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BUILDING THE CITY UNDER FINANCIAL FRICTIONS

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Abstract

The construction process of many residential buildings in African cities proceeds very slowly and may take over a decade. I document this phenomenon in a newly assembled dataset containing information on the construction duration of individual buildings in Nairobi. To explain the stylized facts and understand their consequences, I develop a heterogeneous agent model with financial frictions in which households engage in the construction of individual housing units. The model is calibrated to match key characteristics of the housing market in Nairobi. Counterfactual simulations show that improvements in credit provision can (a) substantially speed up the expansion of the aggregate housing stock which facilitates rural-urban migration, and (b) increase the city's density by enabling the construction of taller buildings. The model also predicts that in the absence of reliable savings accounts, investments in incomplete structures emerge as an alternative savings vehicle.

Keywords: Urban growth, Housing investment, Financial frictions.
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1 Introduction

Unfinished buildings are common in the cityscape of many low-income African countries. The construction process from commencement to completion of simple structures can take decades. These observations raise substantial concerns regarding the efficiency of the allocation of capital and its consequences for city development. Rapidly expanding populations in cities are in a desperate need for housing. The efficiency with which housing is produced and supplied is therefore a vital element of an economy's development path. Yet the economic literature has paid little attention to causes and consequences of slow construction processes and to the preponderance of unfinished construction projects in African cities.

In this paper, I hand-collect detailed data from satellite images covering the 2009-2018 period to provide formal evidence for the slow construction process in Africa. Motivated by this evidence, I introduce an endogenous house construction process into a model of heterogeneous agents and borrowing constraints. Households can initiate construction projects which can be used to meet their own housing needs and can be rented out to others to generate a stream of income. Housing construction requires determination of the size of the building, investment in the foundation and investments in the main part of the structure. The latter part can be implemented over an arbitrary number of periods. There are no technological constraints on the speed of construction. The duration of construction depends only on the households' optimal decisions, which, in turn, are constrained by the availability of funds. Households have strong incentives to complete construction projects as soon as possible because they are income-generating assets. However, in equilibrium the construction processes of individual projects proceed slowly and may take many years.

This outcome emerges because imperfections in financial markets and contracting institutions impose tight borrowing constraints. The large investment required to construct a building exceeds the per period income of most households, however due to the borrowing constraints households cannot finance the construction by debt, so they have to rely on their own savings. In this context, households who have sufficient funds to purchase land start construction, but the process may evolve slowly depending on the dynamic evolution of their income. Taking into account the expected slow pace of construction, households optimally choose to build structures with fewer stories, which leads to negative aggregate implications for city structure and density.

Motivated by the applied microfinance literature, I also explore the role of negative real returns on financial savings. In the presence of negative real returns on financial savings, investments in unfinished buildings emerge as a safe alternative form of preserving the value of money.

I calibrate this model to match key features of the housing market in Nairobi. Then, I employ the calibrated model to conduct counterfactual simulations. I compare an economy with a financially developed system, where moderate levels of collateralized loans are available, to an economy without borrowing. In the long run equilibrium the average building has 50% more stories in the economy with borrowing, compared to the one without. There are also substantial differences between the two economies during the transition phase. It takes less than one third of the time from the economy with collateralized borrowing to reach the half-life of the economy without borrowing, in terms of constructed housing stock.

A large body of economic literature argues that incomes are higher in urban areas and urbanization can improve living standards in developing countries (Gollin, Lagakos, and Waugh, 2013). However, urbanization depends on the capacity of cities to provide proper living conditions to potential migrants from rural areas. According to a report by World Bank (2017) Kenya experiences a rapid urbanization and a large deficit of housing. Furthermore, the urban economics literature has highlighted the role of city sprawl on commuting time (Harari, 2020). The results of the current paper show that policies oriented towards the improvement of credit for residential construction purposes can substantially increase the speed of housing provision, and hence the transition from rural to urban economy. Moreover, it can lead to an equilibrium with taller buildings, which can reduce the city's sprawl and improve its productivity.

This paper contributes to the rapidly growing literature on the economics of cities in developing countries. Several recent contributions in this area that use quantitative spatial models to study the role of policy interventions in the development of housing include Henderson, Regan, and Venables (2021), Sturm, Takeda, and Venables (2021) and Gechter and Tsivanidis (2022). Henderson et al. (2021) use a model with slums and formal housing to quantify the role of land titling rights on the development of the city. Their paper features neither heterogeneity among households nor are there financial frictions. In the context of cities in developing countries, borrowing constraints are introduced in some recent papers. Michaels, Nigmatulina, Rauch, Regan, Baruah, and Dahlstrand (2021) assume that a fraction of owners are financially constrained and impose that they cannot develop high quality housing.[1] In my setting this outcome emerges endogenously. Moreover, that paper assumes that owners should complete the construction process in one period. In Cavalcanti, Da Mata, and Santos (2019) households face borrowing constraints but the entire housing stock is owned by large real estate companies which do not do not face financial frictions. Such an environment does not allow to capture the effects discussed in the current paper. Garriga, Hedlund, Tang, and Wang (2022) develop a model in which agents can own houses (for personal use only) to study urbanization dynamics in the context of China. That paper follows the tradition in the macroeconomic literature, in which ownership appears in the form of shares in the aggregate housing stock.[2] According to this modeling approach, unfinished buildings cannot exist because there are no individual buildings and incremental investments instantaneously expand the aggregate housing stock. I contribute to this literature by proposing a more granular approach for modeling the housing construction process, and show that in this environment

[1]In that model there is no height dimension but there is a quality dimension. Both concepts are similar from the modeling point of view.

[2]There is a larger body of literature considering the role of housing in models with heterogeneous agents in the context of the US economy. For some recent examples see Favilukis and Van Nieuwerburgh (2021); Favilukis, Mabille, and van Nieuwerburgh (2019); Kaplan, Mitman, and Violante (2020); Garriga and Hedlund (2020).

financial frictions have quantitatively very large effects on the development of cities.[3]

In the context of advanced countries and China, the existing modeling approach may be appropriate because it allows to avoid additional layers of complication and it may be a reasonable approximation of reality, given that in these countries construction is conducted by large enterprises with access to finance. However, modeling house construction as a household decision problem is more appropriate in the context of many African cities, where households individually engage in construction. The importance of individuals in the process of house construction is also recognized by economists and policymakers. For example, Romer (2012) and Angel (2012) argue that, given the institutional constraints in those countries, authorities should lay out basic infrastructure on the fringes of cities and allow people to build their own homes. Although I do not have data on the fraction of houses constructed by individuals, from the World Bank report on the housing market market in Kenya we learn that even those who are able to secure credit typically engage in self-construction (World Bank, 2017). Another strong argument in favor of modeling house construction as a household decision problem comes from recent developments in the macroeconomic literature. Over the last decade there was a rapid expansion of studies which model entrepreneurial activity in the spirit of Lucas (1978). From the point of view of this literature, households' direct involvement in the construction process can be viewed as a form of entrepreneurial activity. In this direction my paper shares similarities with Buera, Kaboski, and Shin (2011) and Buera and Shin (2013), who develop models of entrepreneurial activity with borrowing constraints, to demonstrate how financial frictions affect both the long run equilibrium allocations and the transitional dynamics. Relatedly, I am concerned with the implications of financial frictions faced by individual house builders for the speed of the housing stock expansion and the long run density of the city.

There is a growing empirical literature studying cities in developing countries. Some of those papers have proposed novel methodologies for using satellite images to overcome data limitations (see, for instance, Donaldson and Storeygard, 2016; Marx, Stoker, and Suri, 2019; Dingel, Miscio, and Davis, 2021; Harari and Wong, 2021). In this paper I use satellite images to document a new stylized fact that is very prevalent in developing countries and has important implications but has received little attention in the economic literature.

