that needs to be simulated.

In addition, agent displacement becomes evaluated through an AG-specific displacement function. The function provides a numerical expression of the integrated effect of different factors that may cause an agent to move from its current location. These factors may be related to environmental (e.g. lack of greenness) as well as socio-economic factors (e.g. estimated rental prices of the area), while the weight given to each of these factors may vary between the considered AGs. The displacement function may also include a random term to account for uncertainties in the decision of a household to move. At grid cells where the function exceeds a threshold value, the agents living in that cell are removed and the amount of occupied area is updated accordingly. The threshold used

can be uniformly fixed or location-specific. The latter allows simulating specific urban policies, such as the eviction of households from certain areas.

Next, the incoming number of agents settle down by means of an AG specific utility function which expresses the overall living preferences of an AG. The utility function is a numerical expression of the willingness of a member of the AG to live at a location, based on factors that are deemed relevant. Also here, factors can be both environmental or socio-economic. Each factor has its own AG-specific weight to account for differences in residential preferences between the considered socio-economic groups. For example, distance to public transport may be of little relevance for rich, car-owning agents (giving it a very low weight or zero), but highly important for other groups (giving the distance a strongly negative weight). By evaluating the result of this utility function for each cell, the model identifies the areas that are most likely to attract agents of the considered AG. By editing the input layers used for this evaluation, one can easily simulate the expected effect of certain policies. Also here, a random term can be added to the utility function to account for uncertainties in the housing options of agents. When an agent shifts from AG, it will also re-evaluate its residential location through its 'new' AG-specific utility function.

Agents first settle at grid cells with the highest utility value, then the one with the second highest utility, and so on until all agents of that AG are settled. The total number of agents possibly settling on each cell during the current time step depends on the simulation and is restricted by a maximum which depends on the amount of free space left in the cell and the predefined average space usage of the AG. The amount of free space left is the difference between the maximum space available and the space already occupied by agents. Whereas the latter can be calculated from the number of agents living in the cell and their space usage in an initial urban residential pattern map, the former will depend on the grid resolution and building characteristics of the neighbourhood (e.g. high-rise buildings versus one-story buildings). In simple scenarios, one can use a uniformly distributed value of maximum space available. However, it is also possible to vary this upper limit between pixels. This gives the freedom to simulate specific scenarios of urban development (e.g. forbidding further construction in a given area or allowing high-rise buildings in another).

The AG with the highest ranking can first settle and the AG having the lowest ranking is the last group to settle. This to some extent allows accounting for differences in socio-economic power when agents of different AGs are competing for the same areas as a potential allocation site. For example, an AG of rich citizens will likely have an advantage over an AG of poor citizens in acquiring a residence at a given location. Hence, the rich AG is settling first, so that only the remaining free space can be taken by agents of the poor AG. This and the displacement procedure also allow ASSURE to simulate processes of social segregation. The output of the model is the AG-specific urban residential pattern for the considered time step (**Fout! Verwijzingsbron niet gevonden.**), i.e. data layers indicating how many agents of each AG are living in this cell. Based on the average space usage and household size, one can derive other information, such as maps of the total built-up area or population density. These output layers are also used to update the input layers for the next time step.

In case of availability of longitudinal spatial data on socio-economic status, the model can be calibrated through a sensitivity analysis of the weights assigned to the variables in the utility functions for each AG. The sensitivity of the model outcome can be analysed through varying the

weights and evaluating each outcome. The weights that give the best fit between the simulated result and validation data are then used for the utility functions.

Table 2 provides a general overview of the information that ASSURE requires. Since the model was mainly conceived as a general framework, the details of this information (e.g. the number of agents and the factors considered in their utility function) will depend on the simulated situation and the data available. As an illustration, an application is discussed in the following section.

Table 2: Overview of the information required by the ASSURE model

Requirement	Description
Population increase estimates	Agent Group specific estimates of the increase in population for every time step of the simulation.
Agent typology	For each Agent Group: the average household size of an agent, the space usage per agent, a rank number (determining the allocation order), a dislocation function and a utility function
Environmental and socio-economic factor maps	Data layers for each of the factors included in the utility and displacement functions (case dependent). These may either be physical or environmental factors (e.g. distance to a road) or socio-economic factors (e.g. land prices). Likewise, these factors can remain fixed (e.g. elevation) or updated throughout the simulation (e.g. population density). Data layers used do not necessarily need to present the actual situation but may be adapted in order to simulate scenarios of specific policy strategies.
Initial urban residential pattern	For each Agent Group: a data layer indicating the estimated number of agents living in each cell before the first time step of the simulations.
Maximum space availability	Indicates how much space is available for living and therefore influences how much agents can be allocated to each cell. This will depend on the grid cell and can be derived from population density estimates, but can also be adapted to simulate specific scenarios (e.g. forbidding new construction in specific areas).

4. A case study for Kampala: model set up

4.1 Background information

Kampala, the capital and largest city of Uganda, is with an average yearly growth of 5.6% one of the fastest growing cities of Sub-Saharan Africa (Nyakaana et al., 2007; Vermeiren et al., 2012). Recent official census data are lacking, but most recent estimates assess that around 1.7 million people lived within the official territory of Kampala municipality in 2012 (UBOS, 2012). Kampala can be considered as a typical “horizontal” African city (Lwasa, 2004) with very little high-rise (except for the Central Business District). Horizontal cities are characterized by relatively low population densities (due to the lack of high-rise buildings). In combination with a rapid population growth such cities face large challenges such as urban sprawl, traffic jams and results in low quality housing and a lack of utilities. This makes Kampala a highly interesting and representative African case study. Like many other

African cities, Kampala will probably convert to a more vertical city with higher population densities during the following decades.

When the urban sprawl is considered (which reaches far out of the official boundaries of Kampala), the city's total population is estimated at 2.6 million (UBOS, 2012). As this urban sprawl becomes increasingly relevant, the Kampala Capital City Authority (KCCA) is working on a new, enlarged administrative unit called the Greater Kampala Metropolitan Region (GKMR) which includes surrounding municipalities into the jurisdiction of the city council. At its growth rate, GKMR is yearly confronted with at least 150.000 new residents. Evidently, this poses important challenges in terms of urban planning.

