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Modelling the impacts of urban upgrading on population dynamics

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ABSTRACT

Due to the rapid pace of urbanization, cities in the global South are growing with most of this growth occurring in informal settlements. Urban upgrading aims to improve living conditions in such settlements by improving the infrastructure but might lead to unexpected effects such as income segregation. InformalCity, a spatially explicit agent-based model, simulates the implications of urban upgrading in an artificial city. Our simulation experiments show that maintenance of the upgraded infrastructure, the scope of upgrading efforts, and timing (early vs. late investments) affect infrastructure quality, housing development and income segregation. However, we also find that urban upgrading interventions can have contradictory effects; for example, maintenance increases the quality of infrastructure and income segregation. Thus, policy makers need to establish clear targets for upgrading projects, and empirical evaluation studies should consider studying the impacts of urban upgrading on an entire city's development rather than limiting them to informal settlements.

1. Introduction

Most urbanization is currently taking place in the global South, where urban development often occurs in the form of informal settlements (Martínez et al., 2008, UN Habitat, 2009). These areas often have high and increasing population densities and low levels of public infrastructure, which can lead to severe public health problems and a low quality of life for their inhabitants. Urban upgrading is often considered as a policy option and implemented to improve living conditions in these areas (Satterthwaite, 2012). It encompasses a variety of measures to improve the quality of housing and the provision of infrastructures and services to settlements at the neighbourhood level, be it informal settlements, slums or other types of settlements (Davidson and Payne, 2000). Despite the many benefits provided by urban upgrading, such interventions might also have unintended negative effects such as increased income segregation within a city or rising living costs (studies summarized in Turley et al., 2013). In addition, urban upgrading might create a vicious cycle in which the greater attractiveness of upgraded settlements gives rise to increased inmigration and thus worsens living conditions (Huchzermeyer, 2008).

Evaluations investigating the effects of upgrading interventions to learn from successes and failures have been completed, for example, on behalf of funding agencies (e.g., I.T. Transport Ltd., 2005) and by independent researchers (e.g., Patel, 2013). Traditional approaches to evaluate interventions of urban upgrading focus on the settlement or neighbourhood scale to analyse the effects of the upgrading efforts on living conditions in the target area. Thus, most evaluations of upgrading do not consider its effects on other parts of the city, even though a “settlement cannot be isolated from the city of which it is a part” (Abbott, 2002a; page 308). Evaluations focussing only on the upgraded area fall short when it comes to systematically detecting the effects of the intervention on other parts of the city. Moreover, Gulyani and Bassett (2007, page 488) argue that upgrading has “to go ‘to scale’”, meaning that upgrading should not focus only on individual settlements, but rather consider the whole city, to provide broader and sustainable benefits. Therefore, it is necessary to widen the scope of evaluations of urban upgrading to the city scale. Many aspects change as a result of urban upgrading, and this paper shows one example of studying such changes at a citywide scale. In this paper, we aim to understand the effects of improved infrastructure provision on residential mobility and the resulting spatial patterns of population distribution. This enhanced understanding could be used to design well-informed upgrading policies and could also support more critical discussions about not only the direct but also the indirect

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impacts of urban upgrading. Our model design is informed by primary surveys, personal observations and discussions with planners and residents in numerous settlements, in addition to studies conducted in informal settlements in Sub-Saharan Africa (SSA) over recent decades (see for example Sheuya, 2004, Sliuzas, 2004, Young and Flacke, 2010 for some background on informal settlement growth in SSA and Dar es Salaam in particular).

1.1. Urban informal growth in SSA

SSA experiences an unprecedented urbanization process over the last 40 years as a result of the inherent demographic processes of natural population growth and rural-urban migration. Simultaneously, many SSA countries have experienced prolonged economic decline, particularly in the 1980s and 1990s, and political instability, and their weak statutory planning systems have exacerbated the problems associated with rapid urbanization (Kombe and Kreibich, 2000). This situation has led to majority of the urban population, especially the urban poor, living in informal conditions, in terms of both housing and employment. Recent figures estimate that approximately 62% of the urban population in Sub-Saharan Africa lives in slums (UN Habitat, 2012).

Urban informal settlements in SSA can generally be defined by two basic characteristics: First, the housing is illegally built and second, few services and community facilities are available in the immediate neighbourhood (Sheuya, 2009). Sliuzas (2004) describes the growth process of these settlements as a gradual incremental process of individual land transactions between traditional (rural) land owners and households seeking to build a new house in the city or in the urban fringe. Though the resulting urban patterns often seem to be spontaneously developed and disordered, they are influenced by a number of physical, economic, and cultural factors, such as site quality in terms of slope and hazards, location and land value, and social networks and kinship ties (Sliuzas, 1988). Nevertheless, these settlements generally have less orderly spatial structures than planned neighbourhoods.

1.2. Urban upgrading

Upgrading interventions comprise a variety of measures, ranging from minor (e.g., paved roads) to major improvements, including legal tenure (Satterthwaite, 2012). Gulyani and Bassett (2007) describe a trajectory of upgrading projects in SSA from first generation projects in the early 1970s, which focused on providing large quantities of affordable housing units, to second generation projects beginning in the 1990s, which included interventions to legalize land tenure, create physical plans, resettle residents, and develop technical infrastructure. Minnery et al. (2013) distinguish a hierarchy of urban upgrading elements from (a) basic physical services, (b) private consolidation (shelter upgrading), and (c) public consolidation to (d) institutional reform. The focus of this study is on the first level of basic physical infrastructure on the neighbourhood or settlement scale. This level includes providing water pipes, sewers, drains, paved roads, footpaths and electricity. Whereas urban upgrading driven by household investments mostly aims at improving housing quality, neighbourhood-wide physical infrastructure is often targeted by community or resident organisations, local governments, and/or external funding organizations (Satterthwaite, 2012). Improvements in public investment are believed to provide a stimulus for private household investments. Apart from immediate increases in housing and infrastructure quality, urban upgrading may also aim towards poverty alleviation, reduction of vulnerability and social integration, both within a settlement and within the city (Abbott, 2002b).

Urban upgrading programmes focussing on physical infrastructure are diverse and can be characterised with respect to the following four configuration parameters: maintenance of the implemented interventions, scope of upgrading, selection of target districts, and cost recovery.

1.2.1. Maintenance

Past upgrading programmes have often been criticised over a lack of provision of maintenance of the physical infrastructure (Satterthwaite, 2012). Patel (2013) shows that for a settlement in Durban, South-Africa, substantial participation of the community in the upgrading process is essential for sustainable success of the implemented interventions.

1.2.2. Scope of upgrading

The scope of an upgrading programme has important social and economic consequences. On the one hand, comprehensive upgrading programmes that also include social services increase costs for the targeted community (Satterthwaite, 2012). Thus, if looking at an entire urban region with limited resources, fewer settlements can be targeted. On the other hand, some upgrading programmes, such as the Kampong Improvement Programme in Indonesia, aim to reach a large number of settlements, but with a lower standard of improvement (Satterthwaite, 2012). Thus, given limited resources, the scope of upgrading interventions lies on a continuum between either higher quality improvements for fewer communities or lower quality improvements for more communities. A quantity-quality trade-off is to be considered in all urban upgrading programmes.

1.2.3. Selection of target districts

Regarding the selection of target districts for upgrading, Huchzermeyer (1999, as cited in Abbott, 2002a) distinguishes between two types of interventions: externally designed comprehensive upgrading and support-based interventions. For example, community-based initiatives aimed at building the capacity of the poor to improve their own housing are often found on the Indian sub-continent, whereas in Latin and Central America, settlement master plans are often developed by combining different data sources in geographical information systems (Abbott, 2002a). When considering an entire urban region, the question of “which settlements are to be upgraded?” arises. For community-based efforts, upgrading initiatives may evolve where the presence of strong community leaders drive community upgrading processes rather than where the needs are greatest (Minnery et al., 2013). By contrast, in top-down upgrading programmes that are strongly steered by external funding or national governments, communities may be chosen according to a city-wide needs assessment or even be biased by political expediency.