The rest of the paper is organized as follows: Section 2 presents my hand-collected data from satellite images and shows that the construction process of many buildings in Nairobi evolves very slowly. Section 3 presents the theoretical model. Section 4 calibrates the model and conducts counterfactual analysis to quantify the importance of financial friction on the transition process and on the steady state. The last section provides some concluding remarks.

[3] There is a large macroeconomic literature that imposes exogenous construction lags on the capital accumulation process (Kydland and Prescott, 1982). In this literature, it takes several periods until investments are converted into productive capital. In the current paper, I propose a framework in which construction lags emerge endogenously.

2 Motivating facts

In this section I provide some information on the state of the buildings and the construction process in Nairobi. The construction of most buildings proceeds very slowly in African cities; however, there are no official data sources which can allow researchers to document these patterns.

2.1 Data construction

Figure A1 provides an example of a building under construction in Sunton neighborhood in Nairobi. The image is taken from Google's Street View feature and was made in February 2018. Sunton is a neighborhood on the outskirts of Nairobi and according to satellite images it almost did not have built area before 2003 (the earliest year for which satellite images are available for that area). Sunton is not a slum neighborhood and buildings from corrugated iron sheets are extremely rare.[4] The vast majority of structures are made from volcanic stone, concrete and iron rods (similar to the one in Figure A1). The construction of a building of the size displayed in that figure in a normal environment takes approximately a year (the corresponding US figures are discussed at the end of this subsection) and it could be that this image was made exactly during that interval. However, the fact that the bottom stories are occupied by residents may suggests that the building might have been in this state for a long period of time. This conjecture can be confirmed with the help of satellite images. In Figure A3, I use historical images from Google Earth to determine the approximate date of the commencement of this construction project. For Nairobi, Google Earth provides satellite images taken each year starting from 2009. I identify the locations of buildings and track the history of land plots on which current buildings are located. Panel (a) of Figure A3 shows an image from March 2009 of the land plot on which the building discussed above is located (red arrow). Panel (b) shows another image from October 2009 of the same area. We can observe that some walls had been erected. Thus, we can conclude that the construction started between March and October of 2009. Panel (c) shows that in January 2010 the ground floor is partly covered. Panel (d) presents an image from December 2017 (this date is very close to the Street View date). This image confirms the observation from the Street View that the building is not finished because there are some walls inside the building but the last floor has no cover.

I apply the above described technique to the streets of Sunton neighborhood, for which Google Street View images are available and collect information on individual buildings. The final sample includes 412 buildings, the locations of which are displayed in Figure A2. The location of Sunton neighborhood on the map of Nairobi is displayed in Figure B1. For each building I determine the commencement date, the number of stories, the completion date (for completed buildings), whether they are currently used, the construction material (corrugated iron sheet/stone) and type

[4] Buildings from corrugated iron sheets are typically the dominant form of housing in informal neighborhoods.

(residential/commercial). The sample was constructed manually which is a very labor intensive task. Henderson et al. (2021) use height data at two different points in time (2003 and 2015) provided by external organizations. Their data cover the entire city and were constructed with the application of machine learning algorithms. My coverage is much smaller but given my objective, I need to pay attention to important details, so more careful processing of images is required. At the same time, while the remote sensing literature has made significant advances in the direction of determining building heights, I am not aware of any study or off-the-shelf techniques that allow researcher to determine signs of commencement dates. The determination of commencement dates involves additional challenges, compared with building heights. For example, I need images for each year rather than two images for the beginning and end of the study period. Each image needs to be inspected carefully and compared with the preceding and following ones. This time-consuming process may reveal some important details. For example, in the study by Henderson et al. (2021), when the authors observe that the height of a given building on a given land plot changed between two periods, they assume that the building was demolished and a new one was built. My hand-collected data reveals that changes in building heights in most cases are the result of an ongoing construction processes. Moreover, with the exception of commencement dates, I need street images to collect information for the remaining building characteristics, that were listed above.

To sum up, my manual approach is very labor intensive but it takes care of important details which are vital for the analysis of the main research questions of this paper. It also should be mentioned that the main objective of this section is to document that the construction progresses very slowly at the level of individual buildings. Expanding the sample is unlikely to affect this argument. I have constructed a smaller sample from another neighborhood and documented similar patterns.[5] I take one additional step to make sure that Sunton is not an outlier neighborhood. In the Appendix B I use satellite images of Sunton and calculate their similarity with various other locations in Nairobi. The results show that the similarity index is very high with many other neighborhoods, especially those that are likely to attract new migrants.

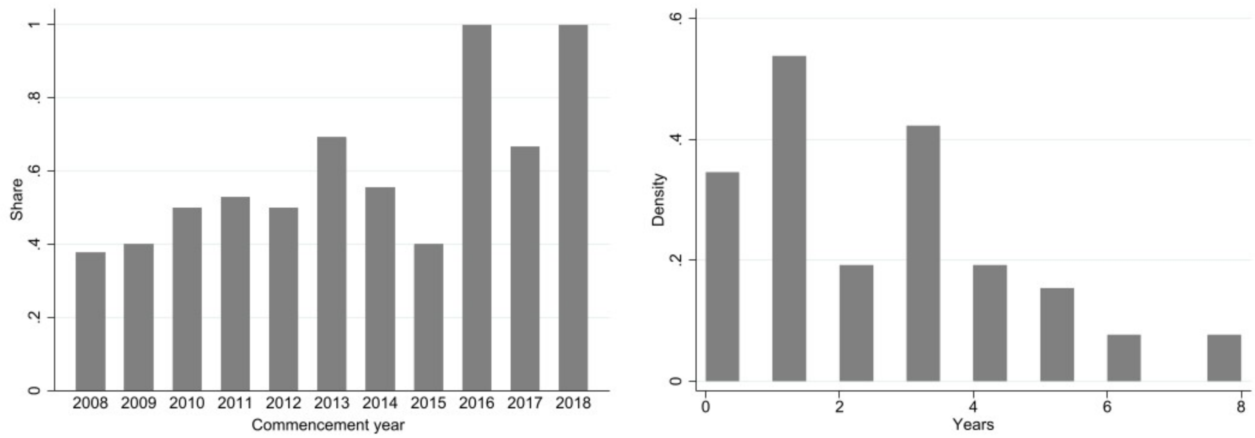
Panel (a) of Figure 1 displays the share of unfinished buildings by the year of the initiation.[6] Since satellite images are available from March 2009, I can approximate commencement dates more precisely from 2009. For this reason for all unfinished buildings that already existed before March 2009 I assign 2008 as a commencement date. As can be seen, for buildings the construction of which started in 2009, about 40% are unfinished after 8 years. Also, we can observe that the share of unfinished buildings is relatively larger for more recent years which is logical. Panel (b) plots the histogram of construction duration in years for completed buildings. As can be seen, for a substantial fraction of buildings it takes more than 3 years to complete. The average duration

[5] Larger samples can be useful for studying some additional questions that are beyond the scope of the current paper. For example, one may be interested in studying weather construction proceeds faster in areas closer to the city center where land is more expensive.

[6] The sample excludes buildings from corrugated iron sheets and commercial buildings (27 units in total).

Figure 1: Completions and durations

(a) Share of unfinished buildings (b) Construction duration



Notes : *Panel (a) plots the shares of unfinished buildings by commencement years. Panel (b) plots the histogram of construction duration in years for completed buildings.*

for completed buildings is 3.4 years.[7]

By comparing these numbers to the US ones we can develop a better understanding whether the patterns observed in Figure 1 are also present in a relatively frictionless economy. The U.S. Census Bureau's Survey of Construction provides information on the average duration of construction process for new residential housing. According to these data for owner-built houses with one unit the average construction duration is 11 months for the 2010-2018 period. The corresponding numbers are 11.2 and 12.5 months for buildings with 2-4 and 5-9 units. This analysis suggests that in Kenya there are bottlenecks which hamper the construction process and cause delays. In this paper, I argue that the main reason behind this observation is volatile income and the lack of funds to finance purchases of inputs. However, before presenting the model, I briefly discuss some alternative explanations and provide some empirical evidence highlighting the importance of financial constraints.