Kampala has a Gini index of 0.47, which indicates high income inequalities within the city (UN-Habitat, 2007). According to World Bank estimates, almost 10% of its urban population is living below the poverty line (United Nations, 2014). These income inequalities are also spatially clearly expressed in Kampala's cityscape. The region consists of more than 20 hill tops while wetland areas dominate the lowest reaches. The hill tops in Kampala are generally occupied by up-market estates for high-income groups while the low-lying areas become overcrowded by the lowest social classes and give rise to wetland encroachment (Vermeiren et al., 2012). The latter is not only leading to health concerns for the wetland-communities, but also pose an ecological threat to the city (Kabumbuli and Kiwazi, 2009). Foot slopes then provide overall acceptable living conditions, but are less preferable than hill top locations. This spatial pattern originated in the racial segregation during the colonial era under the guise of health concerns and persisted during the post-independence period.

A lack of up to date and detailed data on the population of Kampala and their socio-economic status, hampers the insight in the spatial inequality and urban dynamics. This model set up of Kampala is an effort to quantify the residential processes of different socio-economic groups, but still remains largely explorative. The case study is based on empirical data which, in order for the model to become a representative tool for Kampala, needs to be further developed.

4.2 Characterization of the Agent Groups

During 4 field campaigns in the summer of 2010, 2011, 2012, and 2013 ca. 800 households were interviewed. Households were selected by means of a stratified random sampling procedure in various spatially and socio-economically representative regions of Kampala. On the basis of semi-structured interviews information on the households' social and economic livelihood, mobility, housing and longitudinal migration path was collected. For more details regarding the sampling and interview procedures we refer to Vermeiren et al. (2015). Four Agent Groups (AGs) in Kampala were identified based on a cluster analysis of these collected data: extremely poor, poor, middle income and rich households (Figure 2). Extremely poor households are the smallest households (on average 3 members), since a significant share of these consists of single households of recent immigrants. They commonly reside in low quality single room constructions, also called tenements, which are often located in slum areas. Poor households consist on average of 5 household members. They also often reside in tenements but occupy on average larger spaces with better living conditions. Middle income households are commonly extended families of ca 7 members that accommodate detached multi-roomed and (fully) serviced houses. Rich families consist of on average 6 members and reside on large estates. Since access to the housing market is strongly related to income (Greene and Rojas,

2008), we assumed the following allocation order: 'rich', 'middle income, 'poor' and finally 'extremely poor'.

Figure 2: Typical housing for respectively extremely poor, poor, middle income and rich households.

Relying on fieldwork, interviews and aerial photos, extremely poor, poor, middle income and rich households are estimated to occupy on average respectively 76.5, 184, 1261 and 2064m². These areas were derived by looking at homogeneous neighbourhoods of each specific AG and dividing the total area of these neighbourhoods by its number of households. As a result, these values of space consumption include the common infrastructure and public space (e.g. roads, sidewalks, parks) and are therefore to some extent generic. Based on these values of average space usage and typical household sizes, available census data, field observations and interpretation of aerial photographs, the proportion of each of these AGs for every parish (i.e. the smallest administrative unit) of GKMR for 2010 were estimated (Figure 3). Based on these parish-specific estimates, it was assessed that 33% of GKMRs total population was 'extremely poor', 53% was 'poor', 10% belonged to the 'middle income' group and 4% could be classified as 'rich'.

Establishing the 'displacement' and 'utility' function of each AG requires converting qualitative information on housing decision mechanisms into quantitative measures, taking into account the socio-economic data available and expert judgement (Vermeiren et al., 2015). Regarding the displacement functions, it was observed that, once located in the city, rich and middle income households experience little pressure to move elsewhere. However, their presence does potentially force poor and extremely poor households to dislocate because of the increasing housing cost of the neighbourhood. In addition, the presence of rich and middle income households may contribute to the decision to clear slum areas nearby. The model therefore assumed that rich and middle income AGs cannot be dislocated (i.e. their displacement function equals zero), while the probability of displacement for AGs extremely poor and poor was calculated as:

$$Displacement_{AG} = a_{AG} * Fraction_{MR} + b_{AG} * Random \qquad \text{Equation 1}$$

'$Displacement_{AG}$' is the probability that agents of the considered AG are dislocated from the considered cell, '$Fraction_{MR}$' is the fraction of the total population that belongs to the rich and middle income group, living in the vicinity (< 500 m) of the cell and 'Random' is a uniformly distributed random number between zero and one (accounting for the fact that the dislocations remain partly unpredictable). a_{AG} and b_{AG} are AG-specific weights. As explained in section 2, agents (i.e. households) in a cell will be displaced if the result of their displacement function exceeds a given threshold. This threshold is uniformly set to 0.5. Based on the experience that extremely poor agents are slightly more vulnerable to dislocation, a_{AG} and b_{AG} were calibrated so that the model realistically dislocated about 1000 to 2000 poor and extremely poor persons during the first years of our simulations (i.e. a_{AG} = 0.6 and b_{AG} = 0.1 for extremely poor and a_{AG} = 0.5 and b_{AG} = 0.1 for poor

households). This rate corresponds to our best estimates of the number of (extremely) poor persons that are currently dislocated on a yearly basis, based on our field surveys. For rich and middle income AGs, a_{AG} and b_{AG} were set to zero (since we found no indication that also persons with a rich or middle income are dislocated on a statistically meaningful scale). As a result, rich and middle income agents were not dislocated during our simulations.