1.2.4. Cost recovery

Many early upgrading efforts were top-down (Minnery et al., 2013), dominated by externally funded upgrading programmes that did not implement cost recovery from households (Satterthwaite, 2012). Currently, the financial resources for urban upgrading often stem from a combination of contributions, including national, local government and community support. Community support means that residents also have to commit themselves to covering a substantial portion of the costs (Satterthwaite, 2012). However, an evaluation of a number of upgrading projects in SSA showed that in practice, cost recovery from beneficiaries has been problematic in many cases due to residents’ unwillingness to pay or because of a poor project design and hence undesirable or unaffordable project outcomes for the beneficiaries (Gulyani and Bassett, 2007).

1.3. Agent-based modelling of urban upgrading

Empirical data on informal settlement development in general and urban upgrading in particular are often scarce. In such a situation, a modelling study can foster general system understanding (Roy et al., 2014). Furthermore, a modelling study makes it possible to analyse the impacts of different upgrading programme configurations in a comparable way while avoiding the ethical dimensions of real-world experiments. Agent-based models (ABMs) are a useful approach for simulating the effects of urban upgrading interventions on the living conditions of residents. In ABMs, the residents of a city can be represented by their individual decisions and their interactions with other residents and their surroundings.

Compared with the diversity of ABMs for urban sprawl in the developed world (Schwarz et al., 2010), only few models simulate the formation of informal settlements or slums in the global South (Huang et al., 2013; Roy et al., 2014). These models can be grouped into two categories: empirical and theoretical ABMs. Empirical ABMs often focus on one specific case study and aim to mimic its (mostly spatial) details as precisely as possible. Empirical studies differ with respect to the spatial scale: some authors focus on a single settlement within a city. For example, Augustijn-Beckers et al. (2011) simulate the spatial location of individual houses in the Manzese settlement in Dar es Salaam, Tanzania, whereas Young and Flacke (2010) focus on the settlement Hanna Nassif in the same city. Others simulate the whole city. Feitosa et al. (2010) use their simulation model to explain patterns of income segregation within Sao Jose dos Campos, Brazil. Hosseinali et al. (2013) analyse the growth of Qazvin city, Iran. Xie et al. (2005) investigate the effects of the rural population changing its lifestyle in the city of Wuxian, China. Finally, Sietchiping (2004) models the spread of informal settlements in Yaoundé, Cameroon, with a combination of GIS and cellular automata, recommending the addition of an ABM in the future.

Theoretical models aim to explain general patterns of development without referring to a specific case study. Garcia-Diaz and Moreno-Monroy (2012) simulate rural-urban migration in developing countries by explicitly analysing the effects of the informal employment sector and social influences. Patel et al. (2012a) model slum development in inner-city areas of Indian cities and the periphery based on the interplay of households, developers and policy makers. Barros (2003) and Sobreira (2005) investigate the development of spontaneous settlements at the city-level, and the latter author also analyses the spatially explicit location of dwellings on non-occupied land in such settlements. Finally, Barros (2012) uses a theoretical model to simulate the peripherisation of income groups in Latin American cities.

1.4. Aim and organisation of the study

None of the ABMs found during the literature review explicitly tackle the effects of urban upgrading on urban development. Therefore, this paper introduces InformalCity, an ABM that simulates the effects of urban upgrading on both the built environment and the population distribution, including income segregation. For this reason, InformalCity was developed as a theoretical ABM without referring to a specific case study. However, model rules were included with the background of urban development in SSA cities. InformalCity is a first step towards filling this highly policy-relevant research gap.

The paper investigates how the design of urban upgrading interventions in informal settlements affects infrastructure quality and the city-wide population distribution, including income segregation in SSA. The designs of the urban upgrading interventions are differentiated regarding maintenance, the scope of upgrading, the selection of target districts, and cost coverage. Furthermore, the effects of early and late implementation of urban upgrading are investigated. The latter aspect is important because policy makers need to understand how delays in upgrading can affect living conditions in the longer term.

The remainder of this paper is organised as follows: In the next section, we introduce the ABM InformalCity. Section 3 provides the simulation results, describing first growth dynamics without urban upgrading (section 3.1) and then the effects of urban upgrading (section 3.2). Finally, the results are discussed (section 4) and conclusions are drawn (section 5).

2. Model description

The model description is organised as follows: Section 2.1 gives an overview of the model. Section 2.2 provides basic assumptions on the behavioural rules, including their empirical basis. Section 2.3 gives details on the model implementation (i.e., the environment, the agents, and infrastructure quality). Section 2.4 describes the urban upgrading interventions, section 2.5 describes the calibration and stochasticity, and section 2.6 describes the model output. A detailed model description is given in documentation following the ODD + D protocol (Müller et al., 2013) which is published together with the model.

2.1. Overview of the model

The current version of InformalCity simulates an artificial city consisting of 49 districts explicitly located in the city. Within these districts, there are plots for building houses, with one house per plot. Houses can vary in size (see section 2.3.1 for details on the city environment). At the beginning of the simulation, the city is initialised with agents representing households, being either tenants or owners (section 2.3.2). These households settle on a plot in one of the districts and can move to other plots in other districts in consecutive time steps but do not move within a district. Furthermore, owners can add rooms to their house, and tenants can become owners provided enough savings. Details on the decision making pertaining to these issues are given in section 2.3.2. Infrastructure quality is dependent only on household density (see section 2.3.3) and can be enhanced with urban upgrading (described in section 2.4). Each time step represents one year.

When starting the simulation, users can set a number of parameters: These parameters include the calibration: the initial number of households, the number of plots per district, the cost to build three rooms of a house, and the population density threshold for the decrease of infrastructure quality (see section 2.3.3). In addition, users can choose if they want to include urban upgrading in the simulation and can select between various options: the timing of the upgrading, the selection of target districts, the scope of upgrading efforts, cost coverage and maintenance (section 2.4). Changes in the annual population growth rate and income distribution have not been explored in the current study. The settings for all simulation runs are given in section 2.5.

2.2. Basic assumptions on behavioural rules

InformalCity is rooted in location theory and applies the approach of the Alonso model (Alonso, 1964). In the original Alonso model, the utility function of a household combines the plot size, the amount of composite goods that can be consumed, and the proximity to the central business district (CBD). In the original Alonso model, infrastructure provided on the land is not considered explicitly. It is assumed that all land is serviced equally. Households maximise their utility under a budget constraint that covers commuting cost, the cost of acquiring the land with prices depending on the location and the size of the land, and costs for the composite goods. Empirical studies on urban development in SSA encouraged the application of the Alonso model to residential mobility in SSA, because proximity to the CBD is one of the most important aspects in cities in SSA (Young, 2010, for residential mobility in Dar es Salaam, Tanzania, and Linard et al., 2013, for a statistical model on urban expansion in Africa). What is more, poor households in particular often trade-off central locations that offer access to informal income-generating activities against hazards and/or infrastructure quality and create informal settlements in the process (UN Habitat, 2003). To take this process into account and to simultaneously keep the approach as simple as possible, InformalCity deviates from Alonso's assumptions in three points: First, infrastructure quality is added to the utility function, which is supported by Young's (2010) empirical finding that – next to proximity to the CBD – infrastructure-related aspects, such as access to drinking water and roads, were the factors most often mentioned in her empirical study on informal settlements in Dar es Salaam, Tanzania. Second, to simplify the model, the utility function relates only to the utility derived from location choice. Thus, composite goods are not represented explicitly, and only the budget available for housing is considered. Third, the plot size is equal for all plots in the model, and the costs for acquiring a plot are not considered. Empirical data suggest that the price of land in an informal settlement accounts for only approximately 1–2% of the building costs (for Dar es Salaam, Tanzania: Young, 2010, pp 57–58). These building costs are independent of location and depend on the size of the house. Thus, there is no need to consider the cost for acquiring the plot itself in the budget constraint. Thus, in summary, the utility function combines the proximity to the CBD and infrastructure quality, and agents consider only the budget available for housing (equation (1)).

$$\text{Utility} = a \times \text{proximityCBD} + b \times \text{qualityInfrastructure} \quad \text{(Equation 1)}$$

where a: an agent's preference to live close to the CBD;
b: an agent's preference for infrastructure quality;
proximityCBD: 1 – distance to the CBD (with distance to the CBD ranging from 0 to 1);
qualityInfrastructure: the quality of infrastructure in a district as computed using equation (2).