2.2 Alternative explanations

Technological and input constraints. The cost of construction materials might be high in Africa (see Beirne and Kirchberger, 2021). One can also argue that builders in Africa use obsolete technologies. These factors can affect the sizes of structures but they cannot lead to heterogeneous outcomes observed in my collected data, where I observe many buildings with five or six stories that were completed within a year. High material costs and obsolete technologies by themselves cannot explain the slow construction speeds.

[7]Since I assign the year 2008 to structures that existed before 2009, the right bar includes structures which potentially have longer durations. This also means that the average duration is longer than 3.4 years.

Taxes. Property taxes also can create incentives to leave buildings unfinished. According to (Keen and Slemrod, 2021), in Greece, there is a 60 % tax reduction for unfinished buildings. In Kenya there are three types of property related taxes: land rent; the stamp duty (on transactions); and the capital gains tax (Franzsen and McCluskey, 2017). Among those, the most relevant is the land rent/tax. It is calculated based on the value of land rather than on the value of the building or its condition. Thus, the tax evasion motive cannot be the reason behind the preponderance of unfinished buildings.[8]

Property rights. Informality and land rights are also important factors affecting households' planning and construction decisions. As was highlighted, in Sunton the share of corrugated iron sheet buildings is very small (3%). The lack of land rights and high risk of demolition can lead households to build temporary structures from cheap materials in order to minimize expected losses. Meanwhile, in Figure A1 we observe a building, in which substantial amounts of resources have already been invested and the demolition or expropriation of this building will imply large losses for the owner. There is no reason to expect that the completion of this building will increase the likelihood of demolition/expropriation. At the same time, if the owner finalizes the unfinished story, which will require a modest investment, relative to the amount already invested, then he/she can expand the living space. It is critical to stress that the building in Figure A1 is not an exception in terms of its size. In my collected sample, the average unfinished building has 2.39 stories which is slightly higher than the average for finished building.

The fact that most unfinished buildings already have substantial investments in them, allows me to rules out the possibility that they are structures erected by squatters, with the hope of claiming property rights in the future. These types of settlers face high risk of demolition/expropriation and they are likely to make minimal investments. Moreover, squatters are more likely to have low income levels and are likely to plan to build smaller buildings. The fact that the average unfinished building has fewer stories than the finished one runs against this line of thinking.

Both street and satellite images provide further evidence that authorities have control over the neighborhood. Almost all land plots are equally-sized and located next to each other, streets run parallel to each other and have 90 degree intersections (see Figure A2). These are strong signs that the neighborhood was designed by the authorities and they controlled the process of plot sales/allocation. The neighborhood also has powerlines along all its streets without unregulated and intersecting web of connections (Figure A1). From this perspective it is also important to highlight again that the analysis focuses on a very small area (see Figure A2) and large differences in construction speeds can be observed for buildings located immediately next to each other.

Future expansion of families. Households may leave their buildings unfinished if they anticipate that the household size may increase in the future, for example when their children marry

[8] Kelly (2004) reports that, although the Rating Act (1972) allows local authorities to tax either land or land and improvements, all property Rates in Kenya are levied only on land.

and continue to live with parents. This explanation cannot be fully ruled out; however several pieces of evidence suggest that it is not the main reason. First, I can observe that the construction proceeds slow not only in the case of private houses but also in the case of apartment buildings. Second, among unfinished buildings 20% have walls but not covers, similar to the one in Figure A1. If the household is waiting for her children to form families, then it is not optimal to build half of the story and wait for many years. Instead she can either finish the story and rent it out or she can start the construction of the additional story when the date of the family expansion approaches and use the capital for other purposes while waiting. It is also worthwhile to mention that the absence of a roof can damage the building, for example, due to water leakage. So, leaving the building with half-finished walls without a cover is not an optimal decision.

2.3 Empirical evidence

In this subsection I present some suggestive empirical evidence in support of one of the main outcomes of the model developed in Section 3. The World Bank conducted a survey on housing conditions in Kenyan cities in 2012-2013 (Gulyani, Ayres, Struyk, and Zinnes, 2017). In this survey households were asked whether they have used loans to finance their structures. I use this information to study whether a positive response to this questions is positively related with the number of stories in the structure. To implement this analysis I regress the log number of stories in the structure on an indicator variable whether loans have been used, while controlling for household characteristics. Household characteristics include total household income, the number of household members, the number of working age members and the number of members aged below 16 (all variables in logs). I also include city fixed effects. Controlling for household income information is important because one major concern could be that higher income households are more likely to build taller buildings and at the same time have access to loans. I restrict the analysis to households who own both the land and the structure to make it consistent with my modeling approach. Also, those cases that own the structure but not the land may be informal constructions. However, the number of households who own the structure but not the land is very small and does not alter the results.

The estimation results presented in Table 1 show that the indicator variable on the availability of external finance is positively associated with the number of stories in the building. The magnitude of the effect is rather large, given that the mean of the dependent variable is 0.03. The coefficient gets larger for the sample that includes only households with children (Column 3). It should be mentioned that this results provides only a suggestive evidence. More rigorous analysis would require a setting with exogenous variation in access to loans.

Table 1: Determinants of building height

	(1)	(2)	(3)	(4)
Loan	0.030**	0.033**	0.059***	0.033**
	(0.015)	(0.016)	(0.018)	(0.016)
HH income	0.030***	0.028***	0.015*	0.029***
	(0.006)	(0.007)	(0.008)	(0.007)
# members	-0.007	-0.012	0.029	0.019
	(0.007)	(0.010)	(0.061)	(0.017)
# age between 16 and 60		0.011	-0.016	-0.008
		(0.011)	(0.013)	(0.014)
# age $<$ 16			-0.018	
			(0.060)	
# (age $<$ 16) +1				-0.018**
				(0.008)
R-Adj.				
N	2356	2238	1484	2238

Notes: The dependent variable is the log number of stories. *Loan* is an indicator variable if the household has used a loan during the construction. All other explanatory variables are in logs. All regressions include city fixed effects. * (**) (***) indicates significance at the 10 (5) (1) percent level.

3 Model

I present a model of a city populated by agents whose incomes evolve according to a stochastic process. Financial markets are imperfect and agents can trade non-contingent bonds. Residency in the city requires one unit of housing each period. Agents can invest in the construction and build multistory houses which they can use for their own residency and rent out to others.

3.1 Environment

Demographics. There are two types of households: patient households and hand-to-mouth households. At time $t = 0$, N patient households move to the city. Each of these households is endowed with one unit of urban land on which they can reside and build. They also receive stochastic income y, which evolves according to a Markov transition process $z(y, y')$. There is a large number of hand-to-mouth households residing in the rural area. These households migrate to the city only if the expected utility from living in the city exceeds their reservation utility in the rural area. Hand-to-mouth households earn some income, pay per period rent r and consume the rest. These households do not make any intertemporal decisions, their presence is required to generate demand for newly constructed housing. The presence of the hand-to-mouth households and their outside option make sure that r is constant over time. The number of hand-to-mouth households in the city evolves endogenously over time and I denote their number by M_t. The rest of the analysis focuses primarily on patient households and for this reason I use the term household to refer to the representatives of patient households, unless specified otherwise.

I follow Michaels et al. (2021) and assume that the household is endowed with land and do not model the land purchase process because the main objective of this paper is to study the role of financial friction on the construction process rather than on land acquisition. This approach may be relevant from the practical point of view as well because the allocation of land is not always based on the market value. The Sites and Services projects studied in Michaels et al. (2021) is one such example.