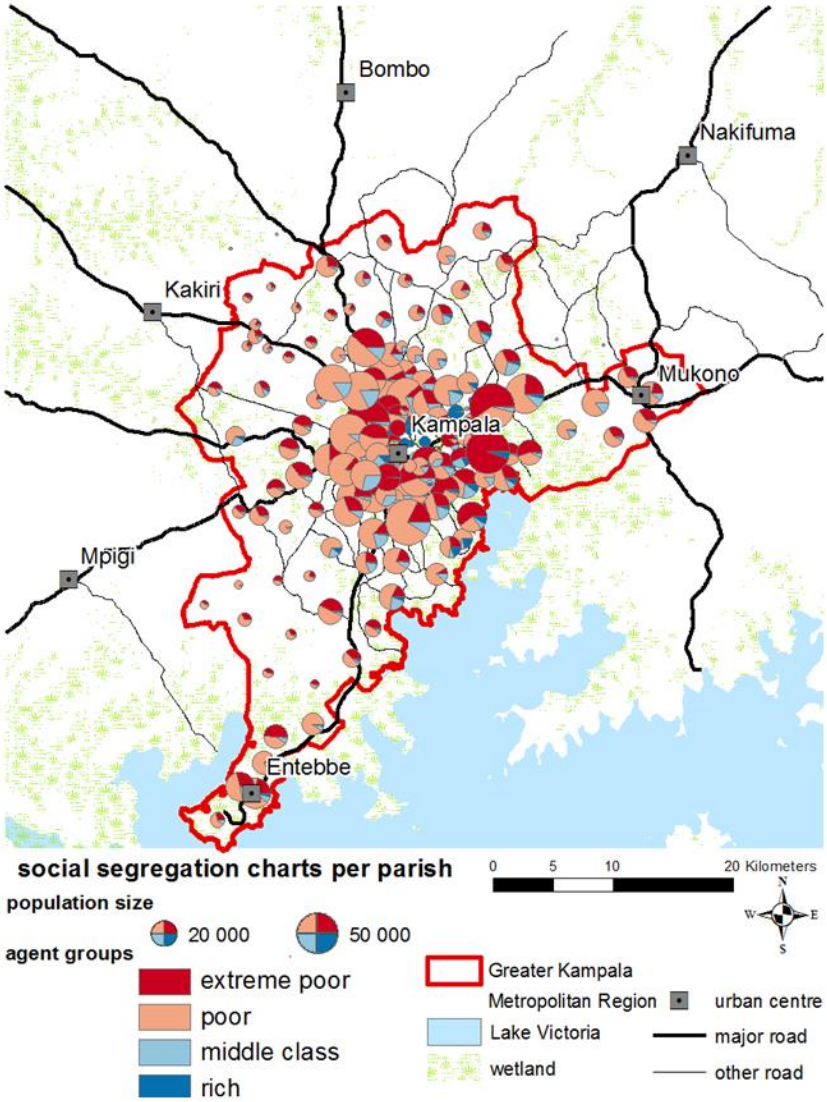

Figure 3: Estimates of the total population and its subdivision in extremely poor, poor, middle income and rich household members for every administrative unit in Kampala for 2010.

Using findings from earlier research, field observations and conducted interviews, an attempt was made to quantify the living preferences and possibilities of each AG into utility functions. The potential suitability of a location for an agent of a given AG was expected to depend on three factors: accessibility, living conditions and affordability. Different data layers were used as proxy variables to describe these three factors (Table 3). The accessibility of a location is expressed by its distance to a main road (DR) and the distance to a city centre (DC). 'Living conditions' were expected to depend on the population density and on whether a location was situated on a hill top, a foot slope or in a wetland. Most of Kampala's built-up area consists of one-floor buildings. As a result, the greenness and living space in a cell negatively correlates to the population density (Vermeiren et al., 2013). Similar as for the displacement functions, the fractionsF of rich and middle income persons were

used as a proxy for affordability because data on housing or land prices were unavailable to us. Evidently these factors do not fully reflect all settlement preferences of households. To account for this also a randomness term was considered (Table 3). Hence, the utility function for each AG could be written as:

$$Utility_{AG} = a_{AG} * DR + b_{AG} * DC + c_{AG} * FS + d_{AG} * HT + e_{AG} * WL + f_{AG} * Dens + g_{AG} * Fraction_{MR} + h_{AG} * Random$$

Equation 2

With 'a_{AG}' – 'h_{AG}' AG-specific weights, and 'DR', 'DC', 'FS', 'HT', 'WL', 'Dens', '$Fraction_{MR}$' and 'Random' variables which are explained in Table 3.

Based on the interviews and field observations, it became clear that – analogue to literature findings – extremely poor families are almost exclusively concerned about their employment status in order to construct their livelihood (Perlman, 2007). Therefore, living close to the city centre is crucial for their job accessibility. Living close to a road may also be relevant but clearly less than living close to a city centre, since paying for (public) transportation is often impossible for them. Likewise, they are often unable to take living conditions into consideration. As a result, the physical location (hill top, foot slope or wetland) or the population density has little influence on their housing decision. However, due to the financial constraints of these extremely poor households, the fraction of middle income and rich persons in the vicinity has a strongly negative influence on a location's utility for the extremely poor. Poor households have slightly higher financial means that allow them to afford some motorized modes of transport. They are therefore expected to be equally sensitive to proximity to roads as proximity to the city centre. Moreover, roads often serve as an important source of income since trading food and commodities forms an important livelihood strategy for this group and many of these commercial activities develop along Kampala's main roads, as in many Sub-Saharan African cities. Due to their higher income, they are also a little more flexible in terms of housing prices and are somewhat more reluctant to live in wetland locations. Since hill tops are generally too expensive, they prefer living on foot slopes. The interviews further indicated that middle income households find it important to live in reasonably accessible areas but that they also tend to seek good living conditions. They therefore strongly avoid wetlands and tend to avoid areas of high population density. Due to price constraints, they will select foot slopes rather than hill tops. However, this difference is less pronounced than for poor households. Finally, rich households prefer above all good living conditions and tend to pay much less attention to accessibility or affordability. They strongly prefer to live on hill top locations and are very averse to live in wetlands. They prefer areas where population densities are low and where other higher social class agents reside, but are still attracted to roads and city centres.