The decision making of one household agent in one time step is sketched in the flow diagram (Fig. 1) and follows these steps:

- New households start as tenants and rent a room if they find one (Fig. 1, part [1]). New households in InformalCity represent either households immigrating from a rural area or other cities or households that are newly formed by young adults already living in the city, moving out of their family home. For both groups, studies on SSA suggest that the majority of households first live as tenants (UN-Habitat, 2003, for Africa in general, Huchzermeyer, 2008; for slum residents in Nairobi, Young, 2010, for an informal settlement in Dar es Salaam).
- At initialisation, the city is empty; neither houses nor inhabitants are present. Hence, when agents are added to the simulation, it is impossible for them to find a room to rent, because there are no rooms (or houses, for that matter) at all. To cope with this situation, a rule was created so that if new tenant households cannot find a room to rent, they become owners and build a house (even without having enough savings) (Fig. 1, part [2]). After owners have built houses and added the first rooms for renting, this behavioural rule is not needed, because a number of free rooms are always available.
- In the following time steps, agents save money (Fig. 1, part [3]). First, the value of their income is added to their savings. Because neither the absolute values for income nor the building costs or initial savings in the model have an empirical background, this process symbolises the general ability of households to accrue savings over time and use them for building a house (Sheuya, 2007; Young, 2010). Renting rooms to tenants is one of the main income sources of homeowners in informal settlements (Sheuya, 2007; Young, 2010), so landlord households can further increase their savings.
- Next, 10% of the agents (randomly selected) enter a decision-making process (Fig. 1, part [4]), which represents events such as the arrival of new family members or other relatives who cannot be accommodated in the current location (Sheuya, 2009; Young, 2010) but the arrival does not change the total number of households.
- If owner agents want to move, they move if their savings are larger than the costs needed to build a house in another district and if they have found a district that better fits to their needs than the current one (Fig. 1, part [5]). The choice for a new district follows a three-step approach: First, a decision tree is used to filter the districts that (a) have empty plots (for owners) or empty rooms (for tenants, see below) and (b) are affordable before entering utility maximisation. Second, for each of these districts, the utility is calculated using equation (1). Third, the agents choose the district with the highest utility. This process reflects the empirical finding by Young (2010) that a substantial share of homeowners in an informal settlement in Dar es Salaam, Tanzania, consider building an extra house in another location.
- Owners can also enlarge their house to accommodate more family members (Sheuya, 2009; Young, 2010, Fig. 1; part [6]) as long as the maximum number of rooms per house (see section 2.5) is not exceeded. Adding rooms to an existing house (also for renting, see below) is due to incremental housing development. The typical Swahili house is usually built in a step-wise process (Sheuya, 2009).
- Tenants may move and become owners if their savings are larger than the building costs and have found a district with empty plots and a higher utility (Fig. 1, part [5]). The importance of savings for tenants to become owners has been documented by Sheuya (2007) and Young (2010).
- If agents have insufficient savings, they remain tenants but may move as a tenant to a new, more suitable district (Fig. 1, part [7]), as tenants move within a city or between cities (Young, 2010).
- If owners do not want to move, they may enlarge their house to rent out additional rooms (Fig. 1, part [8]), thereby supplementing their income and savings.
- Tenants who do not move do nothing else.

2.3. Details on model implementation

2.3.1. The city environment

InformalCity is assumed to be on a plain with a total of 49 districts spread over a grid of seven by seven districts. The CBD is at the centre of these districts (Fig. 2). A user-specified number of plots are present in each district (see section 2.5 on calibration. One house can be built per plot. Houses are built in a stepwise process (three rooms, three rooms, three rooms, and one room) up to the maximum number of 10 rooms per house (section 2.5).

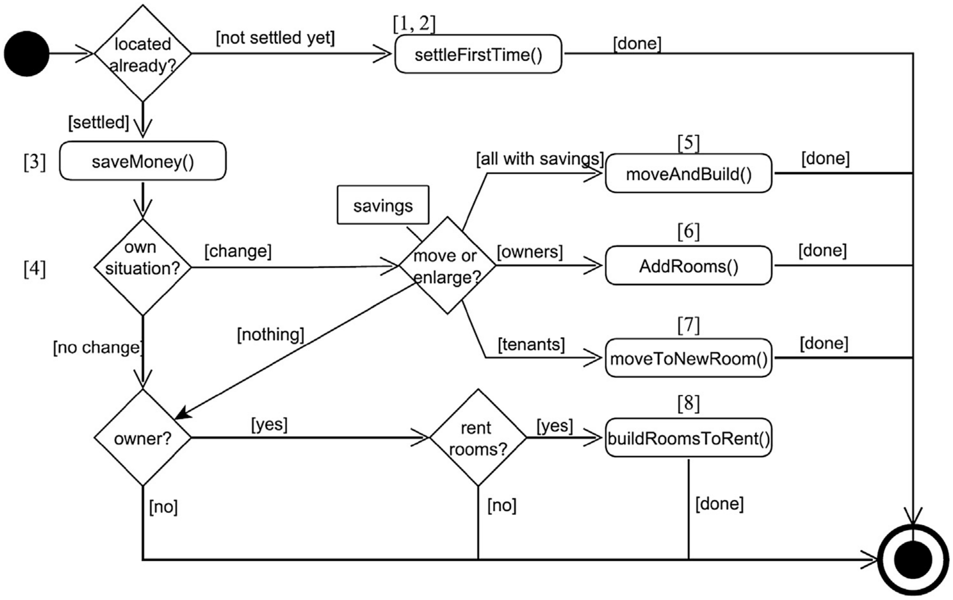

Fig. 1. Flow diagram of agents' decision making in one time-step based on UML. Note: The numbering refers to the explanation given in section 2.2.

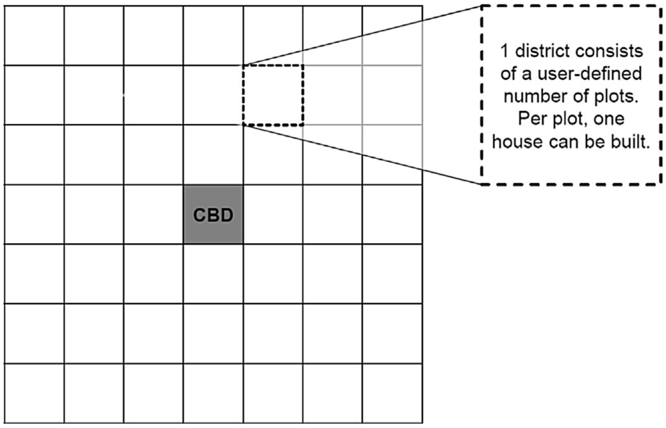

Fig. 2. The artificial city with the CBD in the middle of the grid.