Preferences. The household has utility over non-housing consumption (c) which is the numeraire. The household does not derive utility from housing consumption but in order to reside in the city she needs one unit of housing each period. She discounts her future utility using the discount factor β. The preferences over the non-negative consumption sequence in period 0 are represented by the following expected utility:

$$E\sum_{t=0}^{\infty}\beta^t \frac{c_t^{1-\sigma}-1}{1-\sigma}.$$

Housing. The household starts her life in the city by owning one unit of undeveloped lend. She can erect a temporary structure on it. Temporary structures are modeled in the spirit of Henderson et al. (2021). Such structures are typically made from corrugated iron sheets and require per period maintenance cost m. The household can also engage in the construction of a permanent multistory housing unit. In order to start construction, the household needs to make a decision on the number of stories in the building $\bar{h} \geq 1$ which is an integer number. The construction process can take many periods but the maximum number of stories in the building needs to be determined initially because the building should have sufficiently strong foundations to support the remaining structure. The construction process involves two components. The first one is the foundation and the second one is the building itself. The total cost of construction is given by the following function: $\mu(\bar{h}) = A\bar{h}^{\gamma}$, where $\gamma > 1$. The same functional form is also used by Henderson et al. (2021) and Michaels et al. (2021) who study Nairobi and Dar es Salaam, respectively.

The total cost of construction is split between two components. A fraction of α must be invested in the building and $1-\alpha$ in the foundation. The assumption that the foundation investment is a fraction of the total cost is consistent with industry estimates and is discussed in more detail in Section 4.1.[9] The construction of the main part of the building can be done incrementally. If sufficient funds are available, then the household can add layers of stones/bricks to the building and increase its height in a period. If funds are not available, then the household optimally chooses not to engage in construction in that period. There are no technological constraints on the speed of construction or the conversion of the building into a livable place. The speed of construction is determined by the household's optimal decision rules.

If the household has started the construction but has not yet completed her building, then she

[9]It should be noted the results of the model hold even when $\alpha = 1$. The only assumption required is that the household needs to make an irreversible decision on the number of floors before starting the construction.

can reside in the temporary building or inside the unfinished building. She has to continue to incur the maintenance cost m. When the construction is completed and $h = \bar{h}$, the household stops paying the maintenance cost m. If $h \geq 2$ the owner occupies one of the stories and rents out the remaining stories to hand-to-mouth households. This modeling approach is also supported by the data. According to the World Bank survey conducted by Gulyani et al. (2017), about one fifth of renters report that the owner lives in the same building.

Financial markets. Financial markets are incomplete, households can trade non-contingent bonds (a) and they are subject to a borrowing constraint. Collateralized borrowing is allowed and the size of the maximum debt is restricted by $\underline{a}$, which is equal to the value of land. The interest on borrowing is given by i^l which is determined outside the city. The rate of return on savings or deposits is given by i^d which is also exogenous.

3.2 Decision problems.

At any point in time the household can be a land owner, a builder or a structure owner. Let s denote the status of the household depending whether she is a land owner (L), builder (B) or structure owner (O). Below I present the decision problems of all these types.

The land owner's problem. Each period, the land owner chooses whether she wants to start building a house or continue to reside in the temporary building. This decision is given by:

$$V^C(a,y) = \max_{\{B,L\}}[V^B(a,y), V^L(a,y)], \tag{1}$$

where V^B denotes the value of the builder and V^L the value of the land owner. The latter is defined as follows:

$$V^L(a,y) = \max_{c,a'} u(c) + \beta E V^C(a',y') \tag{2}$$

subject to

$$c + m + a' \leq y + a \times (1+i), \tag{3}$$

$$a' \geq \underline{a}.$$

$$\begin{cases} i = i^d & \text{for} \quad a' \geq 0 \\ i = i^l & \text{for} \quad \underline{a} \leq a' < 0. \end{cases}$$

The land owner receives a stochastic income, incurs the maintenance cost and decides how much to consume and invest or borrow (a'). Next period's expected value function is given by

$EV^C(a', y')$, which is the option of choosing between continuing as a land owner or becoming a builder as described above.

The builder's problem. When the household chooses to initiate a construction project, she transitions to an intermediate stage, the optimization problem of which is given by:

$$V^B(a, y) = \max_{c, a', \bar{h}} u(c) + \beta EV^O(a', y', \bar{h}, 0) \tag{4}$$

subject to

$$c + a' + (1 - \alpha) \times \mu(\bar{h}) + m \leq y + a \times (1 + i), \tag{5}$$

$$a' \geq \underline{a}.$$

$$\begin{cases} i = i^d & \text{for} \quad a' \geq 0 \\ i = i^l & \text{for} \quad \underline{a} \leq a' < 0. \end{cases}$$

During this stage the household makes a decision on the future height of the structure $\bar{h}$.[10] At this stage the household also makes an investment in the foundation of the building given by $(1 - \alpha) \times \mu(\bar{h})$. After making these choices the builder becomes an owner, the value of which is given by $V^O(a', y', \bar{h}, 0)$. The household does not engage in the construction of the stories at this stage and enters into the next period with 0 stories but with with a completed foundation. It is important to note that, while $\bar{h}$ is an integer, h is a continuous variable. After the initiation of the construction the households still needs to incur the maintenance cost m because she still reside in the temporary structure.

The owner's problem. Each owner is characterized by $\bar{h}$ which was determined in the building stage and cannot be changed. The owner takes this value as given and solves the following optimization problem:

$$V^O(a, y, \bar{h}, h) = \max_{c, a', h'} u(c) + \beta EV^O(a', y', \bar{h}, h') \tag{6}$$

subject to

$$c + a' + \alpha \times \mu(h') + 1[h < \bar{h}] \times m \leq y + a \times (1 + i) + \max[0, \lfloor h \rfloor - 1] \times r + \alpha \times \mu(h), \tag{7}$$

$$a' \geq \underline{a}, \quad h \leq h' \leq \bar{h},$$

[10]One can also introduce a fixed cost payment required to convert land from informal to formal use as in Henderson et al. (2021).

$$\begin{cases} i = i^d & \text{for} \quad a' \geq 0 \\ i = i^l & \text{for} \quad \underline{a} \leq a' < 0. \end{cases}$$

If $h < \bar{h}$, then the owner pays the maintenance cost. Starting from this stage, the interpretation of this cost is twofold. The first interpretation is the same as before. While the first floor is not completed the household needs to reside in the temporary structure. The second interpretation is that after completing the first floor the household moves into the permanent building but since the building does not have a roof, the household needs to undertake some maintenance work. Furthermore, living in a building that is under construction implies potential damages to the interior of the building, for example, due to water leakage. It is very common to observe residents in unfinished buildings in Africa (see Figure A1). In the calibrated version of the model (see Section 4.1) the maintenance cost is very small relative to the value of the physical structure, so this assumption is reasonable. The household also engages in the construction of layers. Per period investment in construction is given by $\alpha \times \mu(h') - \alpha \times \mu(h)$. There is no incentive to destroy stories because that does not generate value. If the building is finished ($h = \bar{h}$) the owner stops paying the maintenance cost. The owner generates income by renting out stories of the building to other households. The amount of space available for renting is given by $\lfloor h \rfloor - 1$.[11] This indicates that the household occupies one of the stories herself and rents out the remaining completed stories to other households.[12, 13]

The decision rules together with the stochastic income process determine the evolution of the distribution of agents over y, a, $\bar{h}$, h and s which I denote by $G_t(y, a, \bar{h}, h, s)$ and by $g_t(y, a, \bar{h}, h, s)$ the corresponding probability density function.

3.3 Equilibrium

An equilibrium consists of an initial distribution $G_0(y, a, \bar{h}, h, s)$, rents r, interest rates i^l and i^d, a sequence of decision rules and a sequence of distributions $G_t(y, a, \bar{h}, h, s)$, $t \geq 1$, such that:

1. Decision rules solve the household's problem in equations (1), (2), (4) and (6).

2. Demand for living space equals supply for all $t \geq 0$

$$N + M_t = N + N \times \sum_h g_t(y, a, \bar{h}, h, s) \times \max[0, \lfloor h_t(y, a, \bar{h}, h) \rfloor - 1]. \tag{8}$$

[11] $\lfloor . \rfloor$ is a mathematical notation for rounding down to the nearest integer number.