For each AG, these specific housing preferences were quantified as weights in our utility function by first normalizing each considered proxy variable to a value ranging between zero and one (Table 3) and then estimating the relative importance of each of these variables compared to the 'distance to road'. E.g. for the extremely poor households, our interviews and fieldwork indicated that living close to the city centre was about twice as important as living close to a road. Hence the weight of DC was twice the weight of DR. The sign of each weight depended on whether the considered variable was expected to exert a positive or negative influence on the utility. Once each weight was determined for an AG, they were rescaled so that the sum of their absolute values equalled 0.9, while a constant weight of 0.1 was given to the random term in our utility function (Table 3; Equation 2). This

procedure was evaluated by checking whether 'hotspots' of utility values for the different AGs corresponded with the actual location of these groups in the city.

The resulting weights are given in Table 4.

Table 3: description of the factors influencing the living location of agents

	Factor	Code	Type	Map specifications
Accessi-bility	Distance to roads	DR	Physical	Euclidean distance to the closest paved road (normalized between 0 and 1)
	Distance to centre	DC	Physical	Euclidean distance to the (closest) city centre (normalized between 0 and 1)
Quality of living	Foot slopes	FS	Physical	Zone between the wetlands and the hill tops, delineated based on a digital elevation model and a watershed map (1 = foot slope, 0 = not foot slope)
	Hill tops	HT	Physical	Upper part of hills, delineated based on a digital elevation model and a watershed map (1 = hill top, 0 = not hill top)
	Wetland	WL	Physical	Wetland zones, delineated based on a digital elevation model and a watershed map (1 = wetland, 0 = not wetland)
	Population density	Dens	Demographic	The number of persons per m² living within a radius of 500 m of the considered cell. Note that this data layer is updated during every simulation step. (normalized between 0 and 1)
Afforda-bility	Fraction of middle income and rich	$Fraction_{MR}$	Demographic	The fraction of the population living within a radius of 500 m of the considered cell that belongs to the rich or middle income group. Note that this data layer is updated during every simulation step. (normalized between 0 and 1)
	Random factor	Random	Random	A uniformly distributed random number (normalized between 0 and 1)

Table 4: Agent Group (AG) specific weights given to the terms in the utility function (Eq. 2) of each AG.

	Accessibility		Quality of living				Affordability	
Factors	**DR**	**DC**	**FS**	**HT**	**WL**	**Dens**	**$Fraction_{MR}$**	**Random**
Extremely poor	-0.14	-0.28	0.01	0.01	-0.01	-0.01	-0.42	0.1
Poor	-0.17	-0.17	0.09	0.02	-0.09	-0.02	-0.35	0.1
Middle income	-0.14	-0.22	0.07	0.04	-0.29	-0.04	-0.11	0.1
Rich	-0.12	-0.18	0.06	0.24	-0.24	-0.06	-0.01	0.1

In order to run, ASSURE also requires information on the initial settlement pattern of each AG. Hence, AG-specific population maps were produced for the study area by downscaling our AG-

specific population estimates at parish level (Figure 3) to the resolution of our model (grid cells of 100 by 100 m) through the proposed utility functions.

4.3 Simulated scenarios

The model allows scenarios to simulate future urban growth and segregation under a number of assumptions and strategies for the future development of a city. Our model for Kampala does not claim to be the new benchmark since the available data does not meet the necessary requirements. But nevertheless scenario development has the potential to deliver useful insights in urban dynamics and to illustrate the model's potential.

Using the agent typology discussed in the previous section, four specific scenarios were simulated for a period of 20 years (2010-2030): a business as usual scenario (BAU), a wealth increase scenario, a restrictive scenario and a stimulative scenario (Table 5). The BAU scenario assumes that present trends in urban expansion are continued. The Uganda Bureau Of Statistics (UBOS, 2008) estimated that Kampala yearly grows at a rate of 5.6%. Using this growth rate and – due to a lack of data on socio-economic status – assuming that the relative proportions of the four considered AGs across the entire Kampala area remains constant, the expected population growth for each AG is estimated (**Fout! Verwijzingsbron niet gevonden.**). From these population growth estimates, the number of agents to allocate is derived by taking into account the average household size. As is currently the case, it is assumed that the amount of multi-floor buildings remains very low. Hence the maximum amount of building space available in each cell was assumed to be simply the cell size (10 000 m²).