2.3.2. Household agents

Household agents have the following attributes: tenure status (owner/tenant), income that can be used for savings during one year, total amount of savings, preferences regarding location choice (the quality of public infrastructure and attractiveness of the central business district – CBD), plot id of own home, number of occupied rooms, and, if the agent is an owner and a landlord, list of rented rooms. Households' initial savings are initialised with random numbers from 0 to 15 multiplied by their income. This income means the income after subtracting all living costs and lies between 0 and 1. It is initially assigned using a log-normal distribution (the logarithm has mean of −2 and standard deviation of 1), which represents a high share of low-income households. Income values smaller than 0 and larger than 1 are set to 0 and 1, respectively. Households belong to income classes of low, medium and high for incomes lower than 0.25, 0.75 and 1, respectively.

2.3.3. Infrastructure quality

In InformalCity, infrastructure quality is understood as the general quality of public infrastructure such as drinking water supply, electricity, and public roads. The type of infrastructure is not specified in the model. Infrastructure quality depends on housing density and can be enhanced by urban upgrading. It is assumed that the relationship between infrastructure quality and density is asymptotic: At first, the relationship is robust against increasing density, but then decreases rapidly with growing household numbers above a predefined threshold. This threshold is set by the user of the model. In the model, infrastructure quality is computed per district, using equation (2) (see also Fig. 3):

$$\text{qualityInfrastructure} = -1/\text{Pi} \times \arctan(\text{density} - \text{threshold}) + 0.5 \qquad \text{(Equation 2)}$$

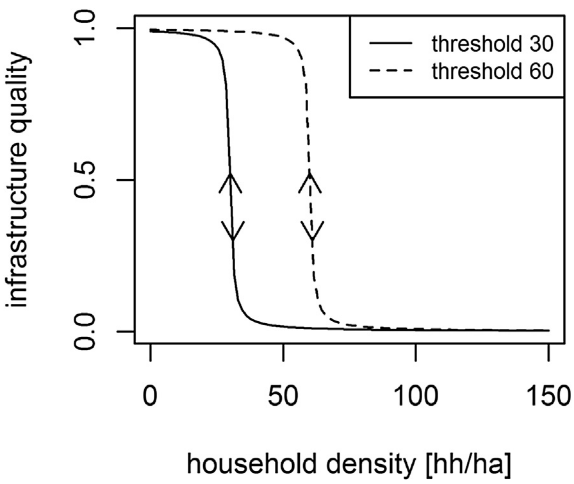

Fig. 3. Relationship of household density and infrastructure quality. The arrows indicate that this process is reversible.

where density: household density in households per hectare, computed per district;
threshold: threshold of household density defined by the user.

The critical threshold for a decline of infrastructure quality is an initial parameter that is set during the calibration. If the maintenance of urban upgrading programmes is included, infrastructure quality is preserved in districts where upgrading has been previously implemented. Without maintenance, the upgrading takes place in one time step and infrastructure quality again changes due to housing density during subsequent time steps.

2.4. *Configuration of urban upgrading*

Five different configuration parameters of urban upgrading programmes can be set by the user: maintenance, the scope of the upgrading, the selection of target districts, cost recovery and the timing of the upgrading. The following paragraphs summarise these configuration parameters, the options from which to choose, and their implementation.

- Maintenance covers the stability of infrastructure quality after upgrading: If maintenance is implemented, the infrastructure quality obtained through urban upgrading will be preserved for the remainder of the simulation run; otherwise, it can decline over time due to over-use depending on housing density.
- The scope of upgrading relates to the way limited financial resources are spread over the city: The upgrading efforts can be either concentrated on a few (here: 10%) districts while aiming at high infrastructure quality of 100% or spread over a larger number of districts (80%) while only slightly increasing infrastructure quality by 20% per district.
- The selection of target districts offers the possibility to steer the way districts are chosen for upgrading: Target districts can be selected randomly to represent community-based initiatives or low-quality districts can be upgraded with higher priority.
- Cost recovery from residents relates to the question of whether the residents of upgraded districts should be asked to financially contribute to the upgrading. Residents in upgraded districts may or may not have to pay a fee of 1 unit from their savings for the enhanced infrastructure.
- The timing of the upgrading, finally, refers to the start of the urban upgrading throughout the city's districts: Upgrading can be implemented either ‘early’, as soon as an infrastructure quality of less than 50% is detected in a district, or ‘late’, only when the majority of districts are affected by such low-quality infrastructure.

2.5. *Calibration and stochasticity*

The model parameters derived from empirical studies are summarised in Table 1. Due to the limited empirical basis, only a few other model parameters were determined. These include the initial number of households in relation to the number of plots per district (i.e., city size), the cost for building three rooms (which is the main unit of incremental building construction, section 2.3.1), and the threshold for decreasing infrastructure quality in the districts. Simulations were performed with a range of values for these parameters. This approach was used to examine the sensitivity of the model results to these parameter values and to calibrate the model accordingly.

Due to computation time, an exhaustive search for calibration values was performed using a limited number of 20,000 agents. The range of tested parameter settings is given in Table 2. All possible combinations of parameters within one set were analysed. The number of simulation runs performed is also given in Table 2. For the calibration, no upgrading programmes were included and the results were analysed after 20 simulation steps.

The calibration aimed to find parameter values such that population growth would occur in the outer districts, but available plots would not be exhausted after 20 simulation steps. The simulation runs indicated that a combination of 750 plots per district and 20,000 initial agents was the most appropriate. The runs furthermore showed that the parameter *cost for building three rooms* had differing results for the cost of 5 versus all other values. To keep the built-up rate of the outer districts low (approx. 25%), the *cost for building three rooms* was set to 10. Finally, the threshold for decreasing infrastructure quality was narrowed down to 30 and 60 households per hectare, which can be seen to represent different types or qualities of urban infrastructure that are more (60 hh/ha) or less (30 hh/ha) robust against rising population density. Using two density thresholds makes it possible to check if the upgrading configurations have different effects for different infrastructures. The parameter values applied are highlighted in Table 2.

Three different sources of stochasticity are present in InformalCity: First, household agents are initialised by drawing from distributions (preference for infrastructure quality, preference for distance to the CBD, initial amount of savings, and income). Second, the decision making of household agents has stochastic elements, as 10% of the agents consider their own situation each time-step and occupy one to three rooms after moving. Third, stochasticity enters the implementation of upgrading via the random selection of target districts. To explore the effects of these sources, ten random seeds were tested for each combination of parameters (Table 2).

2.6. *Model output*

During the runtime, users can inspect the simulation results in the format of time series and grids or analyse the results stored on disk. The effects of urban upgrading are analysed regarding three topics, i.e., changing infrastructure quality, housing development and income segregation. These topics were chosen to evaluate the impacts of urban upgrading interventions on the built environment and the population distribution within the city.

In InformalCity, infrastructure quality is linked with housing density and is bound to decrease because of increasing population.

Table 1
Model parameters derived from empirical studies.

Model parameter	Justification
Plot size = 250 m^2	250 m^2 is the average size of plots in typical SSA informal settlements, derived from empirical data for Dar es Salaam, Tanzania (ITC, 2014)
Maximum number of rooms per house = 10	The mean value of the maximum number of rooms given in Sheuya (2004, p 103)
Annual population growth rate = 5%	Many SSA cities have grown by approximately 5% in recent decades (UN Habitat, 2009)
Income distribution follows a log-normal distribution	This distribution shall represent the high share of urban poverty in SSA (UN Habitat, 2009)

Table 2
Range of parameter values tested during calibration.