[12] The model can easily be modified and calibrated under the assumption that renting is allowed only if the building is fully completed.

[13] I assume that there are no real estate transactions between households. This is an important feature but it introduces substantial computational and quantification complications. It is reasonable to assume that housing transactions are associated with large risks and costs in the context of Nairobi. To keep the model simple, I make a strong assumption that these costs are large enough so that they outweigh potential benefits.

3. The sequence of distributions $\{G_t(y, a, \bar{h}, h, s)\}$, $t \geq 1$, are implied by the sequence of optimal decision rules and the initial distribution $G_0(y, a, \bar{h}, h, s)$.

Equation 8 is the market clearing condition for housing. It states that the total number of households in the city (left-hand side) is determined by housing supply (right-hand side), which is equal to cumulative completed floor-space plus temporary structures. In the summation term one story is subtracted from each building with at least one completed story because the first term on the right-hand side (N) captures either temporary structures or the first floors of permanent structures, depending on the phase of construction. The supply and demand for assets do not necessarily equalize because the lending rate (i^l) and the return on savings (i^d) are determined outside the city.

The key feature of the model is the choice of the planned height of the building $\bar{h}$. When choosing $\bar{h}$, the household faces a trade off. Higher values of $\bar{h}$ generate more rental income. But building high implies two types of costs. The first one is the construction cost, which is a convex function (see Section 4.1). The second one is associated with the longer time required to complete the building. Because of the borrowing constraint the construction process takes longer which negatively affects the household's incentive to plan a tall building.

4 Quantitative analysis

The main objective of this paper is to assess the role of financial friction on the process of housing development in the context of a city in a low-income country that experiences a potential inflow of migrants from the rural area. The quantitative analysis focuses on Nairobi which has experienced a rapid expansion over the last decades and is one of the largest cities in Africa. The recent study by Henderson et al. (2021) also focuses on Nairobi which facilitates the calibration process and comparison of the role of new features introduced in the current study. I also use the information obtained from the satellite and street images (presented in Section 2) in the calibration process. Then I use alternative values for $\underline{a}$, r^l and r^i which describe the level of the development of the financial system, to conduct counterfactual exercises and assess the extent to which financial development affects the speed of the expansion of the stock of housing and its level in the long run equilibrium.

4.1 Calibration

Some parameters are standard and are taken from the literature with heterogeneous agents and incomplete market models (Huggett, 1993; Aiyagari, 1994). The model period corresponds to one year. The coefficient of the relative risk aversion is set to $\sigma = 2$. The parameters of the income process and transition probability matrix are taken from a recent study by Herreno and Ocampo

(2021), who also focus on a developing country. More specifically, they assume $y = \epsilon^{\eta}$ where ϵ follows an AR(1) process with a mean of 1 ($\bar{\epsilon}$), a coefficient of variation of 0.12 (σ_{ϵ} and a serial persistence parameter of 0.17. The authors set $\eta = 3.1$. I discretize the AR(1) process using the algorithm of Tauchen and Hussey (1991).

The per period rental rate (r) is set to 20% of the income of the average household. According to the World Bank survey conducted in Nairobi the average renter spends about 20% of her income on rent (Gulyani et al., 2017). This figure is also close to the one observed in advanced countries (Davis and Ortalo-Magne, 2011). Henderson et al. (2021) estimate that the maintenance costs is equal to 25% of the monthly rent. Thus, I set $m = 0.05$.

As was mentioned during the description of the model, housing is produced with a convex production function, $\mu(h) = Ah^{\gamma}$. I set $A = 1$. The curvature parameter is set to $\gamma = 1.53$. The same value is also used by Michaels et al. (2021). This value comes from a recent study by Combes, Duranton, and Gobillon (2021) who use a detailed construction cost data from France to estimate a housing production function. It should be mentioned that Combes et al. (2021) study family houses and not tall buildings, so in terms of sizes buildings are similar. Henderson et al. (2021) use the same functional form for Nairobi but they do not have construction cost data so estimate the parameter from the model and obtain somewhat larger value. One possibility is that because in their model there are no financial frictions they need a larger convexity parameter to match the relatively low building heights.

To the best of my knowledge in the economic literature there are no estimates of foundation cost functions. For this reason, I turn to engineering estimates. The National Association of Home Builders provides cost breakdowns for the US single family houses. According to the most recent report the share of costs on foundation is 11.8% (Ford, 2020). Thus, I set $1 - \alpha = 0.12$.

The key parameter that describes the level of financial development is $\underline{a}$. Setting this value to 0 and assuming that borrowing is not possible in Nairobi will be unrealistic. According to Gulyani et al. (2017), 35% of respondents who own houses reported that their buildings were financed by loans. For this reason, I divide the population of patient households into two groups. The first group consists of households who do not have access to the financial system. For those households $\underline{a} = 0$.[14] The second group of households do have access to the financial system and they can borrow against the value of their land. The estimated production function of Combes et al. (2021) implies that the the share of land in the total value of the building is 35%. Given the parameters of the production function, for a building with 3 stories this implies a land value of 4.2. Thus, I set $\underline{a} = -4.2$.[15] These households borrow at the interest rate r^l the value of which is set to 8%. This value corresponds to the average real interest rate on loans in Kenya during

[14]One may argue that the ownership of land or house automatically grant access to the financial system. The survey data suggests that that is not the case because the 35% figure mentioned above is among house-owners in Nairobi and not for the general population. This means that there are some other factors determining households' ability to borrow, such as formal income.

[15]It should be mentioned that I need land price to determine the borrowing limit. An alternative option would be to impose an ad hoc limit. According to World Bank (2017) many loans provided for self-construction are unsecured.

the 2000-2015 period, according to the World Bank's World Development Indicators (WDI). The fraction of households with access to the financial system is set to match the 35 % rate observed in the survey data. Finally, the return on financial savings is set to 0. According to the WDI on average the return on deposit rate is not positive (in Section 4.3 I also consider negative returns).

In my hand-collected sample, described in Section 2, the average height is 2.39 stories (excluding corrugated iron sheet buildings).[16] I choose the discount factor to match the average number of stories in the long run equilibrium. This leads to a value of $\beta = 0.96$. The summary of parameters is presented in Table 2.

Table 2: Model parameters

Parameter	Description	Value
β	Discount factor	0.96
σ	CRRA	2
ρ_z	Income shock persistence	0.17
σ_z	Income shock variance	0.12
η	Labor efficiency shifter	3.1
r	Rent (share of average income)	20%
m	Maintenance cost as a share of rent	25%
$1-\alpha$	Cost share of the foundation	0.12
γ	Convexity of the cost function	1.53
A	Shifter of the cost function	1
i^l	Interest on loans	8%
i^d	Interest on deposits	0%
$\underline{a}$	Borrowing limit (with finance)	-4.2
$\underline{a}$	Borrowing limit (w/o finance)	0

As mentioned in Section 3, households hold no housing and no assets at period $t = 0$. This assumption is made to proxy a scenario in which many new migrants join cities in low-income countries from rural areas with low levels of initial assets. Furthermore, this assumption helps to highlight the role of the financial system in the process of the development of the city. In contrast, if I assume that households start their lives in the city with a large stock of assets, then the role played by the financial system will be relatively small.