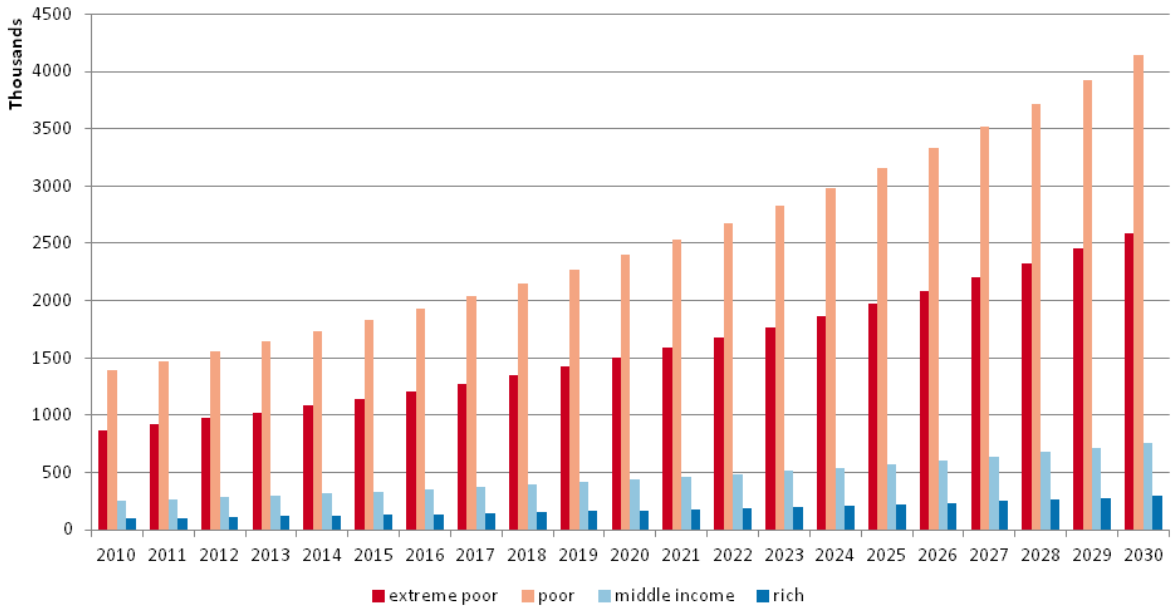

Figure 4: Population projection of each AG of Kampala

The wealth increase scenario not only takes the expected population growth into account, but also the expectation that Kampala will experience important economic growth which may affect the settlement patterns of Kampala's residents. GDP in Uganda is expected to continue to grow, while figures on absolute poverty indicate a yearly decrease of 1-2% (AFDB, 2014). Therefore it is likely to assume that agents can upgrade to a higher social class, what consequently can induce a residential relocation. This process is simulated by yearly upgrading 2% of the extremely poor agents to the

poor, 2% of the poor to the middle income and 2% of the middle class to the rich AG. Such upgrade involves re-evaluating ones living place through the upgraded utility function. For simplicity, the agents experiencing this 'upgrade' are randomly selected.

As discussed in section 3.1, settlements in Kampala's wetlands involve important health risks and environmental problems. Zoning is a frequently used planning strategy to prevent housing in unsuitable areas and thereby safeguarding the urban liveability (Geneletti, 2013, Mozumder and Tripathi, 2014; Harloe and Pickvance, 1990). In the restrictive scenario, it is therefore assumed that Kampala will expand as in the BAU scenario, but that a zoning strategy prohibits new as well as existing habitats in wetland areas, while two popular central slums of Kampala are cleared during the first year of the simulation. This clearing and building restriction was implemented by setting both the displacement threshold and maximum space available to zero in areas where building was prohibited.

Finally the stimulative scenario explores the impact of some infrastructural and developmental measures. In addition to the measures taken in the restrictive scenario, this scenario simulates interventions that frame within the idea of decentralisation and development of satellite towns, as is considered in the Kampala Physical Development Plan report of 2012 (KCCA, 2012). Specifically, this scenario assumes that six towns at 20-40km distance from Kampala will also become attractive city centres. Besides Entebbe and Mukono these towns currently house only several tens of thousands residents but show some urban characteristics. In the case that investments are made in the economic independency, services and accessibility, these towns can grow to independent satellite towns. This scenario therefore adds an update of the physical urban infrastructure whereby the satellite towns become incorporated as attractive city centres that are connected by an outer ring way. Also densification is often mentioned in the debate on sustainable urban development (Jenks and Burgess, 2000). Therefore, this scenario assumed 3-story high residential buildings in the central areas by increasing population densities and thus increasing the maximum space available of to 30 000 m² instead of 10 000 m² per cell. This assumed densification remains fairly limited, but concurs with the observation that living in high-rise buildings is not common to the Sub-Saharan African life style (Olvera et al., 2002) .

Table 5: Characteristics of the simulated scenarios

	5.6% population growth	2% agent upgrade	Wetland clearance	Slum clearance	Satellite town development	Outer ring way	High rise
Business as usual	X						
Wealth increase	X	X					
Restrictive	X		X	X			
Stimulating	X		X	X	X	X	X

4.4 Scenario results and discussion

Figure 5 shows the AG-specific population densities for the initial situation (2010) as well as for the simulated scenarios in 2030. Figure 6 displays the AG-specific evolution of the average distance to the city centre, the population density and the average percentage of rich and middle income persons living in the vicinity (within 500 m) under the four different scenarios. Figure 7 shows the per

parish average wealth increase or impoverishment and Figure 8 the evolution of the dissimilarity index calculated based on following formula (White, 1983):

$$Dissimilarity = \frac{1}{2}\sum_{i=1}^{n}\left|\frac{N_{1i}}{N_1} - \frac{N_{2i}}{N_2}\right|$$

Whereby N_1 and N_2 respresent respectively (extreme) poor and non poor (middle class and upper) and *i* refers to spatial units which are equal blocks of 5 by 5 km. Other studies take administrative units such as the parishes, but this would mean excluding the areas outside the boundaries of the greater Kampala metropolitan region and therefore excluding a significant number of residents as well.

Results for the BAU indicate that rich agents will mainly settle on hill tops that may be relatively far away from the city centre, while middle income agents are scattered in the vicinity of the city centre. Since non-wetland areas nearby the city centre are mainly occupied by these middle income agents, the poor are pushed to locations further away from the city centre but close to the main roads. Since extremely poor seek to remain close to the city centre and are unable to compete with the other AGs for suitable living spaces, 56% of the extremely poor residents end up in the wetlands - in comparison to 32% in 2010 - where population densities can be very high. Hence their need to remain close to the city centre can be expected to result in deteriorating living conditions under a realistic business as usual urban growth. Also in terms of social segregation, the model results indicate that rich income groups will continue to live in neighbourhoods that become more and more exclusively rich (Figure 6). The dissimilarity index predicts an almost doubling of the social segregation in the whole study area (Figure 8). These dynamics lead to a relative impoverishment in some neighbourhoods in the inner city and at the urban fringe and a relative wealth increase in several parishes between the city centre and this urban fringe, especially those comprising attractive hill tops (**Fout! Verwijzingsbron niet gevonden.**).