Parameter	Values
Initial household number	**20,000**
Plots per district	500; **750**; 1000
Costs for building three rooms	5; **10**; 15; 20
Threshold for decreasing infrastructure quality [households/ha]	10; **30; 60**; 100
Number of runs performed	48 × 10 random seeds

Note: Parameter values marked in bold were used for further simulation runs.

Still, the effects of the different configuration parameters of urban upgrading (e.g., scope of upgrading) on infrastructure quality are not straightforward and result from model dynamics, so inspecting changes in infrastructure quality is necessary and fruitful for understanding simulation results.

Infrastructure quality is described using the mean of infrastructure quality across all districts as well as the Gini coefficient for infrastructure quality. The Gini coefficient is a measure of the inequality of a distribution. The coefficient is 0 for perfect equality (e.g., if all districts have the same infrastructure quality) and approaches 1 for an unequal distribution (e.g., if the CBD has high infrastructure quality, and all other districts have an infrastructure quality of 0). Likewise, housing development is characterised by the mean built-up rate as well as the Gini coefficient for built-up rates. Built-up rates represent the sealing of land and are calculated as the number of built rooms divided by the maximum number of rooms (10 rooms per house/plot), whereas housing density refers to the number of households living on a hectare of land. Income segregation is quantified with the Gini coefficient, describing the distribution of low-income households across districts. To describe spatial patterns within the city, correlations are computed between the distance to the CBD and the mean infrastructure quality, the built-up rate and income in a given distance, respectively. Finally, the total number of households and the proportion of tenants among all households are used to describe simulation outcomes. To provide a structured analysis, all output parameters are analysed for all simulation runs.

3. Results

3.1. *Growth dynamics without urban upgrading*

In the simulation runs for population density thresholds of 30 and 60 households per hectare without upgrading, the patterns of residential mobility did not change qualitatively. Thus, in the following, only the results for a threshold of 30 households per hectare are given, until otherwise stated. Simulation runs for 20 time steps with a population growth rate of 5% had the population increase to approx. 50,500 agents (Fig. 4a and b).

3.1.1. *Infrastructure quality*

The mean infrastructure quality decreases steadily to approximately 0.6, the mean value for all districts in time step 20, whereas the Gini coefficient for infrastructure quality increases, indicating that infrastructure quality becomes more unevenly distributed within the city (Fig. 4a and b). Moreover, infrastructure quality is highest in the outer districts and lowest in the centre after 20 time steps (see Fig. 5 middle row and Movie 2, respectively), as indicated by a positive correlation with distance from the CBD.

3.1.2. *Housing development*

The mean built-up rate increases steadily, and its Gini coefficient remains rather stable at a high level (Fig. 4a and b), because the built-up rate is unevenly distributed, with the most sealed areas in the city centre (correlation coefficient with distance to the CBD of approximately −0.9). Housing density, quantified as households per hectares, is closely related and thus also increases and is highest in the centre (Fig. 5 upper row, Movie 1).

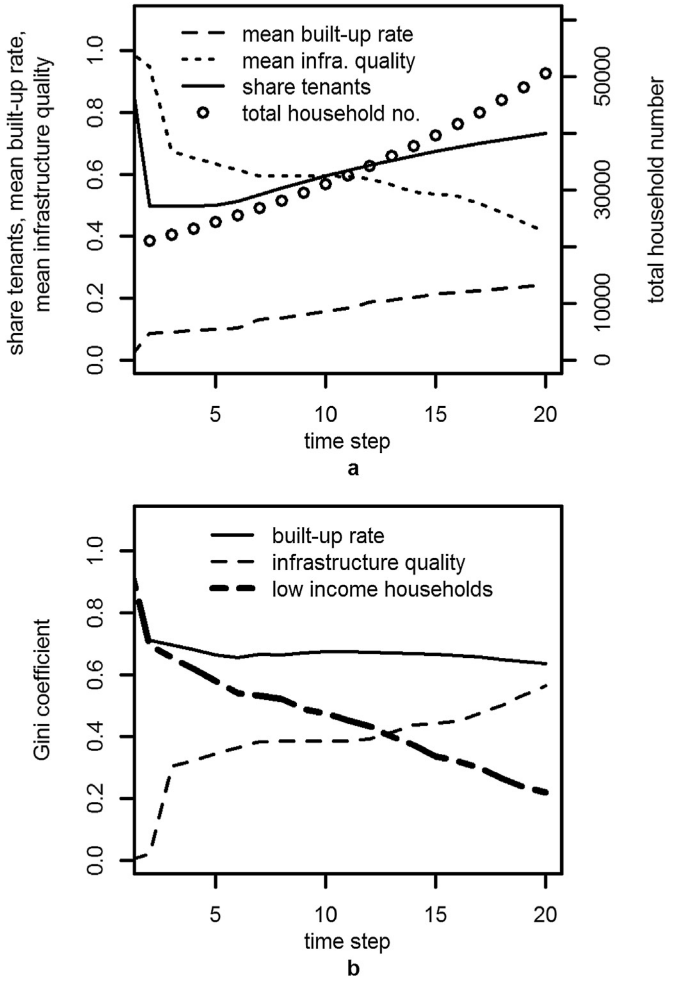

Fig. 4. Selected results of one example run for urban growth dynamics over time without urban upgrading: mean built-up rate, mean infrastructure quality, share of tenants, total number of households (4a), and Gini coefficients for the built-up rate, infrastructure quality and low-income households (4b).

3.1.3. *Income segregation*

As for the spatial distribution of household income, the Gini coefficient for low-income households decreases over time (Fig. 4b). Thus, low-income households are spread more evenly across the city. At the beginning of the simulation, households having the highest income are mostly situated in the inner districts (Fig. 5 lower row, time step 5, and Movie 3), as indicated by a strong negative correlation with distance to the CBD. In later time steps,