4.2 Counterfactuals

In this section, I consider two counterfactual economies which have different levels of financial development. In the calibrated model 35% of households have access to the financial system and the remaining 65% do not have access to the financial system. The first counterfactual considers a scenarios when all households do not have access to the financial system ($\underline{a} = 0$) and the second

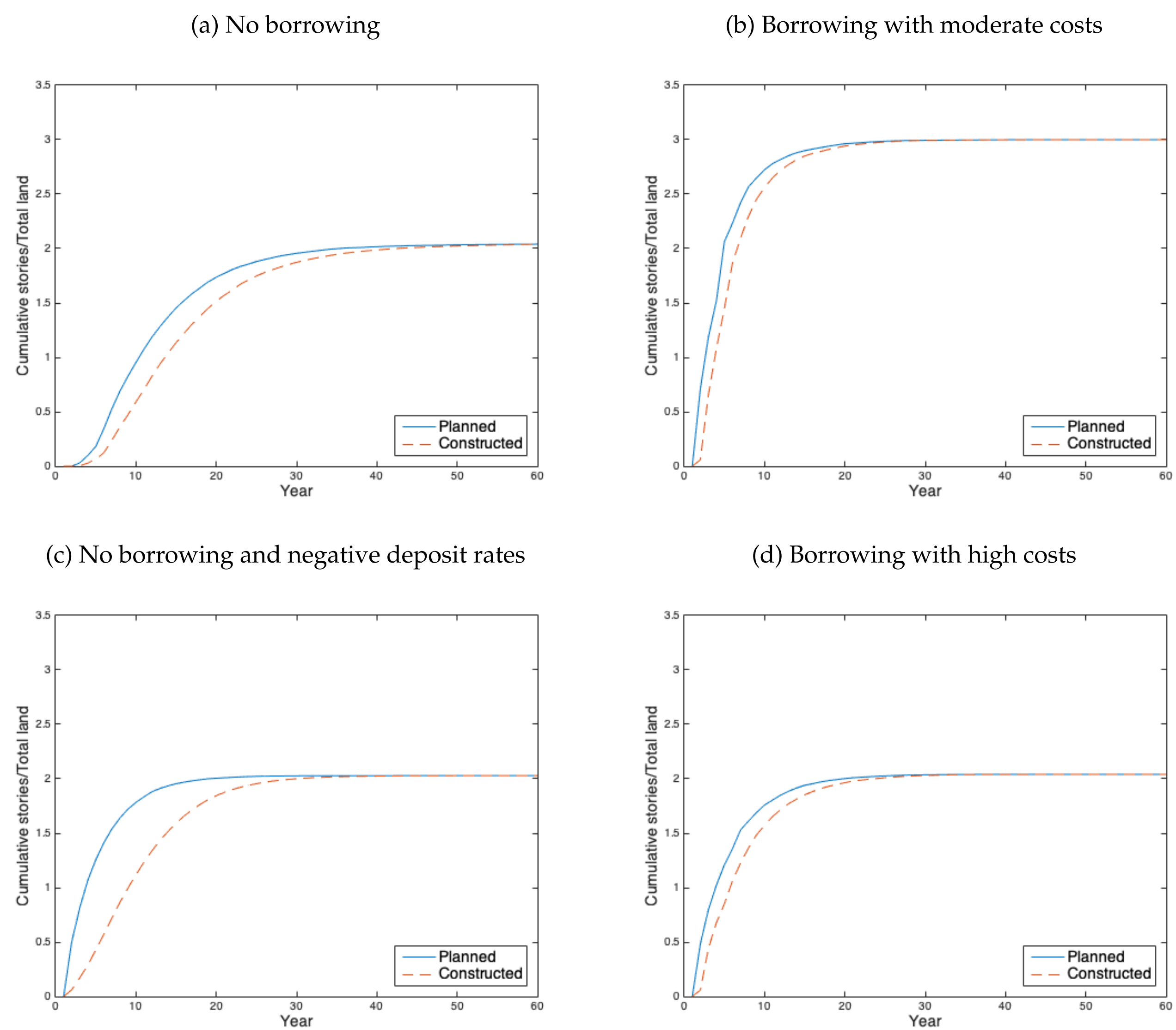
[16] In the survey data Gulyani et al. (2017) this number is 2.5 for buildings in Nairobi with walls from stone, brick or block.

counterfactual considers a scenario in which all households have access to the financial system ($\underline{a} = -4.2$).

Figure 2 displays the dynamics of main variables in the city. Panel (a) considers the case with no financial system. The first time series (solid line) is the ratio of cumulative planned stories to total land area available for development in the city or the number of patient households (N).[17] Since I assume that all households start their lives in the city with zero assets, it takes several periods until households, who are experiencing large positive income shocks, accumulate some assets to cover the costs of the investment in the foundation. After that there is a raise in the stock of planned projects. As more households start their projects, the number of potential builders and newly planned buildings decrease which is reflected in the declining slope of the solid line. The average household plans to build a house with about two stories. The dashed line shows the dynamics of the cumulative constructed stories over total land. This ratio is always lower than the one for planned houses because households first make decisions on the maximum number of stories and then start construction which can take several years. In the long run both measures converge.

[17]Because patient households are the only developers in the city and each of them is endowed with one unit of land both numbers are equal.

Figure 2: Counterfactuals



Notes : *These figures plot the dynamics of (i) cumulative planned stories divided by total land area and (ii) cumulative constructed stories divided by land area. Panel (a) plots the dynamics of time series for the counterfactual with no borrowing* ($\underline{a} = 0$, $i^d = 0\%$). *Panel (b) for the counterfactual with borrowing* ($\underline{a} = -4.2$, $i^d = 0\%$, $r^l = 12\%$). *Panel (c) for the counterfactual with no borrowing and negative returns on savings* ($\underline{a} = 0$, $i^d = -7\%$). *Panel (d) for the counterfactual with borrowing at high costs* ($\underline{a} = -4.2$, $r^l = 12\%$).

On average it takes 4 years from the date of investment in the foundation to complete a project. As was mentioned during the discussion of Figure 1, in the constructed sample the construction duration for buildings that were completed before 2018 is 3.4. The actual duration should be longer because many buildings are still under construction and when they are completed it will increase the average. Another data moment is the evolution of the fraction of completed buildings. In the collected data the fraction of completed buildings is 35% during the 10 year interval. The corresponding number for the simulated economy without borrowing is 27%. Although these moments were not targeted, the model delivers reasonable results.

Panel (b) presents the same time series for the case when all households have access to the financial system. We can notice that under this scenario all processes take place at a much faster pace. Since the full convergence is a long process, it makes sense to compare the performance of this economy with the half-life of the previous counterfactual. In the model without a financial system, it takes 14 years to build half of the long run living space. In the model with borrowing, it takes 4 years to build the same quantity of housing space. In the economy with borrowing, project completion duration period is 1.85 years. Another important difference is that the average building has 3 stories in the economy with a developed financial system, compared with 2 stories in the economy without access to finance.

These results indicate that the access to the financial system can play an important role in the development of cities in Africa. It can substantially speed up the process of the expansion of the housing stock. At the same time it enables households to choose to build structures that have more stories. Thus, in the long run equilibrium there is more living space per area of land which implies higher density and less urban sprawl. This means that a better financial system can allow cities to expand and benefit from positive agglomeration externalities and at the same time mitigate the negative consequences of congestion. The slow construction process can also be a source of negative externalities. For example, Michaels et al. (2021) argue that there is a complementary between the quality of private buildings and public infrastructure. An unfinished building or a building under construction is one form of low-quality building. Such buildings do not look nice and they are sources of dust and noise. These factors have negative externalities on neighbors. Even if all buildings are expected to be completed eventually, both in the data and in the simulations there are large numbers of unfinished buildings even after 10 years. In the model such buildings do not have negative effects on the neighborhood but if one assumes that buildings under construction create negative externalities, then households anticipating the slow evolution of the construction in the neighborhood can update their initial plans and build lower quality houses themselves.