Many of the trends and patterns observed in the BAU scenario appear to be amplified in the wealth increase scenario. The yearly upgrade of 2% of the extremely poor, poor and middle income AGs to a higher income class, leads to a 44% increase of built-up area and thus an even stronger urban sprawl of Kampala (Figure 5). Due to this increased urban sprawl, members of the poor AG are forced to seek residence even further away from the city centre (Figure 6). Extremely poor agents, on the other hand, continue to cluster in high density neighbourhoods nearby the city centre that are often located in wetlands (Figure 5; Figure 6). Since the increase in extremely poor agents is 2% lower than in the BAU scenario, population densities initially remain fairly constant for this group. However, as the demand for suitable housing locations nearby the city centre further grows, population densities rise faster after 2017 and reach in 2030 a similar level as in the BAU scenario. Most neighbourhoods, especially in the urban fringe, strongly enrich (**Fout! Verwijzingsbron niet gevonden.**). However, social segregation can be expected to be larger compared to the BAU scenario as indicated by the differences in the percentage of rich and middle income persons (Figure 6). The dissimilarity index evolution as well indicates a severe increase compared to the initial state and the BAU scenario (**Fout! Verwijzingsbron niet gevonden.**). In conclusion, this scenario indicates that, although the population of poor and extremely poor lowered compared to the BAU scenario, their housing conditions are likely to deteriorate: poor households are forced to live further away from the city

centre, while extremely poor households continue to end up in wetland neighbourhoods with rapidly increasing population densities. This does not mean that economic growth is something negative, but governments need to be aware of the associated problems and risks and such insights deliver opportunities to anticipate them.

Under the restrictive scenario, wetlands are no longer available for residence (Table 5). This would affect mainly the extremely poor population: while some of the non-wetland high density neighbourhoods near the CBD remain, the prohibition to live in wetlands would force many extremely poor households to live in neighbourhoods further away, E and NE of Kampala (Figure 5, Figure 6). The segregation is predicted to rise a bit less than in the BAU scenario (**Fout! Verwijzingsbron niet gevonden.**). Overall, the simulated restrictive policy seems to have only a limited effect on wealth increase and impoverishment patterns across Kampala (**Fout! Verwijzingsbron niet gevonden.**). Evidently, suddenly clearing wetland and slum areas can have dramatic socio-economic consequences for the former inhabitants (Bhan, 2009). Likewise, it must be acknowledged that the model does not fully capture the increased housing cost and livelihood impacts that such former slum dwellers would be likely to experience. Nonetheless, it is noteworthy that the model suggests that clearing slum and wetland areas may eventually lead to improved living conditions for extremely poor households. First of all, as a consequence of the scenario assumptions, none of them would live in unhealthy wetland areas. Secondly, population densities for extremely poor households will be clearly lower than in the BAU scenario (Figure 6). Despite the fact that extremely poor households are forced to move away from the centre, the average distance to a city centre remains comparable with the BAU scenario (Figure 6). This is because many of the extremely poor households would settle around the centre of the adjacent town Mukono. So, provided that Mukono can indeed provide employment opportunities, our scenario suggests that wetland and slum clearance would have only a limited impact in terms of accessibility. With its 60000 residents Mukono currently lists among Uganda's twenty largest cities (UBOS, 2008) and already is attractive for low class families thanks to the presence of industries and trade markets.

The idea that the development of satellite cities may be an important tool in Kampala's urban planning was further explored in the stimulative scenario. Our simulations indicate that the implemented measures would clearly relieve pressure on Kampala, resulting in a much less urban sprawl (Figure 5).