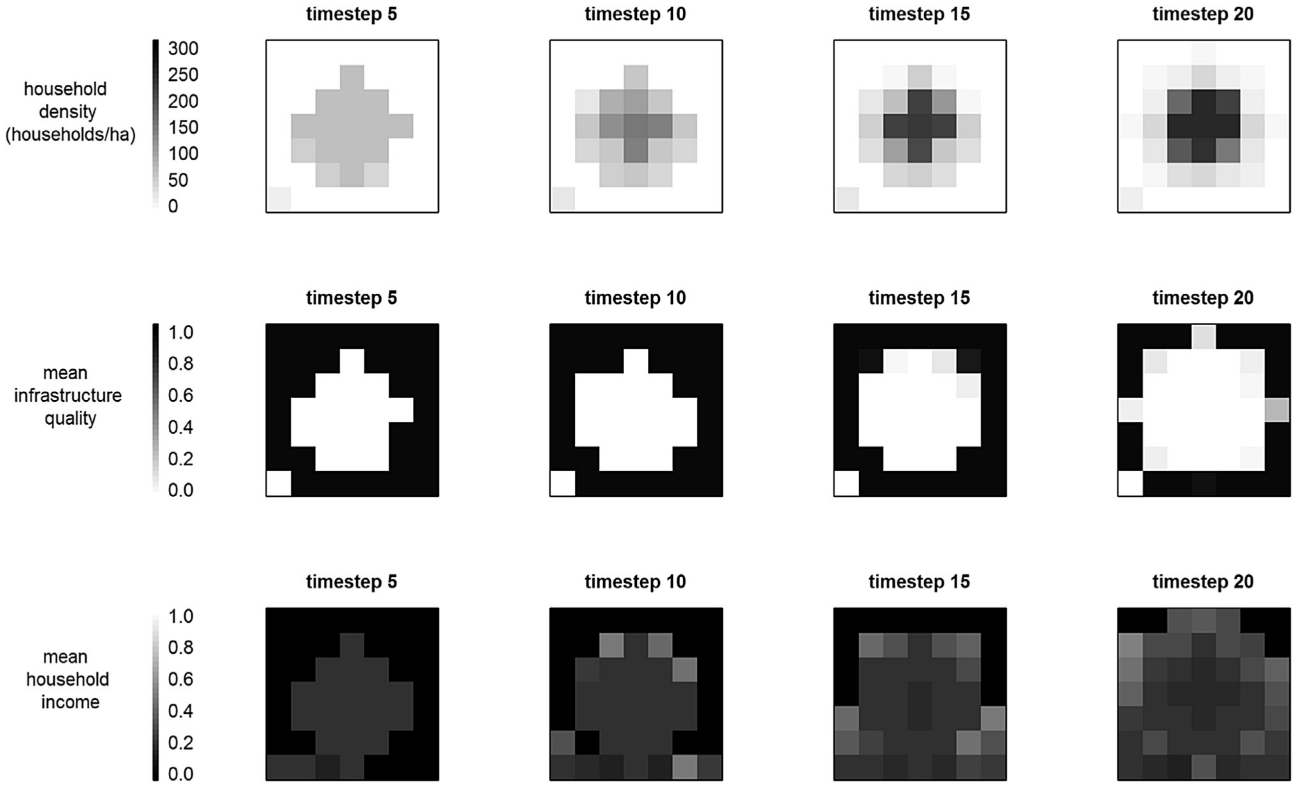

Fig. 5. Snapshots of selected output variables for one example run. In the electronic version of this article, animated results are given in movies 1 to 3.

spatial differences in household income level out, as indicated with the decreasing Gini coefficient (Fig. 4b). These dynamics are likely the effect of a high infrastructure quality at the beginning, leading to high-income households realising their preferences, i.e., high infrastructure quality and low distance to the CBD. In later time steps, high income households concentrate in a ring around the city centre (Fig. 5 lower row, time steps 10 to 20), where they are farther from the city centre but already in an area with higher infrastructure quality than in the centre. Interestingly, infrastructure quality is highest even farther from the city centre, but high-income households value these districts less because of their larger distance to the city centre.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2015.12.009

(Stills of these animated simulation results: see Fig. 5 top – middle – bottom)

3.2. *Effects of urban upgrading*

All scenario runs for investigating the effects of urban upgrading had identical initial values for the number of agents (20,000), plots per district (750), costs for building three rooms (10) and annual population growth rate (5%). The threshold for decreasing infrastructure quality was set to either 30 or 60 households per hectare to represent different types of physical infrastructure. Again, a log-normal income distribution was chosen to account for a high share of low-income households. All urban upgrading options described in section 2.4 were included in the scenario runs, and all combinations of options were run with 10 random seeds, yielding 640 simulation runs in total.

Wilcoxon rank-sum tests were performed to check for significant differences in the scenario outcomes, which were not normally distributed. Fig. 6 shows the boxplots for the main scenario results differentiated by the urban upgrading options and gives the results of the statistical tests. The options regarding cost recovery, the selection of target districts and random seeds did not have a significant influence on the results and were thus omitted from Fig. 6. Only effects with a significance level of $p < 0.05$ are reported.

3.2.1. *Infrastructure quality*

Fig. 6 indicates that mean infrastructure quality is significantly affected by maintenance, timing and the scope of upgrading efforts. In detail, implemented maintenance leads to higher mean infrastructure quality (Fig. 6a). Early timing for upgrading also leads to higher infrastructure quality (Fig. 6b). Finally, the scope of many districts with low improvements induces a higher mean infrastructure quality (for a threshold of 30 households per hectare, Fig. 6c). Likewise, the Gini coefficient for the distribution of infrastructure quality within the city is significantly influenced by the same options. These effects are also visible in lower Gini coefficient values, i.e., more equal distributions of infrastructure quality (Fig. 6d, e, f). However, the effects of scope on the Gini coefficient are smaller than for the other two options.

The sizes of the boxplots of Fig. 6a to f indicate that certain combinations of urban upgrading interventions have the potential to substantially increase infrastructure quality: combining early timing, maintenance and a distribution of upgrading to many districts with low quality increases the mean infrastructure quality from 0.6 (for all simulation runs combined) to 0.8. Simultaneously, the Gini coefficient for infrastructure quality decreases from 0.4 (all simulations) to 0.2 (early timing, maintenance, many districts with low quality), indicating greater equality.

3.2.2. *Housing development*

The mean built-up rate for the whole city is significantly influenced by both maintenance (Fig. 6g) and timing (Fig. 6h). However,

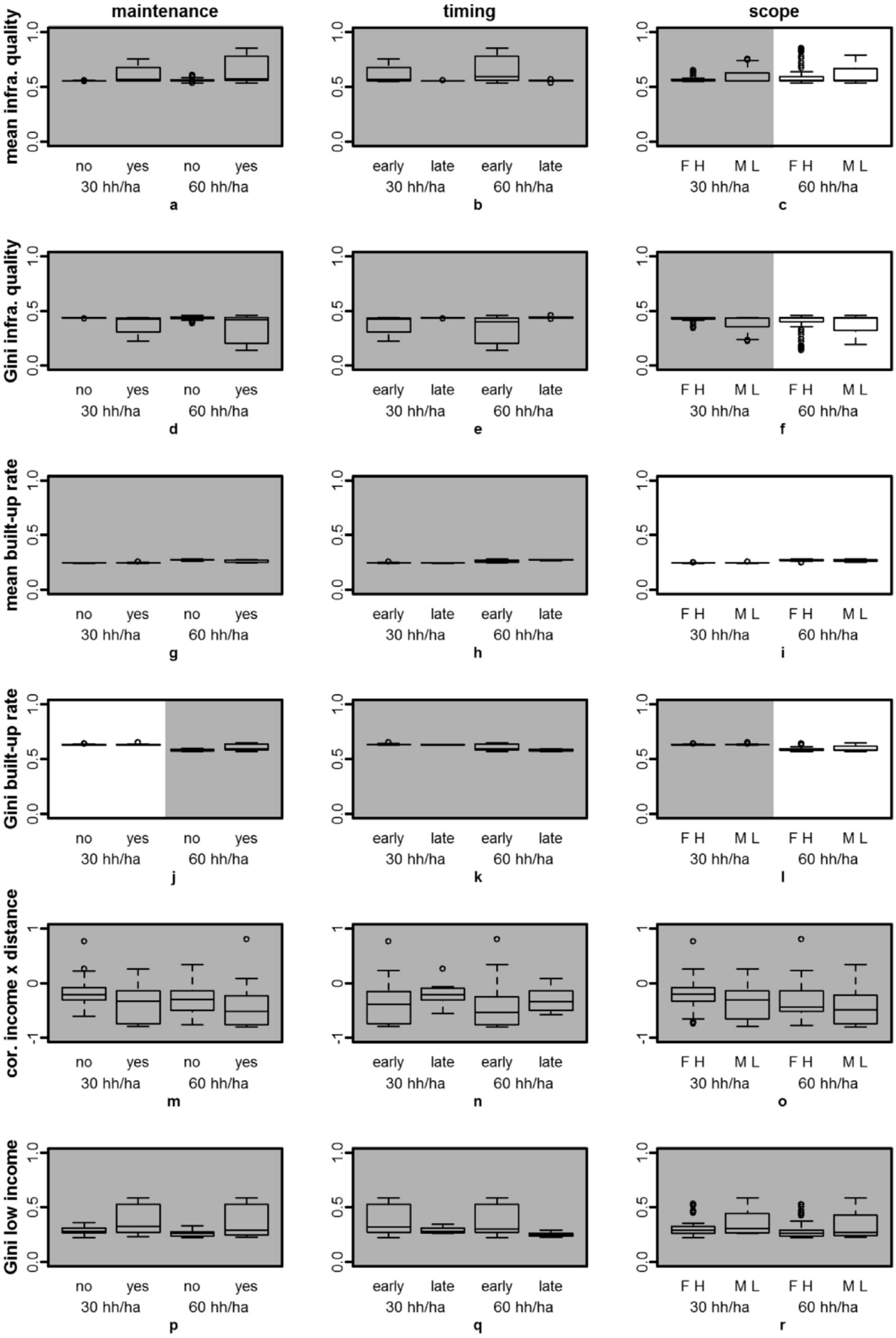

Fig. 6. Boxplots showing the effects of three urban upgrading options (maintenance (no/yes), timing (early/late) and scope (FH (few districts with higher quality infrastructure)/ML (many districts lower quality infrastructure))) on selected indicators for two thresholds of density decrease (30 and 60 households per hectare). A grey background indicates statistically significant differences between the two options for the respective threshold using the Wilcoxon rank-sum tests with $p < 0.05$.