4.3 Interest rates

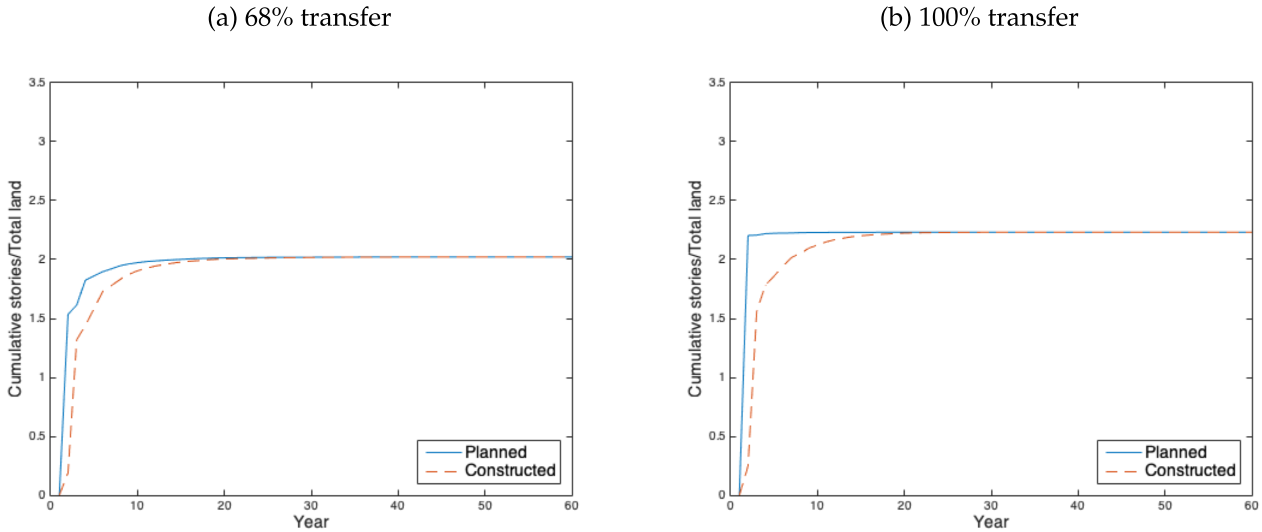
Figure 2 presents the results for two additional counterfactual simulations. The counterfactual in Panel (c) is a modification of the one in Panel (a) with the difference that savings deliver negative returns ($\underline{a} = 0$ and $r^d = -7$). In the context of low-income countries, in addition to low returns on safe accounts, there are a number of additional factors that prevent households from generating positive real returns on their savings such as, the lack of access to bank accounts, social pressure to help friends and relatives and theft (see, for instance, Dupas and Robinson, 2013).

One interesting result that emerges from this exercise is that with negative interest rates (Panel c), the built up of the total housing stock proceeds faster, compared with the specification with no borrowing but with 0 interest rates (Panel a). In the model with non-negative rates, the half-life is reached in 14 years, while in the model with negative rates, the corresponding figure is 8 years. The intuition behind this result is that in the case of negative rates households start the construction projects earlier because investments in the building serve as an alternative means for asset accumulation. Conditional on starting a project, on average it takes 9.5 years to complete a building. The corresponding figure in Panel (a) is 4 years. Compared with conventional non-contingent bonds, small investments in construction do not allow households to smooth consumption in response to temporary income shocks because it is not possible to destroy a fraction of a building and sell it. But when it comes to households' long term objective of completing the housing project, households find it optimal to make small investments in the project rather than accumulate liquid assets and make a large investment at a later period because such accumulated assets depreciate over time. Thus, with negative interest rates investments in unfinished buildings emerge as an alternative to conventional deposits. Meanwhile, in the scenario with zero rates, households prefer to accumulate liquid assets and make large investments because there is no risk of depreciation. In this case, households also enjoy the advantage of being able to smooth consumption in response to temporary income shocks. It should be highlighted that faster construction speeds in Panel (c) do not imply that households are better off, in terms of welfare, because they are not able to smooth their consumption.

In the presented framework the concept of welfare takes into account only the welfare of patient households and for them the implications of financial frictions under various scenarios are obvious. Given the rental rate, hand-to-month households are marginally indifferent between staying in the rural area or migrating to the city, thus the migration does not affect their welfare. However, as was discussed in the previous subsection, in this context there is substantial room for externalities through different channels, which I have not modeled.

Panel (d) presents the results for an economy which is a modification of the financially developed one with the difference that the cost of borrowing is higher ($\underline{a} = -4.2$, $i^d = 0$, $i^l = 12$,). The dynamics of main time series evolve slightly slower in the scenario with higher borrowing costs but the differences are rather small, compared with the counterfactual case with borrowing at a lower interest rate (Panel b). More importantly, the number of average stories is affected and decreases to about 2. This result indicates that policymakers can implement interest rate subsidies and increase the average heights of their buildings. The model allows to calculate the cost of such a policy and compare it with alternatives.

Figure 3: Counterfactuals with transfers



Notes : *These figures plot the dynamics of (i) cumulative planned stories divided by total land area and (ii) cumulative constructed stories divided by land area. Both panels plot the dynamics of time series for the economy with high borrowing costs* ($\underline{a} = 0$, $i^d = 0\%$, $i^l = 12\%$) *in which at period* $t = 0$ *households receive a lump sum transfer. In Panel (a) the transfer is equivalent to 68% of the average household income. In Panel (b) the transfer is equivalent to 100% of the average household income.*

More specifically, we can consider an interest rate subsidy program according to which the government subsidizes the difference between interest rates in both economies which is 4 percentage points. I consider two scenarios. Under the first scenario the subsidy is in place for 60 years and under the second for 15 years. The present discounted cost of this policy is 100% of the average household income under the firsts scenario and 68% under the second one. I use the model calibrated discount factor to calculate present discounted values ($\beta = 0.96$).[18] Despite substantial differences in the durations of programs, cost differences are not large. Of course this has partly to do with discounting but primarily it is driven by the fact that most households borrow heavily in the early stages. Next we can consider an alternative scheme under which the government provides lump sum transfers of equivalent amount to households in period 0. The results of the simulations are presented in Figure 3. In the case of a transfer equivalent to 68% of the average household income, the average number of stories is not affected. In the case of 100% transfer, the number of average stories increases to 2.24, which is below the economy with 8% lending rate.[19] Thus, interest rate subsidies dominate transfers in terms of increasing households incentive to build taller buildings.

[18]The calculations are made under the assumption that households do not anticipate that the policy will be withdrawn. In the case of 60 year scenario this assumption is unlikely to make a noticeable difference compared to the one when households anticipate the end of the policy.

[19]The welfare of patient agents is higher in the economy with 8% interest rate compared with the one in which the interest rate is 12% and households receive a transfer equivalent to 68% of the average income at $t = 0$. But it is lower compered with the one where they receive a transfer equivalent to 100% of the average income. However, these calculations ignore potential benefits from externalities.

5 Conclusions

The main objective of this paper is to highlight the slow construction process of buildings in African cities and explore the implications of this phenomenon on the urbanization process and the structure of cities. To this end, first I assemble a dataset from satellite images to document the slow construction process and the preponderance of unfinished buildings in Nairobi. Next, I introduce housing construction decisions into a model with heterogeneous agents, income risk and borrowing constraints to explain the stylized facts observed in the data. I use the calibrated model to conduct counterfactual simulations and quantify the role of different types of financial imperfections. The results show that the possibility of borrowing can substantially increase the speed of the construction process and allow the city to expand vertically. The model also shows that in the presence of negative returns on conventional deposits, households invest in unfinished buildings because such buildings allow them to preserve the value of their savings.

These results have important income and efficiency effects for developing countries. According to a large body of economic literature in many developing countries the productivity in urban areas is higher than in rural areas. Many economists and development organizations see rural-urban migration as an important channel for closing income gaps between rich and poor countries. However, a vital element in the rural-urban migration process is the availability of housing and the structure of cities. This paper highlights the role of the financial system in shaping the structure of the city and the speed of provision of housing.