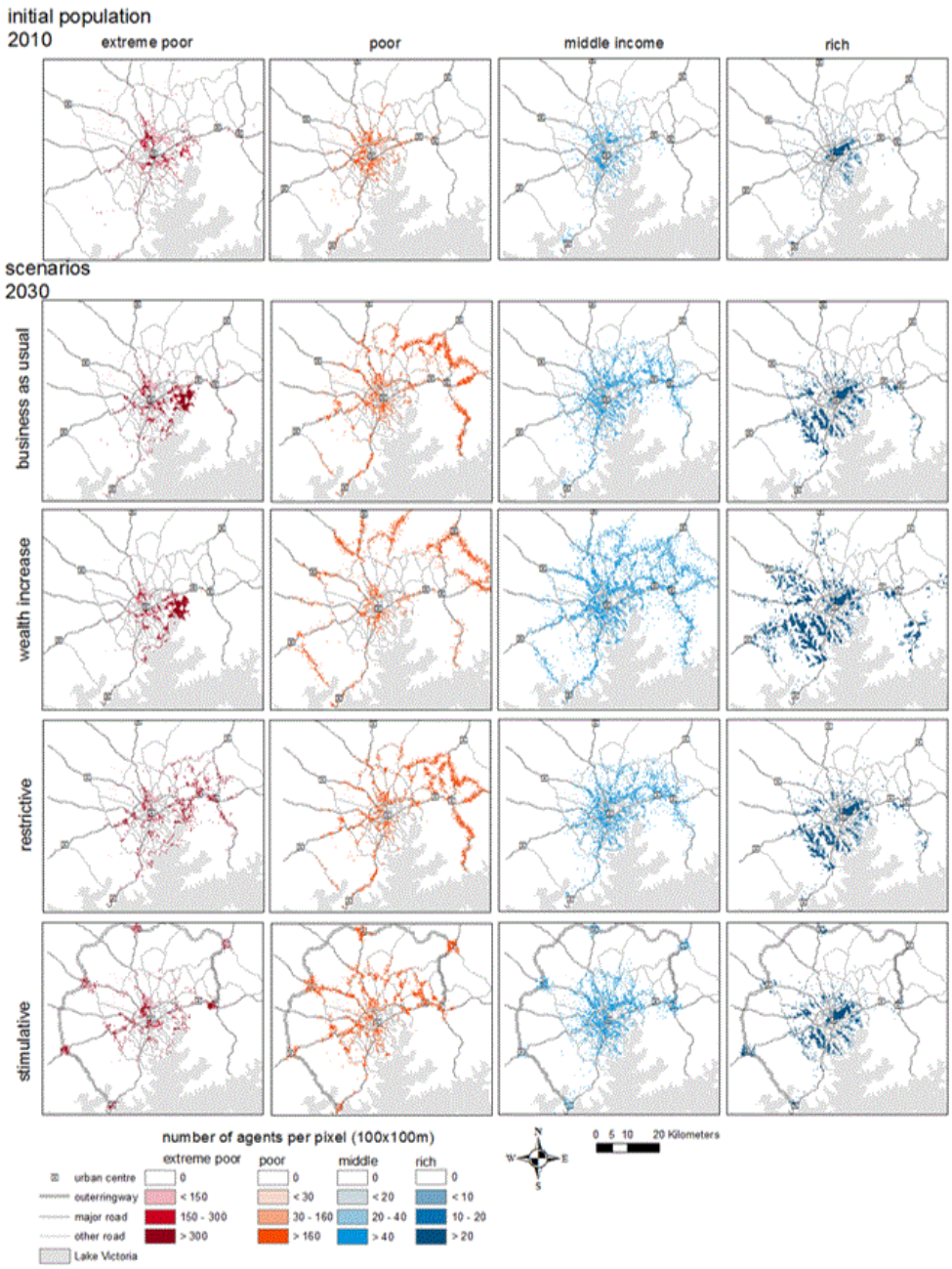

Figure 5: Simulated spatial patterns of population densities for the four considered Agent Groups.

Population densities are clearly higher for all AGs, but especially for the extremely poor (Figure 6). It should be noted, however, that these higher densities do not necessarily reflect poorer living conditions, but are here mainly a result of the assumption that people will start living in multi-story buildings. As could be expected, also the access to city centres increases for all AGs.

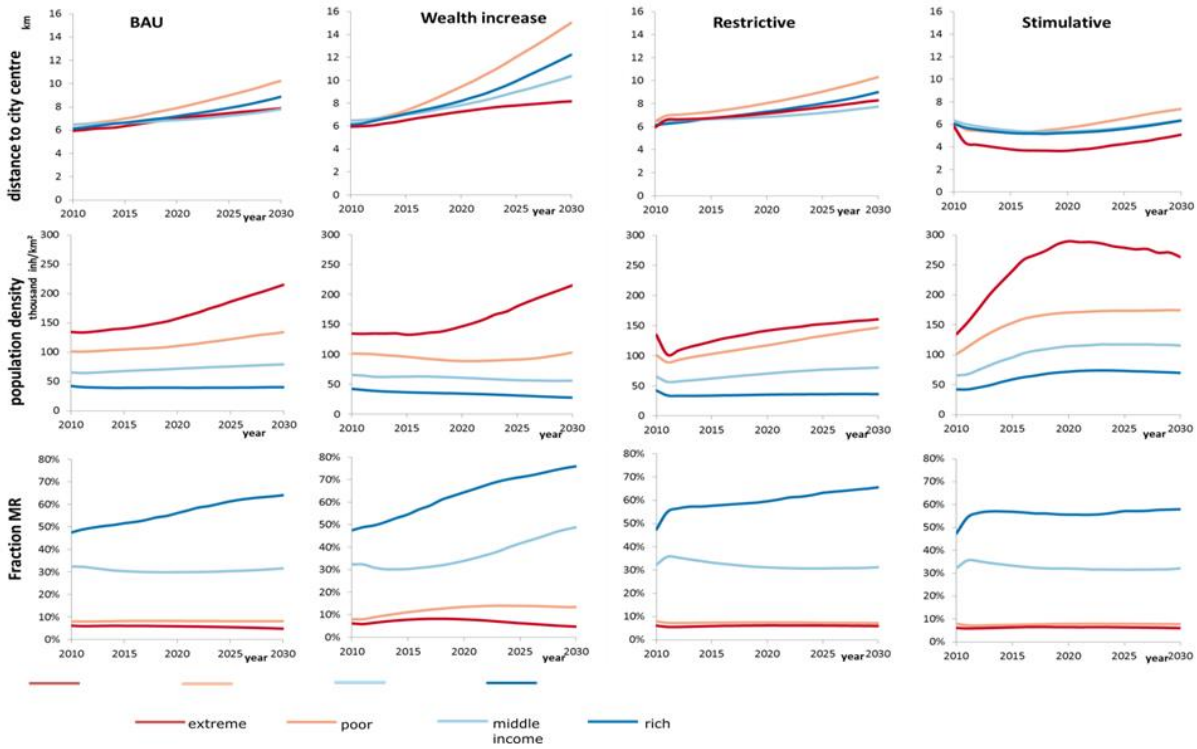

Figure 6: Evolution of the average distance to a city centre (top), average population density (centre) and the average percentage of the rich and middle income people living in the vicinity (bottom) for the four considered Agent Groups under the four simulated

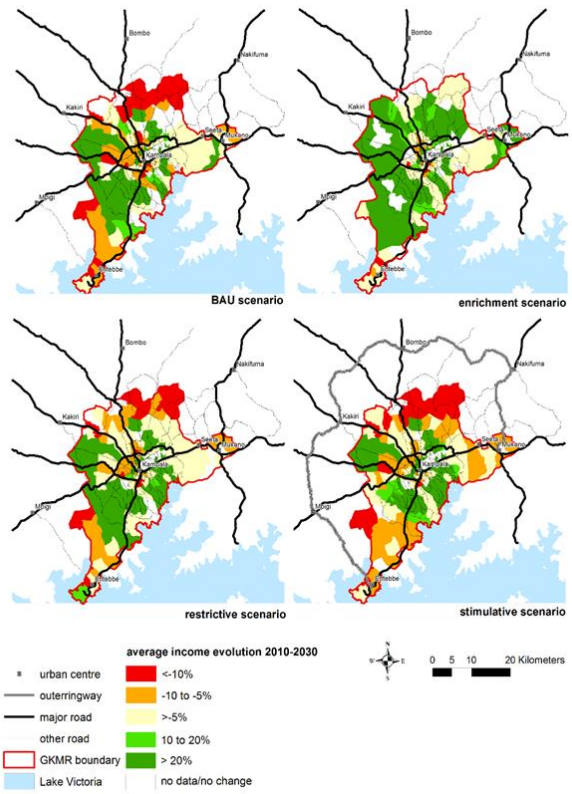

Figure 7: Evolution of average income per parish under the four simulated scenarios

It is noteworthy, however, that the stimulative scenario is the only one where a fraction of middle income and rich in one's neighbourhood is not predicted to increase in comparison to the initial situation. Also the dissimilarity index is expected to increase less than in previous scenarios (**Fout! Verwijzingsbron niet gevonden.**).