both options show opposite effects for the different infrastructure types. While implemented maintenance and early timing both increase the mean built-up rate for a threshold of 30 households per hectare, the opposite holds for a threshold of 60. Although both effects are statistically significant, the differences between these options are rather small: approximately 0.1% for a threshold of 30 for both maintenance and timing, and 0.3% and 0.5% for a threshold of 60 households per hectare for maintenance and timing, respectively.

By contrast, the Gini coefficient for the distribution of the built-up area in the city is affected in the same direction for both thresholds (30 and 60 households per hectare) by timing (Fig. 6k). The scope of upgrading affects the Gini coefficient for the threshold of 30 only (Fig. 6l), and, on the contrary, maintenance affect the Gini coefficient for the threshold of 60 only (Fig. 6j). For both scope and maintenance, the effects are in the same direction for both thresholds even though one threshold remains statistically insignificant. These findings imply that through the early implementation of upgrading, maintenance, and/or aiming at many districts, higher inequality in terms of built-up areas may result. As with the mean built-up rate, differences in the Gini coefficients for the different scenarios are rather small (maximum of approximately 0.01).

3.2.3. Income segregation

Whereas the mean built-up rate is not strongly influenced by urban upgrading, the effect of upgrading on the spatial distribution of households is remarkable. This effect is visible in the correlation of mean household income with distance to the CBD: Maintenance (Fig. 6m), early timing (Fig. 6n) and a distribution of relatively low quality upgrades over many districts (Fig. 6o) lead to negative (between −0.3 and −0.4) correlations, whereas for the opposite options (i.e., upgrading fewer districts to a higher quality, late timing and no maintenance), the correlation is only around −0.2. Thus, maintenance, early timing and choosing many districts with lower quality lead to a stronger concentration of households with higher incomes closer to the city centre. This stronger concentration is also reflected in higher Gini coefficients for the distribution of low-income households for those options (Fig. 6p to r).

4. Discussion

Few empirical findings exist regarding the effects of urban upgrading, especially over long time periods. Those that are available suggest that urban upgrading is likely more successful if the general population density is not too high, because space is needed for the upgrading interventions, and if the share of tenants is low (Satterthwaite, 2012). Our simulation study adds more theoretical results to the ongoing discussion.

4.1. Effects of the different upgrading options

Based on our simulations, maintenance has strong effects on the outcomes of upgrading interventions, such as a higher mean infrastructure quality, but also leads to more social segregation for low-income households. Thus, the often-criticised lack of infrastructure maintenance (Satterthwaite, 2012) has both disadvantages as well as advantages for the success of urban upgrading – if urban upgrading is assessed by taking social aspects into account, rather than focussing only on increasing infrastructure quality. Other aspects such as community participation during maintenance (Patel, 2013) could possibly reduce impacts on segregation but were not investigated in this study.

Choices regarding the scope of upgrading, specifically comprehensive upgrading programmes with high costs per targeted community versus upgrading schemes trying to reach a large number of settlements but with a lower standard of improvement, also have distinct effects on the outcomes. In our simulations, the latter approach increases the social segregation of low-income households, because high-income households tend to concentrate in the city centre. This effect might be attributed to a relatively higher mean infrastructure quality in the city centre, which attracts high-income households.

The selection of target districts is affected by the initiators of the interventions: for community-based efforts, upgrading does not necessarily target the settlements with lowest quality, as may be the case for top-down upgrading programmes. In this study, the selection of target districts is not crucial for the immediate indicators of success of upgrading, such as the mean infrastructure quality or less income segregation.

Not surprisingly, the timing of the upgrading has significant effects on all variables analysed here, with early timing (i.e., as soon as the first district shows an infrastructure quality below 50%) leading to higher mean infrastructure quality, a more equal distribution of infrastructure quality, higher and more unequal built-up rates as well as stronger income segregation because of a higher concentration of high-income households in the centre. Timing also has contradictory effects on the aims of urban upgrading such as high infrastructure quality but low income segregation.

Currently, cost recovery of the targeted districts does not have a significant influence on any of the simulation results. This result is very likely due to the current way cost recovery is implemented in the model without any advance notice. This means that household agents are forced to spend some of their savings for the upgrading and have no means to avoid the costs. In reality, households may anticipate rising costs and might choose to avoid them by moving to another district. This topic could be explored in future studies.

4.2. The “ideal” urban upgrading scheme?

Urban upgrading interventions can have different targets. An obvious target is an increase in infrastructure quality, but urban upgrading can also include aspects such as decreasing or inhibiting income segregation or development goals such as limiting maximum housing density. This study suggests that the different options of urban upgrading analysed here do not achieve all objectives of inclusive urban development simultaneously. For example, while the scope of upgrading efforts is relevant for a target such as low income segregation, it showed only slight effects for mean infrastructure quality. What is more, one upgrading intervention might have positive effects on one target but negative effects on another. For example, maintaining infrastructure positively influences mean infrastructure quality but also fosters income segregation. In fact, this trade-off between contesting objectives is common for planning, in which wicked problems are very prominent (Schönwandt et al., 2013). Simulation models such as InformalCity can foster system understanding (Augustijn-Beckers et al., 2011) and draw attention to such unintended effects and trade-offs between contesting objectives. Thus, simulation models can serve as decision support tools to conduct thought experiments before implementing policies (Patel et al., 2012b) such as urban upgrading. It might even be helpful to involve stakeholders in the modelling process itself (Voinov and Bousquet, 2010) and thereby engage residents in urban upgrading (Jenkins et al., 2010) to better appreciate the wickedness entailed by upgrading packages.

First, it is impossible to suggest a general “ideal” urban upgrading scheme that achieves all possible social objectives, because the effectiveness of the different options very much depends on the exact targets that should be fulfilled with the upgrading scheme. Second, it is unlikely that a single set of options can unambiguously achieve more than one target. By contrast, the negative effects of one option might have to be counter-balanced with another design option. For example, maintenance's negative impact on income segregation (i.e., higher segregation) could be balanced by focussing upgrading on fewer districts that are selected for their low infrastructure quality. Furthermore, the simulation results suggest that the type of infrastructure (in the sense of dependency on household density) mostly does not influence the general pattern of influence, but, in some cases, does influence the strength of the impacts.

A take-home message for policy makers is the need to critically examine the need and scope for strong countervailing measures to combat certain undesirable side-effects of complex settlement upgrading processes. These multi-dimensional upgrading projects and even their ensuing maintenance programmes can give rise to unexpected and perhaps unwanted side effects that may be contrary to official policy rhetoric and project objectives. Over-simplification of policy aims and project design should be avoided as both the political and the costs to the population can be high.