To the best of my knowledge this is the first attempt in the literature to document the slow construction process of houses in developing countries and to study the role of the financial system in explaining this phenomenon. Both the collected data and the model imply that the quantities involved are large and have important implications for the urbanization process and urban structure in developing countries. Given these results, there is substantial room for future work. By deploying machine learning algorithms it may be possible to expand the dataset and study the relationship between neighborhood characteristics and construction durations. Such data can be valuable both for academic purposes and for local authorities. The presented model is rather parsimonious and can be enriched in several dimensions. For example, in the current version there is no endogenous production and no role for agglomeration effects. The presence of agglomeration effects can deliver new insights and policy implications (see, for example the discussion in Section 4.2). Another dimension is space which is homogenous within the city and commuting costs do not play a role. In this respect, the model can be extended by introducing commuting costs and dropping the assumption on the fixed supply of land. These are all important factors and can enrich the environment but are left for future work.

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Appendix

A Data construction

Figure A1: An unfinished building

Notes: An image of a building in Sunton neighborhood in Nairobi in February 2018. The image is from Google Maps' Street View option.

Figure A2: Geolocations of buildings

Notes: This map shows the geolocations of buildings in Sunton neighbourhood of Nairobi for which information was collected.

Figure A3: Determining the commencement dates

(a) March 2009

(b) October 2009

(c) January 2010

(d) December 2017

Notes :Images show the satellite view of the building in Figure A1 on different dates. Images are from Google Earth.

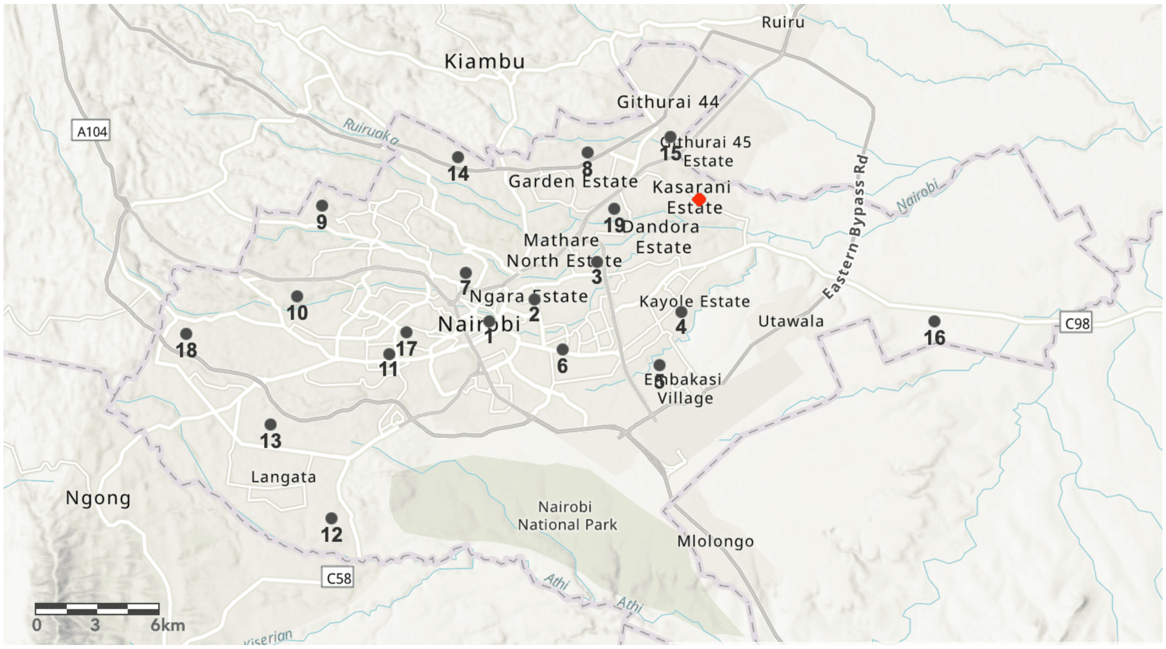
B External validity

In this section I compare satellite images of the Sunton neighborhood with various parts of Nairobi to asses the relative representatives of this specific neighborhood. First, I created 100 $\times$ 150-m satellite image blocks of Sunton. I excluded the parts of the neighborhood without buildings. As can be seen from Figure A2 the East-central part of Sunton is relatively empty, which is due to rather rugged geography. Next I collected images of the same sizes in various parts of Nairobi. Figure B1 shows the geolocations of those points. I selected these locations to evenly cover various parts of Nairobi. Within each part I selected a point which has residential buildings. The objective of the exercise is to compare the similarity of residential buildings in various parts and avoid comparisons of residential buildings with parks, stadiums, airports and other objects.

Then I used a Python library called image-similarity-measures to calculate indices of bilateral similarities between the collected images. Similarities were calculated using the Structural Similarity Index. The similarity index is a value between 0 and 1. When images are identical the index is equal to 1. The results of the exercise are presented in Table B1. The first row presents the bilateral similarities between all pairs of images within Sunton neighborhood. There are 13 ($150 \times 100 - m$) images which leads to 78 pairs. This information provides some reference point to assess the similarities of other neighborhoods with Sunton. In the remaining rows I compare each point from Figure B1 with each of the 13 images in Sunton and present descriptive statistics. Sunton is a rather homogeneous neighborhood with low standard deviation and the minimum value within this neighborhood is 0.777. As can be seen from the table most points are rather similar to Sunton because their mean and even minimal values are above this level. Locations with mean values above 0.8, which is the mean for the within Sunton comparison, can be considered as highly similar. Substantial dissimilarities are observed in locations 9, 11, 12, 13, 16 and 18. This is not strange because in the western parts of Nairobi most neighborhoods are wealth with very large single-family houses with wide and fenced green areas around them. Although such neighborhoods occupy substantial space, they are unlikely to become a destination for rural-urban migrants who need affordable housing. In contrast to that, eastern areas are more densely populated and both within neighborhoods and around them there is spaces for further expansion. Also, these areas are arguably more affordable. Given the high similarity index between Sunton and these areas, we can conclude that Sunton is rather representative in population weighted terms. Moreover, it is more representative of locations where future city expansion is likely to take place.

It should be noted that in this section I compared all areas of Sunton with selected points and one may argue that the proper approach should be a comparison with all points with residential buildings. However, it is logical to expect and the visual inspection confirms that within neighborhoods there are no sharp changes and the reader can verify this. Thus, it is unlikely that more intensive comparison will lead to substantially different results.

Figure B1: Geolocations of comparison points



Notes: This map shows the centroids of images used to calculate distance indices with Sunton. The location of Sunton is indicated by a red rhombus.

Table B1: Descriptive statistics for bilateral distances

	Obs	Mean	Std	Min	Max
Within Sunton	78	0.803	0.013	0.777	0.834
Location 1	13	0.788	0.006	0.778	0.800
Location 2	13	0.808	0.014	0.788	0.833
Location 3	13	0.796	0.008	0.779	0.808
Location 4	13	0.818	0.011	0.801	0.840
Location 5	13	0.801	0.012	0.779	0.820
Location 6	13	0.802	0.009	0.785	0.815
Location 7	13	0.787	0.008	0.771	0.805
Location 8	13	0.819	0.011	0.804	0.838
Location 9	13	0.711	0.010	0.696	0.723
Location 10	13	0.802	0.009	0.789	0.818
Location 11	13	0.736	0.009	0.718	0.750
Location 12	13	0.688	0.007	0.678	0.701
Location 13	13	0.625	0.008	0.618	0.641
Location 14	13	0.690	0.010	0.670	0.709
Location 15	13	0.812	0.010	0.794	0.832
Location 16	13	0.734	0.009	0.720	0.753
Location 17	13	0.763	0.007	0.755	0.777
Location 18	13	0.794	0.009	0.783	0.815
Location 19	13	0.812	0.009	0.799	0.834

Notes: This table show the descriptive statistics for bilateral distances calculated using the Structural Similarity Index. The first row displays the results for all pairs of images within Sunton (13 images). The remaining rows display the results for each point (numbers correspond to locations shown in Figure B1) with all images in Sunton.