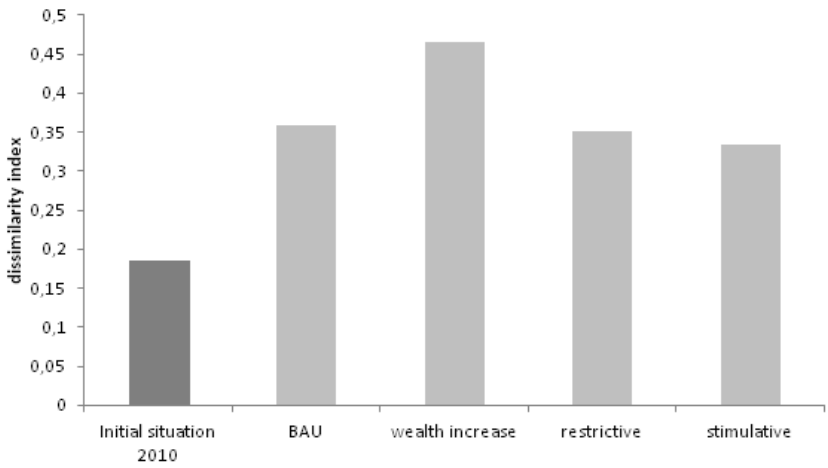

Figure 8: Evolution of dissimilarity according to the scenarios

Apart from a small increase in segregation due to our simulated slum and wetland clearing, the mixture of high and low incomes remains almost constant throughout the simulations for all AGs. These simulation results also concur with findings of earlier studies, indicating that high rise buildings can improve social mixture (Burton, 2000). Results of such scenarios can be used by urban government to evaluate the considered efforts to invest in the suggested town as satellite towns. However, a progressive strategy as in our stimulative scenario requires a large spatial framework to assess the effects in the potential satellite towns. In this case, the relevant area reaches much farther than the proposed Greater Kampala Metropolitan Area. Hence, this suggests that even Kampala's current efforts to prepare for future urban growth by enlarging the administrative urban perimeter might be insufficient.

5. Conclusions

In this paper ASSURE was presented, a spatially and temporally explicit model that can simulate urban growth and social segregation, taking into account differences in livelihood strategies between different socio-economic groups and their interactions. The ASSURE model framework allows us to translate expert judgement and realistic assumptions on urban growth, living preferences and social segregation mechanisms into simple equations that facilitate the scientific discussion on what the key processes of urban transformation are.

Evidently, many assumptions underlie the simulations for Kampala as presented in this paper, including expectations on the urban growth and the subdivision of citizens in different socio-economic classes (AGs). Depending on the research needs and data availability, these assumptions and the (flexible) model framework presented here can be further refined. For example, more detailed census data would allow us to model agents along a continuum of characteristics rather than clustering them in distinct groups with only 1 utility function per group. Secondly, processes of

re-locations may be modelled more explicitly in the future. Currently, our model application only simulates the forced movement of agents. A better understanding of the settlement preferences of the different agents could lead the inclusion of 'voluntary movements' of households in the model. Thirdly, one could think of further fine-tuning the utility functions which are at present simple linear equations, by adding e.g. interaction terms or considering different equation types. Fourthly, some of the scenarios are implemented in a rather abrupt way. For example, we modelled the introduction of high-rise here by assuming that the available living space drastically increases in one year. Although this is not so unrealistic in the case of Kampala, it might also be interesting to introduce more gradual change processes in the model.

At present, ASSURE can't be used as a predictive tool. This would require more empirical data to allow for a quantitative calibration of the utility functions and an explicit model validation. Nevertheless we believe that, even in its current stage, ASSURE can be highly useful, both for scientific research and applied decision making. For example:

1) ASSURE helps by translating qualitative information on urban growth and segregation theories into a quantitative, spatially and temporally explicit framework. Doing so can pull the scientific debate on urban development and planning out of the sometimes esoteric discussions that often lack focus and lose themselves in semantics. This does not imply that qualitative research cannot provide us with highly valuable ideas and theories. On the contrary: qualitative research is commonly crucial for our understanding of urban dynamics. However, we believe that quantifying the findings of such research in a spatially and temporally explicit way is often a vital step to allow for more structured debates and further development of these understandings.
2) ASSURE can reveal new research questions and policy strategies. For example, our simulations show that economic growth and an associated general wealth increase may lead to a decrease in the number of (extreme) poor households. However, this may also further deteriorate the living conditions of the remaining (extremely) poor households. Given that growing social inequality is considered as a major challenge, alternative development strategies that not focus solely on maximising overall economic growth could be further explored.
3) Causes and consequences of specific interventions may be better understood with this model. This study showed that forbidding settlements in wetland areas may in the long run result in better housing conditions for extremely poor households, provided that they are given the opportunity to settle in the vicinity of economically relevant centres. Our simulations also indicated that stimulating high-rise buildings and economic activities in satellite cities may be a highly effective strategy in reducing urban sprawl and social segregation, leading to overall better living conditions. However, they also showed that such strategies need to be implemented over a much larger area then the current official administrative boundaries of Kampala. These are useful insights that may aid the development of targeted programs to support sustainable urban and economic growth (e.g. the construction of suitable infrastructure in specific neighbourhoods).
4) Models such as ASSURE will facilitate targeted data sampling campaigns by scientists and (non-) governmental organizations. As stated throughout this manuscript, lack of data is an important constraint that affects the understanding of the urban evolution of many cities in developing countries. It is likely that this data gap will be filled in the near future. The

presented model structure could present guidelines on what information is mostly needed. For example, it allows us to explore the expected impact of certain processes or factors (such as population growth, wealth increase, policy decisions) on patterns of urban expansion and social segregation. This can help in optimizing data collection efforts or designing specific validation strategies.

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