4.3. Assumptions made in the model

InformalCity is an abstract simulation model that was inspired by empirical findings but is primarily theoretical. Therefore, many of the assumptions made for the model concept can be questioned. For example, the sole preferences entering the utility maximisation in this model are distance to the CBD and infrastructure quality. While both were the most relevant factors mentioned for an informal settlement in Dar es Salaam (Young, 2010, p. 59), it is conceivable that the distance to the CBD might not be so relevant for informal settlements that themselves have substantial informal employment opportunities. Furthermore, in InformalCity preferences for distance to the CBD and infrastructure quality are independent from each other, i.e., rich and poor inhabitants have the same (normally distributed) preferences. However, in reality, the urban poor and rich could also have different preferences. Regarding infrastructure quality, the shape of the curve on decreasing quality with increasing housing density builds upon a threshold or tipping point assumption and thus is rather dramatic. One could well argue that a gentler decline in infrastructure quality is more appropriate. Finally, tenants have the possibility to become owners if they have enough savings. The amount of savings that are possible over the years leaves room for debate and should be tested in further versions of the model. However, both during the simulation and in reality, many tenants do not turn into owners but rather stay tenants, whereas owners incrementally enlarge their houses (Sheuya, 2007).

4.4. Limitations of the study

This abstract model on informal settlement development and urban upgrading has been informed by empirical data on population dynamics in SSA in general (e.g., UN Habitat 2009) and several empirical case studies in particular (Sheuya, 2004; Sliuzas, 2004; Young and Flacke, 2010). However, no specific empirical data, neither regarding population dynamics or regarding the effects of urban upgrading as implemented in this model, are available to validate the results. For such a validation with independent empirical data, one would need spatially explicit time series data on population development (both absolute numbers as well as for income groups) and infrastructure. Although censuses are being conducted in several countries in SSA, the data are, especially regarding details on intra-urban socio-economic conditions, rather poor, for instance, lacking comparability over time due to changing survey methods or changing delineations of inner-city districts. Although attempts are being made to improve population estimates across the African continent (Linard et al., 2012), they do not address intra urban data and socio-economic status. In fact, the lack of empirical data on the effects of urban upgrading was the main motivation for this modelling study in the first place. Therefore, no output validation using independent empirical data (Schmolke et al., 2010) was possible for this study.

Conceptual model validation (e.g., Sargent, 2013), i.e., checking if the model representation of the real world system is reasonable for the purpose of the model, was possible. This was done using conference presentations (Schwarz and Flacke, 2013) in front of urban planning experts with a focus on developing countries. While the general approach was accepted, several possible model extensions were suggested.

4.5. Possible model extensions

First, the implementation of urban upgrading options can be enhanced for further investigation. As mentioned above, cost recovery could be improved for future analysis, possibly also taking into account participation during maintenance as a way for poorer households to contribute. In addition to the current focus on physical infrastructures, changes in legislation and the institutional framework, such as land tenure (Satterthwaite, 2012) could be included as a next step. Furthermore, the upgrading of infrastructure could also be taken in a stepwise process (“progressive improvement”, Abbott, 2002a; Choguill, 1999). The model could also be extended to analyse the effects of urban upgrading with variable household income levels to analyse effects of urban upgrading on poverty alleviation. The impact of site quality is another issue that could be examined by including provisions for occasional hazards that can damage infrastructure as well as private houses, such as floods or landslides, and therefore impact infrastructure quality, household savings, household health through water-related diseases and possible income segregation. Finally, due to the abstract modelling approach, no concrete interventions or targeted infrastructures are named. Therefore, the effect of integrating different sectors in urban upgrading interventions (Abbott, 2002b) cannot be analysed with the current approach. Thus, a different approach to extend the model could be to use this theoretical model as a basis for an empirical case study and include concrete interventions or infrastructures.

Second, the model could be adapted to distinguish between formal and informal settlements. Currently, InformalCity is focused on informal settlements, as the urban development in SSA is mainly informal. To model formal development in SSA, other actors/agents need to be taken into account, as formal development is much more influenced by planning decisions, and by potential investors. Interaction between formal and informal settlements should also be taken into consideration when extending the model. The formal sector caters primarily to higher income groups, who are better able to fend for themselves and gain access to serviced land. Infrastructure provision in informal settlements can lead to gentrification processes in a highly constrained formal land market, making it worthwhile to study formal settlements and informal settlements simultaneously.

Third, InformalCity could also be used to model the turning of informal settlements into slums. For example, no commercial slum development by non-resident landlords is currently represented in the model, calling for the addition of another type of agent. To model the development of slums, clear indicators on how to monitor slum development are needed. InformalCity offers variables such as household density, built-up density and infrastructure quality as variables that could be used as starting points for such an exercise.

Fourth, the model could be adjusted to cover contexts other than SSA. Cities in the global South commonly have informal settlements and can be subject to urban upgrading. However, cities in other contexts may follow other housing development patterns in some respects. For example, InformalCity currently does not allow for a very large housing density, because it encompasses single-storey Swahili-type houses. In many cities, e.g., Mumbai, Rio de Janeiro, and Carracas, adding another floor to the house would also be an option for owners, so this behavioural rule would need to be implemented. Furthermore, the issue of homelessness and street dwellers could also be relevant in many contexts.

5. Conclusions

This paper introduced the agent-based model InformalCity to investigate the effects of different urban upgrading options on infrastructure quality and income segregation in a hypothetical city. Its aim was to analyse the effect of different upgrading designs for the entire city and, in this way, to generate system understanding and tentative information for policy makers. To this end, InformalCity models residential mobility by tenants and homeowners who take into account the distance to the CBD as well as the infrastructure quality in their decisions on where to live. Different options of urban upgrading were explored in scenarios to analyse their effects on various indicators, such as the mean infrastructure quality and income segregation. Systematic simulation experiments indicate that the timing of the upgrading interventions, the scope of upgrading (few or many districts) and maintenance have distinct effects on various measures to evaluate outcomes, such as the mean infrastructure quality, sealing rates and income segregation. What is more, these effects are mostly independent from the infrastructure type, simulated here by linking different thresholds for decreasing infrastructure quality to household density.

The options analysed in this study do not show uniform effects on all potential aims that could be pursued through upgrading. On the contrary, favouring one option (for example maintenance) might have a strong positive impact on one target (mean infrastructure quality) but a negative impact on another target (reduction of income segregation). Thus, these simulation experiments are very valuable for policy makers, because they first show the strong need to clarify the exact aim(s) of any urban upgrading intervention. Second, the results highlight the hidden wickednesses of urban upgrading and their entailed trade-offs. If the aims of upgrading are to be balanced then knowledge of such effects is essential for conceptualising the upgrading interventions. Simulation experiments such as those in this study may be valuable for this purpose, because they provide a first indication of possible results if systematic empirical research is missing, as our literature search revealed is often the case. In short, such simulation experiments are relatively easy to accomplish, generate system understanding and might foster critical reflection about policy instruments. Thus, they can serve as decision support tools that generate thought experiments about the intended and unintended effects of urban upgrading policies, which are receiving increasing importance in the cities of the global South.

Future research on urban development in general and urban simulation models in particular should shift more attention to informal settlements and urban upgrading, because this has a high societal relevance when considering both absolute population numbers and population growth rates. Simulation experiments can assist here as decision support tools, but should ideally be accompanied by systematic empirical research to substantiate or refine the findings of simulations. Meta-analysis of the evaluation of urban upgrading is dearly needed to cross-check the simulation results.

Software availability

The InformalCity model is implemented in Repast Simphony Java 2.1. A detailed model description is given in documentation following the ODD + D protocol (Müller et al., 2013), which is published together with the model on the website openabm.org (https://www.openabm.org/model/4276/version/2/view) and can be downloaded free of charge.

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